The Measured Upstream Impedance for Clarinet Performance and its Role in Sound Production

by

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Abstract

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The performer's use of the airways, including the mouth, tongue, throat, and lungs, during clarinet performance was studied by measuring the airway resonances. This research tested the theory that the performer tunes airway resonances to the harmonic frequencies of a tone, producing a more stable pressure oscillation. The resonances were determined from the upstream (airway) impedance, which was measured for clarinet performance directly using a one-microphone method and indirectly using the linear continuity of flow equation, the measured downstream (instrument) impedance, and simultaneous measurements of the upstream and downstream pressures. The indirect method was verified for single, normal tones at low pressure levels in the clarion and altissimo registers. Chalumeau-register tones had greater uncertainty in the magnitude, and the phase was indeterminate.

The airway resonances were examined during performance of several musical phenomena. Resonances were slightly stronger at piano dynamic levels, compared to forte, consistent with a decreased glottal opening at piano. A "closed throat" had resonances that were stronger and broader than an "open throat", which produced the better tone quality. The airways may have a role when playing clarion tones without the register key, although the reed resonance may also be involved. For tones with pitchbend, the performer created a strong airway resonance at the fundamental frequency. For multiphonics, the performer created an airway resonance at a frequency that was a simple linear combination of the instrument resonance frequencies, and

adjustment of airways resonance frequencies produced different multiphonics with the same fingering. In musical excerpts, the performer tuned the airways to the first or second harmonic, but there were also a number of tones that did not have an airway resonance aligned with a harmonic. In addition, the airways were involved in crossing register breaks, and there were variations that indicated the performer's use of the airways depended on the musical context.

In summary, the role of the airways in clarinet sound production is important, and more research is needed to fully understand the complex relationship between the performer's airways and the clarinet.

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Chapter 1

INTRODUCTION

It has often been noted that two people can produce totally different sounds on the same instrument. Musicians attribute this to the fact that everyone has their own conception of the sound that they carry around with them: you always sound like yourself, no matter what instrument you play on.

From a physics point of view, there must be something that the performer is doing to influence the sound. While the sound that a musician produces on a musical instrument depends on the instrument itself, the mouthpiece, the reed, and other equipment, the musician also has many adjustable physiological parameters that can influence the sound, including the formation of the embouchure and the position of the throat and tongue. By adjusting these parameters a musician can produce similar sounds on different instruments or different sounds on the same instrument.

How the performer influences the sound is a complex subject and is complicated by the fact that most of what the performer does is hidden away inside the mouth and throat behind the lips. It is difficult to observe what the performer is doing, unless one uses X-ray photography, and human performers do not have conscious control over many of the physiological variables, which makes it difficult to study systematic effects.

This study focuses on one physiological variable that the performer can adjust when playing the clarinet: the airways, which include the mouth, throat, and lungs, in order to understand how they influence the sound. Although it is debatable whether the use of the airways can be separated from all the other adjustments the performer makes, including embouchure and air flow adjustments, it is useful to study the airways alone to learn as much as possible about their influence before studying their interdependence with other variables.

The rest of this chapter reviews the literature of research on clarinet sound production, both including and omitting the performer's airways, and then presents the theories that will be tested and the major questions that will be addressed in this dissertation.

1.1 Review of the Literature

The first section of this literature review will describe the physiological system of the airways. Next, the registers of the clarinet will be briefly discussed, information that will be helpful in the following sections. Then the performance and pedagogical literature will be reviewed to present the ideas of performers and how they believe the airways influence sound production. The statements of performers have been tested by studies of physiological changes during clarinet performance. These studies will be summarized and their results compared to the pedagogical literature. The rest of the literature review consists of an overview of acoustical research on clarinet sound production. First, the theory of reed instrument acoustics will be summarized and physical models developed with this theory will be described. Then, sound regeneration theory and the theoretical role of the airways will be presented. The next two sections summarize the acoustical research done specifically on the clarinet, both with and without a consideration of the performer's airways. Finally, the questions left unanswered by this acoustical research will be summarized.

1.1.1 The Airways

The airways are the respiratory tract of the performer and consist of the vocal tract and the lungs. The vocal tract (Sundberg [70]) includes the mouth and the pharynx. The mouth, or oral cavity, contains the tongue and is bounded on top by the soft and hard palates and on the sides by the cheeks. The pharynx, or what is usually called the throat, is a wide tube extending from the bottom of the nasal cavities down to the top of the trachea. Contained in the bottom of the pharynx is a smaller diameter tube called the larynx. At the bottom of the larynx are the vocal folds, or vocal cords, which are two folds of muscles that form an opening called the glottis through which air flows for breathing, speaking, and wind-instrument playing.

The terms "vocal tract", "airways", and "upstream" will be used throughout this dissertation, and it is necessary to define precisely what each of these means.

The *vocal tract* is that part of the human anatomy consisting of the mouth and the throat, down to and including the larynx. These are the structures that the performer controls and adjusts. The instructions of teachers to students are given in terms of its components.

The *airways* are defined by the American Physiological Society [65] as "all passages of the respiratory tract from the mouth or nares down to and including the respiratory bronchioles." Thus the airways include the vocal tract as well as the lungs. When the impedance is measured, it is for the system of the airways, at the position of the lips and looking towards the lungs.

The *upstream* system is the same as the airways. This term is particularly convenient for describing the airways as they relate to physical models of wind instrument performance since the upstream system has a downstream counterpart, namely, the instrument.

1.1.2 The Registers of the Clarinet

The range of the clarinet is divided into three sub-ranges, or registers (Figure 1.1):

1. The chalumeau is from $E3$ to $B\flat 4$. Clarinetists designate the tones of the upper chalumeau register from about $E4$ or so up to $B\flat 4$ as "throat tones".

2. The same fingerings, with the register key open, give the tones in the clarion range, from $B4$ to $C6$.

3. The lifting of the first finger of the left hand produces the tones above and including $D\flat 6$, which is the altissimo register.

The "pitch" of a tone will refer to the pitchclass and octave of the tone produced by that fingering. All pitch names represent the written pitch. The $B\flat$ clarinet actually sounds a whole step lower, so that the written pitch $B4$ is 440 Hz.

1.1.3 Performance and Pedagogical Literature

Most teachers maintain that correct use of the vocal tract is necessary in order to play the clarinet well. According to Stein [67], the throat, tongue, larynx, oral cavity, overhead sinuses, and nasal and head cavities are all used to "voice" or shape the tone. It is questionable whether a performer has conscious control over all these parts, and teachers usually give their directives to students in terms of the throat and the tongue.

Teachers claim that the proper throat shape is essential for good tone quality, and Heim [36] states that "the position of the throat, that which is in an open relaxed shape, is one of the most vital factors for assuring good clarinet tone." Richmond [61] agrees and says that "the throat should be kept open and relaxed as in singing". Although an "open" throat is "good", a throat that is too open can also cause problems. According to Howard Klug [53], a yawn-like tongue position spreads the sound, producing a fuzzy, dull tone in the low register and an edgy quality in the third register. Intervals across register breaks become difficult to play.

The position of the tongue also affects tone quality, as well as articulation technique:

> The proper position of the tongue while blowing is advantageous in creating a better tone quality, a better and more fluid legato playing and, finally, when the tongue moves, a better attack and staccato. Therefore, according to this criteria, the tongue in its backward motion should always be held behind the lower denture, slightly arched downward. (Tosé [73])

A common instruction to students is to think of the sound /a/ as in "father" in order to lower the tongue for the low register. For the high register, students should think of the sound /i/ as in "eat", which raises the tongue and supposedly has the effect of increasing the air speed.

Klug states that the tongue position is critical for good tone quality in the throat tones, the tones in the upper chalumeau register:

> The so-called throat tones of the clarinet may be so named because they are located in the throat of the instrument rather than the throat of the player, but there is little doubt that the configuration of the student's throat has the most impact on these short tube notes. Opening the throat will produce an airy, unfocused sound; raising the tongue to an even higher E position than normal should give the tones the tonal core they require. (Klug [53])

In addition to its role in normal clarinet playing, the vocal tract is also thought to be important in producing nontraditional techniques such as pitchbend (or portamento) and multiphonics. Pitchbend, or portamento is the lowering of the playing frequency below its usual value. Rehfeldt [60] states that

> Portamento is accomplished by adjusting lip pressure, as well as the shape of the oral cavity, in such a way as to produce a pitch somewhat below the normal pitch.

The vocal tract is usually listed as one of the variables the performer changes when producing a multiphonic, which is two or more pitches played simultaneously, often with unusual timbres. Rehfeldt [60] mentions embouchure adjustments in addition to the requirement of a relaxed throat:

> The technique for obtaining multiple sonorities is basically identical to that for any other pitch. Higher and louder requires more jaw pressure on the reed at points farther down (toward the bell). Jaw movements cause the lower teeth to roll beneath the lower lip, the lip remaining basically stationary on the reed. The position of the facial configuration, the basic embouchure set, also remains stationary. For maximum resonance and proper tone center, the throat is relaxed.

Gerald Farmer [26] describes the technique in terms of embouchure, oral cavity, throat, and air pressure:

> Relaxation of the embouchure and oral cavity along with slightly less pressure from the bottom will often allow greater sensitivity to reed vibration, thus producing more reliable multiphonics. It is important, too, for the throat muscles to remain relaxed in order that a focus on a single tone be avoided. Air pressure may usually be described as less forced, with an attempt toward a slow, steady flow of air.

William O. Smith (Rehfeldt [60]), a pioneer of multiphonic technique on the clarinet, claims that expertise in the use of the throat might make multiphonics easier to play:

For some reason the multiphonics over a low E seem very difficult for others to play and I've sometimes wondered if my jazz background (especially throat control in the use of glissandi, etc.) has given me a set of peculiar characteristics (especially in terms of throat flexibility) that are not typical of those clarinetists trained only in the classical tradition.

1.1.4 Physiological Studies

Physiological studies have examined the positions of the tongue and throat during performance and have correlated these with tone quality and musical tasks. These studies have used two observational techniques: X-ray photography and laryngoscopy. X-ray photography gives a side view of the vocal tract and its structures. Laryngoscopy involves inserting a laryngoscope through the nasal cavity and positioning it in the larynx to provide a view of the vocal folds and the back of the tongue.

Anfinson [1] used X-ray photography to study vocal tract changes during articulation and during transitions between different registers on the clarinet. For register transitions he found virtually no adjustments when playing in the low (chalumeau) register. Noticeable adjustments began in the lower clarion register with concert *B*♭4 or *D*5 (written *C*5 or *E*5). He found that, as the pitch increased, the high point of the tongue lowered and moved farther forward, the throat opening became larger, the back of the tongue moved forward, and the posterior portion of the tongue withdrew slightly farther back and down.

Mooney [56] carried out a similar experiment, using X-ray photography to study the position of the tongue in different registers of the clarinet, and confirmed Anfinson's results. From *E*3 to *C*5, the tongue was arched back in the mouth, with the tip curved down and back from the lower teeth. The throat opening was small. From *C*5 to *E*5, there was a gradual lowering of the tongue as the tip moved forward and the throat opening became larger. For low tones the tongue was in a position similar to that used for /u/ as in "boot", with the back of the tongue high and arched. For high tones, the tongue had a shape used for "a" as in "father" or in "class", with all of the tongue low and flat. This contradicts the teachers who tell their students to use /i/ as in "eat" for the high register. Mooney said that what teachers really want is for the cheek muscles to be drawn up tight. In the /i/ position, the tongue almost closes off the air flow to the reed. He noted that the position of the tongue affects the amount and direction of air flow to the reed, as well as the size of the throat opening. Thus the shape of the vocal tract exerts an influence over many important factors.

Clinch, et al. [21] made X-ray fluoroscopic measurements of the vocal tracts of performers of the clarinet, soprano saxophone, and recorder. For the clarinet and saxophone, they found that the tongue position was similar to positions used for spoken vowels. On the clarinet, they found that as the pitch increases in the low register, the tongue and larynx rise, which for spoken vowels would cause an increase in the vocal tract resonance frequency corresponding to the vocal tract shape for the vowel "ah". In the high register, the tongue and larynx lower with increasing pitch as the tongue moves more forward in the mouth as for the vowels in "heed", "hid", and "head", which contradicts the results of Mooney, who found that the shape of the vocal tract for high tones was more like the vowel /a/.

Compagno [22] used a laryngoscope to examine the larynx and the back of the tongue of flutists and clarinetists during the performance of musical tasks that included articulation and register changes. For clarinetists, he found that some subjects had laryngeal movements during register changes and others did not. The movements included a sudden raising or lowering of the larynx and a lateral opening or closing of the glottis. Subjects who had these movements also had an interruption in the tone during the register change. Subjects who kept these structures motionless were able to make a smooth slur. He found that, as the pitch increased, the larynx ascended and the pharyngeal cavity increased in size as the tongue moved down and forward, confirming the results of Anfinson and Mooney. He also found that as the dynamic level increased from piano to forte, the glottal opening increased and the larynx ascended.

1.1.5 The Theory of Reed Instrument Acoustics

This section reviews the early theoretical work in wind instrument acoustics, and in clarinet acoustics in particular, that emphasized the role of the reed. Benade and Larson [13] and Benade and Kouzoupis [12] have summaries of these results and later work in the theory of sound regeneration.

Weber [74] was the first to study the role of the reed in wind instrument sound production. He modelled the reed as an undamped, driven, linear harmonic oscillator. Although he was dealing with metal reeds on organ pipes, he did show that pipe mode frequencies less than the resonance frequency of the reed are lowered slightly by the presence of the reed.

Helmholtz [37] also treated the reed as a damped harmonic oscillator and formulated a linear theory for the oscillations of a reed and pipe. He theorized that, since the reed needs large pressure fluctuations in order to operate, and since the pressure fluctuations at the closed end of a pipe are large, then an end of a pipe with a reed attached acts like an effective closed end. He determined that the playing frequency has to be either near the reed resonance frequency or just below a modal frequency of the instrument. He found that clarinets have odd harmonics and observed no experimental evidence of even harmonics.

Bouasse [16] did not present any mathematical theories, but he did conduct extensive experiments on wind instruments that formed the basis for later nonlinear theories. One of his observations was that the reed motion is stabilized if there is an air column mode at a harmonic of the sounding frequency.

Backus [3] developed a linear theory for small amplitude oscillations of the clarinet that allowed him to calculate the threshold blowing pressure and the operating frequency. He determined experimentally the nonlinear function of the clarinet reed relating the flow u though the reed tip to the pressure difference p across the reed and the reed tip opening x:

$$u = 37p^{\mu}x^{\nu} \tag{1.1}$$

where $\mu = 2/3$ and $\nu = 4/3$, and all quantities are in CGS units.

Nederveen [57] developed a theory based on that of Backus, including reed motion. He calculated the impedance of the instrument by successively replacing each open tone hole by an equivalent length. He then set up the three equations for the forces on the reed, the motion of air in the reed slit, and the total flow, and solved them for small amplitude vibrations. He applied his theory to double reeds and found that the nonlinear flow function for double reeds differs from that for single reeds, with $\mu = 1/2$ and $\nu = 1$. Later work by Gilbert [33] and Keefe and Waeffler [46] showed that the different exponents obtained for the single reed are due to flow through the sides of the reed, and that in fact single reeds are similar to double reeds since $p^{2/3}x^{4/3} = (\sqrt{p}x)^{4/3}$.

1.1.6 The Theory of Sound Regeneration and the Role of the Airways

The rest of the theory literature review will outline in detail the theory to be used in this dissertation. This section will review the current state of the theory of wind instrument sound regeneration in both the linear and nonlinear formulations and how the performer's airways fit into this theory. First, the linear regeneration condition that must be satisfied in order to sustain an oscillation will be derived. Then, the second-order nonlinearity is included, and the implications are discussed. An expression for the total impedance of the instrument, reed, and airways system will be derived, and this expression shows how the airways enter into the regeneration process. Finally, an expression for the airway impedance will be derived that can be used to study the role of the airways experimentally.

The theory that will be discussed is formulated in the frequency domain in terms of impedance. The impedance of a resonant system, such as a clarinet or the airways, gives the pressure response as a function of frequency when a unit flow impulse is transmitted from the input end, e.g. the reed tip of a clarinet. The impedance $Z(\omega)$ is related to the pressure $P(\omega)$ and the volume flow $u(\omega)$ by the equation:

$$Z(\omega) = \frac{P(\omega)}{u(\omega)} \tag{1.2}$$

Throughout this dissertation, $Z(\omega)$ will be written simply as Z, but frequency dependence is implied.

Impedance is a useful quantity for the study of reed wind instruments because peaks in the impedance curve correspond to the resonant modes of the system and are called resonances. An input flow at the frequency of an impedance peak produces energy at that frequency, which can help sustain an oscillation.

The inverse of the impedance is the admittance Y, defined as $Y = 1/Z$. In some situations it is more convenient to use admittance since it often simplifies algebraic expressions. Both admittance and impedance will be used in the work presented here, depending upon the situation at hand.

The Linear Theory of Sound Regeneration

The linear theory of regeneration describes the conditions necessary for a sustained oscillation and has been presented in two different frameworks: that of the reed transconductance and that of the generator admittance. Thompson [71, 72] derived the role of the reed transconductance, which was further discussed by Benade [7] and Hoekje [42]. The generator admittance and its relation to the air column admittance were derived by Fletcher [28] and discussed by Fletcher and Rossing [30] and Keefe [48]. Keefe noted that the formulations with the generator admittance and with the reed transconductance were equivalent. The presentation here will follow that of Fletcher [28] and Keefe [48].

In order to derive the conditions for sound generation, one must consider the physical processes at the reed tip, the location where the sound generation occurs. Assuming that the air flowing through the reed tip is an ideal, incompressible fluid and that the Bernoulli relation is valid for flow with steady and oscillatory components, the flow u through the reed tip is described by:

$$u = B\sqrt{\frac{2}{\rho}}wx\sqrt{p} \tag{1.3}$$

B is a scaling factor of order unity, ρ is the density of air, w is the effective reed width, and x is the reed displacement.

The pressure difference p across the reed is $p_u - p_d$, where p_u is the upstream pressure and p_d is the downstream pressure (see Figure 1.2). The terms "upstream" and "downstream" refer to the systems relative to the direction of the air flow coming from the performer at the reed tip.

The variables x, p, and u are expressed as sums of their DC and AC components:

$$\begin{aligned} x(t) &= x_0 + \tilde{x}(t) \\ p(t) &= p_0 + \tilde{p}(t) \\ u(t) &= u_0 + \tilde{u}(t) \end{aligned} \tag{1.4}$$

Substituting for x, p, and u into the flow equation 1.3 and keeping only linear terms, under the assumption that the oscillating components are much less than the steady components, gives a linearized version of the flow equation:

$$\begin{aligned} u &= u_0\{1 + (\frac{1}{2}\frac{\tilde{p}}{p_0} + \frac{\tilde{x}}{x_0})\} \\ u_0 &= B\sqrt{\frac{2}{\rho}}wx_0\sqrt{p_0} \end{aligned} \tag{1.5}$$

Assuming a periodic solution, the equation for the nth Fourier component of the flow is:

$$\frac{u_n}{u_0} = \frac{1}{2}\frac{p_n}{p_0} + \frac{x_n}{x_0} \tag{1.6}$$

The variable u_n is defined as the nth Fourier component of $\tilde{u}(t)$ at the frequency nf, where f is the sounding frequency, and p_n and x_n are defined similarly.

The ratio x_n/x_0 is found from solution of the reed equation of motion for the inward-striking single reed of the clarinet:

$$\ddot{x}(t) + g_r\dot{x}(t) + \omega_r^2\{x(t) - H\} = -\frac{1}{\mu_r}p(t) \tag{1.7}$$

g_r is the reed damping coefficient. ω_r is the reed resonance (radian) frequency. H is the static reed opening. μ_r is the dynamic mass per unit area of the reed. Transforming Eqn. 1.7 to the frequency domain and solving for x_0 and x_n gives:

$$\begin{aligned} x_o &= H - D_r p_0 \\ x_n &= -D_n p_n \end{aligned} \tag{1.8}$$

D_r is the static reed compliance:

$$D_r = \frac{1}{\mu_r\omega_r^2} = \frac{H}{p_c} \tag{1.9}$$

where p_c is the closing pressure of the reed. D_n is the dynamic reed compliance:

$$D_n = \frac{D_r}{1 - (n\omega/\omega_r)^2 + jQ_r^{-1}(n\omega/\omega_r)} \tag{1.10}$$

ω is the fundamental frequency in radians and Q_r is the reed quality factor:

$$Q_r = \frac{\omega_r}{g_r} \tag{1.11}$$

Equation 1.6 for the flow then becomes

$$\frac{u_n}{u_0} = \frac{p_n}{p_0}\left(\frac{1}{2} - \frac{D_n p_0}{H - D_r p_0}\right) \tag{1.12}$$

The nth component of the acoustic generator admittance Y_{Gn} is defined looking back upstream as:

$$Y_{Gn} = \frac{u_n}{p_n} = \frac{u_0}{p_0}\left(\frac{1}{2} - \frac{D_n p_0}{H - D_r p_0}\right) \tag{1.13}$$

The pressure and flow are also related to the dissipative admittance Y_n of the system consisting of the instrument, airways, and reed. The nth component of the dissipative admittance Y_n is defined looking in the opposite direction:

$$Y_n = \frac{u_n}{-p_n} \tag{1.14}$$

The pressure difference $p = p_u - p_d$ is the difference between the upstream pressure p_u and the downstream pressure p_d (see Figure 1.2). The admittance is defined in terms of $(-p)$ since the pressure in the mouthpiece ultimately is transformed into the radiated sound.

The condition that must be satisfied in order for sound to be generated at the frequency $n\omega$ is

$$Y_n + Y_{Gn} = 0 \tag{1.15}$$

Since both Y_n and Y_{Gn} are complex quantities, there are actually two conditions that must be satisfied:

$$Re(Y_n) + Re(Y_{Gn}) = 0 \tag{1.16}$$

and

$$Im(Y_n) + Im(Y_{Gn}) = 0 \tag{1.17}$$

The real part of the admittance expresses the energy loss or gain of a system. Since the resonating system is a lossy system, $Re(Y_n) > 0$, and Eqn. 1.16 states that the losses of the resonating system must be balanced by the energy input of the generator. This implies that $Re(Y_{Gn}) < 0$, and this inequality is the source of the term "generator", since a negative resistance generates energy. For inward-striking reeds such as on the clarinet, $Re(Y_{Gn})$ is negative only for frequencies less than the reed resonance frequency, and therefore sound can only be generated for frequencies $\omega < \omega_r$.

Equation 1.16 also determines the minimum blowing pressure for sound generation. The minimum blowing pressure p_{min} at which energy can be generated is the pressure for which $Re(Y_{Gn}) = 0$, and energy can be generated for pressures larger than p_{min}, up to the closing pressure of the reed. The blowing pressure at which Eqn. 1.16 itself is satisfied is the threshold blowing pressure p_{th} and is the pressure at which the energy input by Y_{Gn} exactly balances the energy dissipated by Y_n at each frequency nf.

The condition fulfilled by the imaginary parts of the admittance, Eqn. 1.17, determines the playing frequency. For an inward-striking reed, $Im(Y_{Gn})$ is positive for pressures larger than p_{min}. Therefore, $Im(Y_n)$ must be less than zero, which implies that the playing frequency must be less than the frequency of a resonant mode, since the imaginary part of admittance is always negative at frequencies just below a resonance. If there is more than one mode that satisfies this condition, then the mode that sounds will be the one for which $Re(Y_n)$ is the smallest, that is, the mode with the lowest losses.

The generator admittance Y_G here (omitting the subscript n) is equivalent to the quantity Y_r in Fletcher's [28] notation, and this discussion has been similar to his. Thompson [71, 72], who derived the same results simultaneously, worked from the viewpoint of the reed transconductance A, where $A = -Y_G$. In terms of his notation, the regeneration conditions are

$$|A| = \frac{1}{|Z|} \tag{1.18}$$

and

$$\alpha = \zeta, \tag{1.19}$$

where Z is the combined impedance of the air column and the reed, and α and ζ are the phases of A and Z, respectively. Thompson pointed out that these conditions are satisfied if the playing frequency is near a Z peak or if the reed resonance frequency f_r is near a harmonic frequency, and the strength of a pressure harmonic is increased if there is a Z peak near a harmonic frequency.

Equations 1.16 and 1.17 give two conditions that must be satisfied in order for sound to be generated. These conditions must be satisfied exactly at each frequency $n\omega$ for a stable oscillation. If they are not satisfied exactly, then the oscillations will die out or grow out of control. This changes when higher-order terms are retained from the expansion of the pressure-flow relation Eqn. 1.3. Benade and Gans [9] were the first to point out that when the second-order terms are kept, the oscillations at harmonics frequencies are coupled together, and this phase-locking stabilizes the spectrum. Energy is shared between different frequency components, and the regeneration conditions no longer have to be satisfied exactly at every frequency. The energy generated at one component can go to feed the oscillation at another component, and the resulting oscillation is a compromise among the conditions at the different harmonic frequencies. Worman [75] formalized this theory mathematically and solved the coupled nonlinear equations for a "clarinet-like" system, which was a clarinet mouthpiece attached to a tube with a single resonance.

The Total Impedance of the Instrument, Reed, and Airways

The performer's airways enter into the regeneration process via the dissipative admittance in Eqn. 1.15 or, equivalently, via the impedance in Eqns.1.18 and 1.19, which contain a contribution from the airways. In order to determine exactly how the airways influence sound production, an expression must be derived for this dissipative term. Working in terms of impedance simplifies the derivation, and so an expression for the dissipative impedance will be derived, which can be transformed into the admittance in Eqn. 1.15 by $Y = 1/Z$.

The role of the performer's airways in the sound generation process was developed simultaneously by Benade and Hoekje [10] and by Elliot and Bowsher [25] in two slightly different ways. Benade and Hoekje derived the theory for wind instruments in general, while the derivation of Elliot and Bowsher was in the context of brass instruments, although both derivations give equivalent results. The description that follows is along the line of the work of Benade and Hoekje, which was further described by Benade [7], Hoekje [42], and Keefe [48].

The role of the performer's airways can be studied by determining how they contribute to the total impedance of the combined system of the instrument, performer, and reed. The total impedance Z is just the inverse of the admittance in Eqn.1.14:

$$Z = \frac{1}{Y} = \frac{-p}{u}, \tag{1.20}$$

where the subscript n has been suppressed. This total impedance must be related to the impedances of the instrument, the airways, and the reed.

The instrument impedance is defined as the downstream impedance Z_d:

$$Z_d = \frac{p_d}{u_d}, \tag{1.21}$$

where p_d is the downstream pressure measured inside the mouthpiece tip, and u_d is the downstream flow just inside the mouthpiece tip.

The impedance of the performer's airways, measured at the mouthpiece tip looking into the airways, is defined as the upstream impedance Z_u:

$$Z_u = \frac{p_u}{-u_u}, \tag{1.22}$$

where p_u is the upstream impedance measured inside the performer's mouth at the mouthpiece tip and u_u is the upstream flow from the airways into the mouthpiece tip. The minus sign is needed because the upstream impedance Z_u is calculated looking into the airways while the upstream flow u_u is coming out of the airways.

The acoustic impedance of the reed Z_r is related to the flow u_r swept out by the reed and the pressure difference p across the reed:

$$Z_r = \frac{p}{u_r}. \tag{1.23}$$

The volume flow u_r is the product of the reed tip velocity $\dot{x}$ and the effective reed area S_r:

$$u_r = j\omega S_r x \tag{1.24}$$

The reed impedance is found by combining Eqns. 1.23, 1.24, and 1.8:

$$Z_r = \frac{1}{-j\omega S_r D_n} \tag{1.25}$$

To relate these three impedances together, it is sufficient to note that continuity of flow implies that the flow u_u coming into the instrument from the airways is equal to the flow u_d just inside the mouthpiece tip, and both are equal to the total flow $u + u_r$:

$$u_u = u + u_r \tag{1.26}$$

$$u_d = u + u_r \tag{1.27}$$

Substituting the expressions 1.21, 1.22, and 1.23 for the flows in equations 1.26 and 1.27 gives:

$$Z = -\frac{p}{u} = \frac{Z_r(Z_d + Z_u)}{Z_r + Z_d + Z_u} \tag{1.28}$$

Z is the total impedance of the instrument, reed, and airways combination. The instrument and airways are in series, and their sum is in parallel with the reed:

$$\frac{1}{Z} = \frac{1}{Z_r} + \frac{1}{Z_d + Z_u} \tag{1.29}$$

Written this way, it is clear that the instrument and airways act as a single system, and it is the sum of their impedances ($Z_u + Z_d$) that affects the oscillation.

In the linear theory, oscillations will occur at frequencies where the total impedance is large. If we restrict the analysis to frequencies below the reed resonance frequency, which is the fundamental frequency range of the clarinet, the term containing the reed impedance Z_r can be neglected in Eqn. 1.29 since Z_r is large in this range, and the total impedance is just the sum of the upstream and downstream impedances. In this frequency range, the linear theory predicts that oscillations can occur at frequencies wherever there are peaks in Z_d or Z_u. The effect of the reed, when its effect is included, is to lower the oscillation frequency slightly from that of the impedance peak.

When second-order terms are retained in the expansion of the nonlinear flow relation (Eqn.1.3), harmonic frequencies are coupled together, and sum and difference frequencies are generated to produce a phase-locked oscillation with harmonic components, as described by Benade and Gans [9] and Worman [75]. They recognized that impedance peaks aligned with harmonic frequencies will stabilize the oscillation. The total impedance is approximately ($Z_d + Z_u$), and the peaks of this total impedance will stabilize the oscillation if they are aligned with harmonic frequencies. This can be accomplished by having the peaks of Z_u and/or Z_d harmonically aligned.

Benade [7] realized that the harmonic alignment of upstream impedance peaks has musical implications since the performer can affect the sound that is produced by changing the upstream resonances. He theorized that by aligning Z_u peaks performers create tones that are easy to control, which would lead to a good musical performance. The use of airways then becomes one way that the performer can influence the sound.

Measuring the Upstream Impedance

In order to study the role of the upstream impedance Z_u experimentally, a way to measure it must be found. An expression that can be used to determine Z_u experimentally can be derived from the consideration of the continuity of flow at the reed tip. Since there is no net flow produced in the region of the reed tip, the upstream flow is equal to the downstream flow:

$$u_u = u_d \tag{1.30}$$

Substituting for the flows from Eqns. 1.21 and 1.22 gives:

$$\frac{-p_u}{Z_u} = \frac{p_d}{Z_d} \tag{1.31}$$

Note that the reed flow u_r cancels out in this derivation because there is no net flow produced by the reed, and therefore this relation between the upstream and downstream pressures and impedances is independent of Z_r.

Elliot and Bowsher [25] were the first to derive this equation, although in the context of brass instruments. They represented the system of the performer, reed, and instrument as an electrical circuit with the pressure source as a steady pressure in series with a Thevenin impedance, which is equivalent to Z_u here. They divided the lip reed impedance into a component on the mouth or source side and a component on the instrument side, since the lips do not necessarily move symmetrically in both directions. They derived that the ratio of the mouth and instrument pressures is proportional to the ratio of the lip reed impedances defined on each side of the lips and is also proportional to the ratio of the source and instrument impedances. Elliot and Bowsher noted that one can estimate the ratio of the impedance magnitudes by comparing the mouth and instrument pressures, and they presented analyses of experimental data where they did just this. Although they did not calculate Z_u explicitly, they did infer its value relative to Z_d from the pressure ratio, and they recognized the importance of this expression in obtaining information about Z_u.

Keefe [48] derived Eqn. 1.31 in the framework of flow continuity presented earlier and noted the importance of this relation, that the upstream impedance can be calculated from the instrument impedance and simultaneous measurements of the upstream and downstream pressures. Knowledge of the reed parameters is unnecessary since this expression is independent of the reed. Eqn. 1.31 is an indirect measurement of the upstream impedance, which cannot be measured directly with any current system during performance. If this equation can be experimentally verified, it could then be used to find Z_u in situations where it cannot be measured directly, for example, during performance of a musical excerpt.

In order to apply this indirect method of measuring Z_u in practice, the upstream and downstream pressures must be measured simultaneously during performance. The pressure measurements, along with a measurement of the instrument impedance Z_d, are used to calculate Z_u. This method assumes that the instrument impedance measured under small-signal conditions with zero mean flow is equal to the impedance under playing conditions, which are large signal and non-zero mean flow. In other words, the pressure standing wave should be due to linear acoustic effects only and nonlinear flow effects should be negligible. The accuracy of this assumption will be discussed in Section 4.1.

1.1.7 Physical Modelling of the Clarinet

Several researchers have used this theory to model the behavior of the clarinet numerically. The following studies do not include any effect of the performer's airways.

Schumacher [62] used an impedance-based model to calculate the reflection function of the clarinet in the time domain. The results he obtained were plausible for an actual clarinet, but he did not make corresponding measurements. He showed the effect of the register hole and the reed parameters on the impedance. Impedance curves were shown for both normal tones and multiphonics. His results agreed with Backus [4, 5] for high notes and multiphonics, but for low tones his peaks had a lower quality factor Q and the cut-off frequency was low.

Stewart and Strong [68] modeled the clarinet and mouthpiece as a lumped element transmission line and the reed as a non-uniform bar clamped at one end. The resulting differential equations were solved for the pressure and volume velocity in the tube and mouthpiece and for the reed position. They observed self-sustained oscillations, a threshold blowing pressure, frequency shifts, and the spectra of mouthpiece and radiated pressures for both beating and nonbeating reeds. All were similar to a simplified clarinet. The differences between their results and the measurements of Backus were attributed to differences in reed Q, reed stiffness, and other parameters.

Gilbert et al. [34] applied the method of harmonic balance to a model of the clarinet. In this method, the resonator is modelled in the frequency domain and the excitation is modelled in the time domain. Although this method does not give transients, it does give all possible periodic regimes and it is well-suited for demonstrating the effect of parameter changes on playing frequency and spectrum. They showed their results for playing frequency and spectrum as a function of pressure difference as well as displacement, pressure, and volume velocity waveforms. Their results agreed with Worman [75] and Schumacher [62].

Keefe [49] described a real-time model of a clarinet based on Schumacher [62] as three first-order differential equations with time delay using as variables the reed displacement, the reed velocity, and the air flow through the reed aperture. The blowing pressure and the reed resonance frequency f_r were the parameters that were varied. He found no enhancement of peaks aligned with f_r and no frequency locking of f_r with a harmonic. This was attributed to the realistic broad reed resonance ($Q_r = 3$). However, the sounding frequency was strongly influenced by f_r. As f_r increased, the sounding frequency increased, bounded by the frequency of the impedance peak.

1.1.8 Experimental Research on the Clarinet

Experimental research on clarinet sound production has focused on impedance measurements and pressure spectra, and more recently on nonlinear hydrodynamical effects. Research on these topics that has not included the airways will be reviewed in this section, as well as the research that has been done on the role of the reed resonance.

Impedance Measurements of the Clarinet

Backus [4, 5] used a capillary-tube method to measure the impedance of the clarinet, bassoon, oboe, and saxophone for normal and multiphonic fingerings. For the clarinet, he attached an adapter to the reed window to measure the impedance directly at the mouthpiece tip. Impedance peaks ranged over 400–1600 CGS ohms for the various instruments. (All ohms are CGS acoustic ohms: 1 CGS ohm = 1 dyne-second/cm^5.) For the clarinet he measured the first peak in the chalumeau register to be 800–1000 CGS ohms and the second peak was 500–700 CGS ohms. For the lowest note $E3$, the first two peaks were 790 and 500 CGS ohms. The resonance peak of the fundamental always had the highest impedance value, except for notes at the top of the clarion register and higher. The instrument actually played 40-70 cents flat of the impedance peaks, as predicted by the linear theory. He found that for chalumeau register notes the resonances were compressed relative to the fundamental, and in the clarion register the resonances were randomly distributed in relation to the harmonics.

Thompson [71] showed impedance curves measured on a *Bb* clarinet for the fingerings of G3, C4, and G4, although he did not specify the method used, and the curves are uncalibrated.

Hoekje [42] measured the input impedance of the clarinet, alto clarinet, tenor sax, trumpet, and trombone by measuring the response to a flow impulse generated by a piezoelectric disk. He did not specify how the transducers were positioned at the input end of the instrument. He found the height of the impedance peaks to be in the range 100–1000 CGS ohms. The one note that he reported for the clarinet ($C4$) had a first peak of 650 CGS ohms and a second peak of 420 CGS ohms.

Gibiat and Laloë [32] used a two-microphone-three-calibration method to measure the input impedance of a soprano clarinet and a bass clarinet. They showed results for only one note on each. In their measurements, the mouthpiece was replaced by a cylindrical tube of the same volume as the mouthpiece and the same diameter as the inner bore at the top of the barrel. They stated that this gives good approximation to the impedance at the reed tip when the impedance is high, i.e. at the peaks. Their impedance graphs appear to be in units of $Z/(\rho c/S)$, although it is printed as $Z/\rho c$. For the soprano clarinet they showed the impedance curve for $E3$. The first and second peaks had values of 900 and 450 CGS ohms, respectively, which agree approximately with the values of Backus [4], although the higher frequency peaks do not show the irregular structure that Backus measured.

Benade and Keefe [11] showed impedance curves up to 2000 Hz for the fingerings from $E3$ to $C5$ measured on a Buffet clarinet and on Benade's NX clarinet. The impedance was uncalibrated and the measurement method was not described. The NX clarinet was a modern Boehm instrument with an air column that had been modified to improve its modal frequency alignment. Compared to the Buffet, the impedance of the NX clarinet was more smoothly varying with respect to pitch, which would lead to smoother variations in the sound spectra across the different registers.

Pressure Measurements of Sustained Clarinet Tones

Backus [2] used an artificially-blown clarinet with DC "mouth" pressures of 5–20 inches H_2O (12.7–50.8 cm H_2O) and observed the reed tip opening and the mouthpiece pressure. To measure the mouthpiece pressure, he inserted a microphone into the side of the mouthpiece just upstream of the ligature. For soft tones, the reed motion was nearly sinusoidal. For loud tones, the reed closed completely for about 1/2 cycle. He found that for loud tones the maximum reed opening occurred when the mouth and mouthpiece pressures were equal. He gives waveforms for the tones $E3$, $E4$, and $G4$ at loud, medium, and soft dynamic levels. For the tone $E3$, the amplitude of the pressure waveform inside the mouthpiece increased from 160 dB to 166 dB (all dB refer to Sound Pressure Level: SPL) when the dynamic level increased from soft to loud. (He did not specify whether this was peak or RMS amplitude.) For the tone $E4$, the increase was from 158 to 165 dB. Since the increase measured outside the instrument was much larger, he concluded that the increase in loudness with blowing pressure was due to an increase in the higher harmonics.

DC pressures have been measured inside the mouthpiece of the clarinet and inside the performer's mouth. Since the DC pressure in the mouth is much larger than in the mouthpiece, the mouth pressure has been easier to measure.

The first known measurement of DC mouth pressure was by Stone [69] who measured the pressure during performance for several wind instruments by inserting into the corner of the performer's mouth a small glass tube that was connected to a water manometer. For notes played at a mezzo forte dynamic level, he found that the DC mouth pressure of a clarinetist was 15 inches H_2O (38.1 cm H_2O) for lower notes and 8 inches H_2O (20.3 cm H_2O) for higher notes. He found that the clarinet was exceptional among all wind instruments in that mouth pressure decreased as the pitch increased.

These results were confirmed by Bouhuys [17] who used a small air-filled balloon (volume = 2–3 ml) in the performer's mouth. A thin polyethelene tube in the corner of the mouth connected the balloon to an Elema pressure transducer. For a fortissimo low note on the clarinet, he measured 44 mm Hg (59.8 cm H_2O) and for a fortissimo high note, he measured 35.6 mm Hg (48.4 cm H_2O). He also found that the clarinet was the only wind instrument that had decreasing mouth pressure with increasing pitch.

Kobata and Idogawa [54] reported DC measurements of the mouthpiece pressure for an artificially-blown clarinet with all tone holes closed (fingering for $E3$). They measured DC mouthpiece pressures of 0.30-0.35 kPa (3.0–3.6 cm H_2O) for all vibration states that they studied. They found no evidence of flow into the mouth, which would occur if the sum of the DC and AC mouthpiece pressures were greater than the sum of the DC and AC mouth pressures at any single instant in time, although they were not able to measure DC and AC mouthpiece pressures simultaneously. In a separate paper (Idogawa et al. [43]) they reported vibration states over a range of mouth (i.e. blowing chamber) pressures of 2–12 kPa (20.4–122.4 cm H_2O) and found that lower pitches required greater blowing pressures, in agreement with Bouhuys and Stone.

One component of the pressure spectra that has received little attention in experimental work has been the noise inherent in the sound generation process. This sound generation noise has been recognized as an important component of realistic sounds, from both musical instruments and the voice (Chafe [20], Chafe [19], Cook [23]). When incorporated properly into synthesis algorithms, this noise produces a more realistic tone quality. Certain features of the noise, such as low amplitude subharmonic peaks, have been indirectly detected using the norm difference method (Schumacher and Chafe [64], Schumacher [63]) but have never been directly observed in the pressure spectra.

Multiphonics

The current knowledge of the physics of multiphonics has been gained through the study of their pressure spectra. Benade [8] and Backus [5] both studied the pressure spectra of multiphonics. Benade looked at two clarinet multiphonics and one oboe multiphonic and explained the spectra as the interaction of four independent oscillation frequencies. Backus studied multiphonics played on the bassoon, clarinet, oboe, and flute and found that Benade's description could be simplified by considering only the two strongest components in the pressure spectra. All other frequency components could be expressed as linear combinations of these two frequencies. The two strongest frequency components, which correspond to the audible tones, generate the other components by heterodyne modulation at the reed, which has a nonlinear flow control characteristic that is favorable for harmonic generation.

Schumacher [62] found that the components in the multiphonic spectra of Benade and Backus could be represented as

$$f_{nm} = nC + mD. \tag{1.32}$$

n and m are positive integers and C and D are two basis frequencies, not necessarily the frequencies of the audible tones. With his computer model of clarinet tones, he numerically generated the two multiphonics studied by Benade and found that for both of them $C = D$; in other words, both numerically-generated multiphonics had a single basis frequency and they were in fact periodic.

Keefe and Laden [51] analyzed the spectra of Benade and Backus and found that C and D are both themselves multiples of a fundamental frequency f_o and that the ratio C/D is a ratio of small integers. The oscillation is phase-locked to a basis frequency f_o, and this provides the stability for the oscillation. Fletcher [27] showed theoretically that such mode-locking is possible on musical instruments when the mode frequencies are nearly harmonic, the mode amplitudes are large, and there is a large nonlinearity in the driving force. Nonharmonic modes, as in multiphonics, can also produce a stable oscillation if their frequencies are in a ratio of small integers.

In summary, the pressure spectra of multiphonics consist of two main oscillation frequencies and their intermodulation components. Each component is also a multiple of a single fundamental basis frequency f_o.

Hydrodynamics of the Clarinet Mouthpiece

The hydrodynamics of the air flowing through the mouthpiece are affected by the design of the bore. Slight changes in the design of the mouthpiece can affect the air flow and the sound produced by the instrument. These flow effects must be understood for a complete picture of how the clarinet works.

The clarinet mouthpiece (Figure 1.3-a) is nonuniform and rapidly-changing near the tip. The bore at the tip is fairly narrow with flat, nearly parallel side walls and increases rapidly. At the midpoint of the mouthpiece there is a discontinuity as the bore changes from one with straight side walls to a cylinder. The mouthpiece can be generalized as a nonuniform bore (the half nearest the reed tip) connected to a uniform, cylindrical bore by a discontinuity. At the very tip of the mouthpiece is the reed channel (Figure 1.3-b), a narrow passageway of length L and height h formed by the reed and the mouthpiece. There are also open spaces along the sides of the reed (not shown in the Figure) where it does not contact the mouthpiece in its equilibrium position. Due to the narrow reed channel, the quickly-varying bore shape, and the sharp edges at the midpoint transition, hydrodynamic effects could become important factors in determining pressure variations.

Research related to flow in the clarinet mouthpiece has focussed on nonlinear flow effects due to the construction at the reed tip (Hirschberg et al. [40], Van Zon et al. [77], Hirschberg et al. [38]). Hirschberg et al. [39] give a good summary of the current state of knowledge in this area. The mouthpiece has been modelled as a two-dimensional aperture with no flow through the sides. Due to the sharp edge of the mouthpiece at the transition from the reed channel to the mouthpiece, the flow through the reed channel separates from the mouthpiece wall. For their two-dimensional model, Hirschberg et al. [38] distinguished two types of flow, which depend upon the ratio h/L, where h and L are the reed channel height and length: 1.) For long reed channels ($h/L \leq 0.25$) the jet reattaches to the wall after a distance of about $2h$. 2.) For short reed channels ($h/L \geq 0.5$), the jet does not reattach and there is fully separated flow into the mouthpiece. The transition between the two types of flow is a nonlinear effect and is expected to occur when the reed oscillation is large, since a changing h will create a range of h/L values during the course of a cycle.

The position of the flow separation point is important since it will determine the jet width and therefore the volume flux. Hirschberg et al. [38] theorized that if the transition from the reed channel to the mouthpiece is smooth, then the separation point will not be fixed and this could lead to unsteady flow. This is an example of how small changes in mouthpiece design can drastically alter sound production.

Gilbert [33] made similar measurements, although using a clarinet mouthpiece and air column rather than a two-dimensional model, and found that the flow through the sides made an important contribution. He was not able to observe a transition between the fully separated jet flow regime and the reattached flow regime, and in fact he observed no separated regime.

In their models, Hirschberg et al. [38] and van Zon et al. [77] assumed that the mouthpiece pressure is uniform and equal to the pressure at the end of the reed channel. Van Zon et al. measured the mouthpiece pressure and stated that the pressure variation over the mouthpiece was less than 3% of the dynamic pressure in the jet.

There has been no work done concerning the transition at the midpoint of the mouthpiece. The sharp edges at that transition could also cause flow separation and vortex shedding.

The Reed Resonance

The resonance of the reed deserves its own separate section because some of the effects attributed to the upstream resonances have also been explained as effects of the reed resonance. This section will review the research that has been done on determining the reed resonance frequency and its effects. Summaries of the effect of the cane reed resonance and its inclusion in physical models of wind instruments are given by Benade [8], Plitnik and Strong [59], Benade and Kouzoupis [12], and Benade and Keefe [11].

Worman [75] measured the resonance frequency of the clarinet reed to be about $f_r = 2500$ Hz and its quality factor to be about $Q = 3$. This implies a resonance bandwidth of $\Delta f = f_r/Q = 800$ Hz, and so the reed resonance could affect frequencies approximately in the range 2000–3000 Hz.

Thompson [71, 72] studied the effect of the reed resonance frequency and its role in tone production, and he concluded that the performer exercises considerable control over tone quality by modifying the resonance frequency of the reed through changes in embouchure pressure on the reed. He used an artificially excited clarinet and a metal reed with a resonance frequency of about 2500 Hz which was adjustable, and a Q of 10 [11]. One aspect in which the artificial system that Thompson used differed from a human performer was that the silicon used to simulate the lip had much lower damping than actual lips, which gave the reed an unrealistically high Q. He found that when the air column resonance was damped with glass wool and the reed vibration supported by an electronic feedback loop, a tone in the range of 2–3 kHz could be produced by varying the embouchure. Thompson took the frequency of this oscillation to be the resonance frequency of the reed, f_r. When this frequency was adjusted to match a harmonic, he found that the amplitude of that harmonic was increased and the oscillation was stabilized. He suggested that this is how a performer plays in the clarion register without opening the register key (bugling): f_r is adjusted to align with one of the harmonics. This is in agreement with performers, who claim that embouchure changes are responsible for this effect. Clarinetist Charlie Neidich [58] stated that as the teeth are moved down the reed, higher partials are possible, and one of the clarinetists in this study (B) said that it was helpful to bite harder and use more mouthpiece in the mouth. Another function of the reed resonance could be alignment with a harmonic for tones in the clarion range and above in order to stabilize them and improve their tone quality, since these tones have only one instrument impedance peak. Thompson hypothesized that f_r is always within 10% of the playing frequency when playing in the reed regime, and the difference is due to the fact that the playing frequency is a compromise that maximizes the total amount of energy produced by the harmonic alignment of pressure and impedance peaks.

Keefe [49] found in computer simulations that the alignment of f_r with a harmonic frequency did not significantly change the results, in disagreement with Thompson [71, 72], but an increase in f_r did give an increase in the playing frequency. He concluded that the performer can control intonation with changes in the embouchure.

Keefe and Waeffler [46] measured the f_r and Q of clarinet reeds with an impact hammer and found f_r = 2.8–3.1 kHz and Q = 5–10 for a moist reed. Both values were higher than those measured by Worman [75]. In addition, multiple resonances were observed at higher frequencies.

Benade and Keefe [11] pointed out complicating factors in determining the influence of the reed. As the performer makes embouchure adjustments, the reed stiffness and mass (and therefore f_r) can be changed, but the changes in the reed tip aperture can also affect the hydrodynamics of the flow through the tip. Several different variables are affected by the performer's embouchure, which can make it difficult to isolate the influence of the reed resonance.

1.1.9 Experimental Research Including the Performer's Airways

The performer's airways can affect musical sound production in different ways and to various degrees. This section describes experimental research concerning the effect of the airways on clarinet sound production and similar work that has been done on other instruments, including the voice.

The Clarinet

The acoustical research on the role of the airways in clarinet sound production has included the correlation of pressure spectra with tone quality, the measurement of the upstream impedance for vowels, and numerical models that included the effect of the airways.

Clinch, et al. [21] made X-ray fluoroscopic measurements of the vocal tracts of performers of the clarinet, soprano saxophone, and recorder, as discussed in Section 1.1.4. For the clarinet and saxophone, they found that the tongue position was similar to positions used for spoken vowels. For the clarinet, they measured the pressure inside the mouth and external to the instrument near the bell and concluded that the quality of the tone strongly depended upon the vocal tract shape. For a "good" quality tone, the external pressure spectral envelope was similar to the instrument impedance, but the mouth pressure spectral envelope was dissimilar. In the example that they showed, the mouth pressure spectral level at the fundamental frequency was much larger than all other harmonics, in contrast to the external spectrum which fell off more gradually. For the same tone played with a "poor" tone quality, the internal spectral peaks followed the external peak levels in relative intensity. They concluded that the upstream resonance frequency must match the fundamental frequency of the tone being played in order to produce a good tone quality.

Benade [7] and Hoekje [42] reported measurements of upstream impedance for airway configurations for different vowel sounds and showed evidence of the influence of the airways on the sound produced. Hoekje correlated the airway configurations with different tongue positions: high and low as well as forward and back. He found that the resonance frequencies of these airway configurations were 500–1100 Hz with heights of 75–300 CGS ohms. The measurements of upstream impedance reported by Benade were slightly different. When the upstream impedance was plotted in dB, there was a broad hump for all vowel shapes centered at about 1000 Hz, which Benade showed was due to a constriction in the airways. Since both the frequency and magnitude of these resonances were in the range of instrument resonances, they concluded that the airways can influence sound production. In fact when an actual clarinet was played and the tongue was moved from a low to a high position, the pressure in the mouthpiece at the 4th harmonic increased by 12 dB and the mouth pressure increased by by 40 dB. In another example, a note was played on a "clarinet" designed to have only one strong impedance peak. The sound produced was heard as a multiphonic, and pressure peaks were produced at the impedance peak of the instrument, one or more upstream peaks, and at frequencies that were sums and differences of those peak frequencies. The conclusion was that the oscillation, which was poorly supported by the instrument, received additional support from the performer's airways.

Backus [6] measured the upstream impedance using the capillary tube method. The player's lips were placed around a sleeve that contained a microphone and the series impedance. The upstream impedance peak magnitudes were measured to be less than 100 CGS ohms, but they depended unpredictably upon the mouth volume and shape. In a second experiment, a person formed an embouchure around the mouthpiece of a clarinet that was being artificially blown in reverse. There were only small changes in waveform, spectra, and tone quality. When the person was replaced with a chamber and a tube of variable length (to vary the resonance frequency), only small changes in intensity and quality were seen. He concluded that the airways have very little effect. Earlier Backus [2] had measured the pressure variations in the mouth to be 30 dB below the variations in the mouthpiece for the blowing chamber and 20–25 dB below the mouthpiece variations for a human performer. He claimed that these levels were close enough to conclude that the size and shape of the airways do not make a difference. However, Johnston et al. [44] pointed out that the sleeve holding the transducers for the upstream impedance measurements and the tube model of the airways attached to the artificially blown clarinet both had diameters that were much larger than the input diameter of the airways. The effects measured were therefore smaller than the effects for actual playing, and thus Backus came to the conclusion that the airways have very little influence, in contradiction to performers' statements and the results of other researchers.

It is important that the glottal opening during measurement of the upstream impedance be in the same condition as during performance. During the measurement the glottis must remain open to ensure a measurement of the impedance of the entire airways including the lungs, since this is the situation during performance. Hoekje [42] suggested using a small tube inserted in the corner of the mouth through which to exhale as though playing a tone. The performer forms an embouchure around the mouthpiece and starts to exhale through the tube as though playing a note. The end of the tube is suddenly closed and the measurement is taken. If the exhalation resumes immediately when the tube is opened then the glottis is assumed to be open.

The only other measurements of the upstream impedance in this configuration besides those of Hoekje and Benade were made by Gupta et al. [35]. Most measurements of upstream impedance are either made at the glottis looking towards the mouth or at the lips looking in but with an open mouth condition, since experimenters are interested in the upstream impedance for vowels. Gupta et al. made their measurements in order to test a simplified model of the acoustic response of the trachea. They measured Z_u from 50 to 440 Hz as the subjects were in a position to pronounce the letter "P". The subjects sealed their lips around the sleeve of a piston, which produced a known flow, and a microphone, which measured the pressure response. Gupta et al. found a broad peak at about 200 Hz with a peak value of about 25 CGS ohms and a phase that decreased from $+\pi/2$ radians below the peak, through zero at the peak, to $-\pi/2$ radians above the peak. Both Benade and Hoekje detected this peak at 200 Hz.

Some researchers have presented results for numerical models of the clarinet that included the airways. Johnston et al. [44] implemented a computer model of a clarinet based on Schumacher's model that included the effect of the airways as a single resonance. Their model calculated the mouthpiece pressure waveform, given the impedances of the instrument and airways and a reed model. By varying the level and frequency of the upstream resonance, they were able to explore various effects of the airways on the output waveform and to test four predictions that followed from the theory of the role of the airways in sound production (Section 1.1.5):

1. Prediction: "The regime of oscillation can be based on the vocal tract resonance provided that the resonance is lower in frequency than the lowest competing instrument resonance, and that the resonance is strong enough." This is the effect of pitchbend, also called "bending the note" and "lipping down", and is used frequently in jazz. It implies that Z_u must be large at the frequency of the fundamental.

2. Prediction: "We can predict that the register change could also be affected by vocal tract manipulation if the higher resonance peak is enhanced by making a vocal tract resonance coincide with it." This is how one would change registers

without the use of the register key, and it is also called bugling. It also implies that Z_u must be large at the fundamental.

3. Prediction: "Certain alignments of the vocal tract manipulations may assist in their [mulitphonics'] production." This predicts that the vocal tract could produce multiphonics if the Z_u peaks are not in harmonic alignment with Z_d peaks.

4. Prediction: "If the instrument resonances are made weak compared to those of the vocal tract it would be possible for the regime of oscillation to be based on the vocal tract resonance frequency over a wide range of pitch." This is called a "glissando", and is produced by fingering a note loosely so that the tone holes leak. The fundamental frequency can be varied over a wide range by this means.

They modelled the clarinet as an open tube with a high frequency cutoff and a fundamental resonance at 288.3 Hz (between concert $C\sharp 4$ and $D4$–written $D\sharp 4$ and $E4$ for the $B\flat$ clarinet). The reed resonance frequency was taken to be 2500 Hz and the reactive part of the reed opening impedance was from Backus [3]. Z_u was modelled as a single resonance with variable frequency and peak height. They assumed that this was sufficient since the player can control only one airway resonance at a time. They plotted the frequency of oscillation of the pressure waveform output from the calculations as the frequency of the airway resonance was varied from 200 to almost 1400 Hz. They found that all four predictions were verified by their computer model. The size of the effects depended on the peak height ratio $R = |Z_u|/|Z_d|$. The oscillation was based only on the clarinet Z_d for $R = 0.2$ and only on the upstream resonance for $R = 5.0$. Intermediate values produced effects such as bugling, pitchbend, and multiphonics.

Sommerfeldt and Strong [66] included the player's air column in their model as a tube with varying cross-sectional area to give a vowel resonance similar to either /a/ or /i/. The calculated Z_u was consistent with Hoekje's [42] measurements. The calculated Z_u peaks for the /a/-shaped airway were all less than 50 CGS ohms, and an /i/-shaped airway had a resonance at about 900 Hz that could be varied over 170-300 CGS ohms. Only airways with /i/ or /i/-like shapes had impedance peaks greater than 100 CGS ohms. The calculated mouthpiece pressure was similar for constant mouth pressure and for an /a/-shaped vocal tract. In all their simulations, they observed that mouth spectral peaks near upstream resonances were enhanced. They found that an /i/-shaped airway with a resonance of 170 CGS ohms produced a large 4th harmonic peak in the mouth pressure, while the same upstream resonance with a larger peak magnitude of 300 CGS ohms turned the 3rd harmonic into the fundamental, much like playing an upper register note without the register key. This is the bugling discussed by Johnston et al. [44], who also found that it could be caused by altering the upstream resonance. Sommerfeldt and Strong found that the fourth harmonic of the mouth pressure spectrum was 25 dB larger for the /i/ airway shape than for the /a/ shape, similar to the observations of Benade [7] and Hoekje [42] when the airways were "tuned". However, they found virtually no difference in the tube pressure spectral levels, and the reed, air flow, and tube pressure waveforms were all similar with both airway shapes. They attributed this to the decoupling of the clarinet from the performer's air column due to the reed. This differs from the measurements of Benade [7] and Hoekje [42], who measured significant differences in the mouthpiece pressure spectrum when the tongue was moved.

Keefe [48] presented a general time domain model based on the reflection function model of McIntyre et al. [55] for wind instrument sound production. He included the respiratory tract as an upstream reflection function, but did not present any analyses.

Other Musical Applications of the Performer's Airways

The role of the airways has been investigated for various other wind instruments and the voice. These analyses can provide insight into the function of upstream resonances and how these issues might be further investigated for the clarinet.

Elliot and Bowsher [25] were the first to derive the continuity of flow equation (Eqn. 1.31) and to note that one can estimate the ratio of the upstream and downstream impedance magnitudes by comparing the upstream and downstream pressures. They presented data for two tones measured on a trombone at 232 Hz and 464 Hz. The ratio p_u/p_d at the fundamental ranged from 5 to 20%, and they concluded that for some tones Z_u can be a significant fraction of the total Z, and the airways could affect intonation.

They theorized that the use of the correct vocal tract shape could be what allows performers to "buzz" on a mouthpiece with no instrument attached. Performers should not be able to play below the popping frequency of the mouthpiece since the mouthpiece reactance is positive below the resonance and it must be negative in order to satisfy the imaginary part of the regeneration condition (Eqn. 1.17).

Elliot and Bowsher studied three tones buzzed on a trombone mouthpiece at 120, 350, and 590 Hz. The resonance frequency of the mouthpiece was about 600 Hz and the performer noted a "change of feel" as the buzzing frequency was swept through 400 Hz, which was about the frequency where the magnitude of the mouthpiece impedance started to rise appreciably. For the two lowest tones (120 and 350 Hz), they found p_u and p_d to be about the same magnitude but nearly out of phase with one another. Since the reactance of the mouthpiece is positive at these low frequencies, they concluded that the upstream reactance was the same order of magnitude but negative, and therefore the upstream impedance could be the major influence in satisfying the imaginary part of the regeneration condition. On the other hand, for the tone buzzed at 590 Hz, p_u was only about 30% of p_d, and so some mechanism other than the upstream impedance was probably responsible for that oscillation.

Fletcher and Rossing [30] noted that the value of the mouth cavity volume can be important during transients on brass instruments, as the performer must buzz the lips at a constant frequency until reflections return from the bell. The upstream impedance could play a role in this process by acting as a resonator attached to the lips until they can get feedback from the instrument.

Benade [7](Question and Answer section at the end) noted that the performer's airways could play a similar role for the harmonica reed, which is a "free" reed. It is not attached to an external air column and needs something to stabilize a harmonic oscillation. He stated that the frequency of oscillation can be changed by altering the real part of the upstream impedance.

The Australian didjeridu (Fletcher [29]) is an example of how the performer's airways can have a major effect on the tone of a musical instrument. The didjeridu is a tube between one and two meters long with an inner diameter of about 30 mm at the input end and about 50 mm at the output end. It is played by buzzing the lips at the input end as on a brass instrument, and the performance technique includes pronouncing unvoiced syllables while playing. One syllable pattern that is used is "didjeridu", which has become the Westernized name for this instrument. The changes in the vocal tract shape produced by these unvoiced syllables produce large variations in timbre for tones of the same fundamental frequency and loudness. The strong influence of the airways on the tone quality is due to the large input diameter (30 mm), which is close to the input diameter of the airways and provides a strong coupling between the air columns of the performer and instrument. Fletcher [29] observed the appearance of humps in the external pressure spectra envelope as the mouth and tongue positions were varied. These changes were also associated with changes in timbre. He called these humps analogous to the formants of the voice and theorized that they were controlled by the volume of the mouth as determined by the vocal tract shape, which is similar to the explanation of the role of the airways in the buzzing of a brass instrument given by Elliot and Bowsher [25] and Fletcher and Rossing [30].

Both male and female Western opera singers use the resonances of the airways to affect the sung tone quality, in both cases increasing the intensity output [70]. It is known that male opera singers, and female opera singers to a lesser extent, have a broad peak in the vocal tract transfer function (a "formant") near 3 kHz that is not present for the spoken voice. This "singer's formant" is actually the 3rd, 4th, and 5th formants of the spoken voice that have been clustered closely together and so is not truly a single resonance. This phenomenon is created by a lowering of the larynx, which has the combined effect of lengthening the vocal tract and widening the bottom of the pharynx. This action is not due to any special effort, but is a result of relaxing the neck muscles. The acoustical effect is to increase the power output of the singing voice in the frequency range of the singer's formant so that it may be heard above a loud orchestra. Soprano opera singers use a different technique to increase their power output: they tune their first formant frequency to the fundamental frequency of the tone being sung by increasing the jaw opening, producing a power gain of up to 30 dB SIL (Sound Intensity Level). Both male singers and sopranos alter their vocal tract state to create certain resonances that increase sound intensity output. The use of the airways resonances by sopranos is similar to the predictions of how wind instrument players use their resonances, but in the case of wind instrument players, the resonances are predicted to enhance the stability of the tone rather than increase the power output.

1.1.10 Open Research Questions

The conclusion from experimental data is that the performer harmonically aligns an upstream resonance in order to stabilize the oscillation and improve tone quality (see e.g., Clinch, et al. [21], Benade [7], Hoekje [42]). Computer simulations by Johnston et al. [44] and Sommerfeldt and Strong [66] showed that it is possible to include the airways in physical models of the clarinet, and they observed effects such as enhancement of pressure peaks, pitch bending, multiphonics, and bugling. These results support Benade's [7] prediction that the airways will help stabilize an oscillation if it has strong resonance peaks that are harmonically aligned with instrument resonance peaks.

Although these results show good agreement, there has been no direct evidence that the upstream resonances are harmonically aligned with instrument impedance peaks. When the upstream impedance has been measured (Gupta et al. [35], Benade [7], Hoekje [42]) it has been for closed lip airway configurations for spoken vowels. There has been no attempt to measure the impedance of the airways in the configuration for actual clarinet playing. A measurement of Z_u for actual clarinet playing would be a test of the prediction of the harmonic alignment of upstream peaks and would show how close a clarinetist's upstream impedance is to the upstream impedance for spoken vowels.

The role of the reed is still ambiguous. There have been conflicting results as to whether the reed resonance or the performer's airway is responsible for the effect of bugling and for changes in pitch and intonation. Thompson [71, 72] concluded from his experiments with a metal reed and an artificially-blown clarinet that the reed resonance could cause the effect of bugling by alignment with a harmonic frequency. This agrees with performers (Neidich [58]), who claim that playing the overtones of a single fingering requires embouchure adjustments. However, Keefe [49] did not find any enhancement of a harmonic that was aligned with f_r. In fact, the computer simulations of Johnston et al. [44] and Sommerfeldt and Strong [66] showed that the upstream resonances could cause this effect. The simulations of Johnston et al. [44] also showed that upstream resonances could cause the large changes in playing frequency known as pitchbend, but the simulations of Keefe [49] showed that changes in the reed f_r could cause small intonation changes, and performers (Rehfeldt [60]) claim both airway and embouchure (which affects the reed resonance) adjustments are important to produce frequency changes. The relative roles of the airways and the reed in intonation changes have not been clearly determined.

1.2 The Research of This Dissertation

This research will examine the role of the performer's airways in the process of sound regeneration by measuring the upstream impedance and determining if there are airway resonances that could favorably influence the sound generation process, according to the theory. The upstream impedance will be measured indirectly using the continuity of flow equation. The continuity of flow equation will first be verified by comparing the upstream impedance measured indirectly with a direct measurement of the impedance using a one-microphone technique. Once the continuity of flow equation is verified, it can be used to measure the upstream impedance during performance, and the role of the airways can be studied in a variety of musical situations.

In all of the musical situations, two basic predictions of the regeneration theory will be tested. The first prediction comes from the role of Z_u in the total impedance (Eqn.1.28). Since Z_u is in series with Z_d, one would expect that the performer might tune an upstream resonance to a harmonic frequency, since alignment of Z_u peaks with harmonic frequencies should be beneficial for the oscillation. The second prediction is that, if there is a Z_u peak at a harmonic frequency, the regeneration condition Eqn.1.15 should be satisfied if Z_u is included but not satisfied if Z_u is omitted.

The following questions concerning the role of the airways in clarinet sound production will be addressed in this research:

- Is the linear continuity of flow equation valid under quasi-linear performance conditions, that is, at low to moderate playing levels when the reed does not close against the mouthpiece?

- Is an upstream resonance aligned with a harmonic frequency(s)? Does this alignment allow the system to fulfill the regeneration conditions more strongly than if the upstream system were not taken into account?

- What role does the upstream impedance play in various musical situations?

- For single normal tones, is there always an upstream resonance aligned with a harmonic frequency?

- For tones played with an "open throat" and a "closed throat", how does the openness of the throat affect the upstream impedance and the harmonic alignment of the resonances? Could this explain why an open throat is preferred?

- For clarion tones played without the register key, is there a large upstream resonance at the fundamental of a clarion tone that allows that tone to be played without the register key?

- For tones played with pitchbend, is there a large upstream resonance below the frequency of the instrument resonance that lowers the fundamental frequency?

- For multiphonics, does the performer create an upstream resonance that supports the fundamental frequency of one of the individual tones, and if not, what are the frequency relationships between the upstream and downstream resonances?

- How does the performer use the airways in the performance of a musical excerpt?

These questions will be answered by examining the upstream impedance. It can be measured directly by measuring the input impedance of the airways at the mouth, but this has two main disadvantages: 1.) it cannot be measured during performance, and consequently, 2.) the method relies on the performer's ability to accurately reproduce the state of the airways during performance with no feedback from the instrument. A second indirect method to measure the upstream impedance is by calculation using the continuity of flow equation (Eqn. 1.31). However, this relationship must first be verified. Therefore, the upstream impedance will be measured directly for single tones and compared to the upstream impedance measured indirectly with Eqn. 1.31. Once verified, this expression can be used to address the questions listed above. This indirect measurement is independent of the reed parameters. So although in practice it is difficult to distinguish between reed and airway effects, in theory this method should be able to isolate the airway effects.

This study is a means of examining the role of the airways in sound production by looking at the upstream impedance, which is directly related to the physiological state of the airways. Each configuration of the airways creates certain resonances, and these can be observed as peaks in the upstream impedance. This study will test whether clarinetists use these resonances to their advantage while performing.

The second chapter of this dissertation explains the methods used to measure the impedance and the pressure data necessary for the calculations. The next five chapters present the results of the analyses. Chapter 3 discusses the results of the measurements of the downstream (instrument) impedance and the upstream (airway) impedance and compares them to results of other researchers. Chapter 4 presents the results of the pressure measurements. Chapter 5 presents the results for single tones. First, the indirect measurement method is compared with the direct method to verify the continuity of flow equation. Then, results for the following single tones are discussed: tones played at different dynamic levels, tones played with an open and a closed throat, clarion tones played without the register key, and clarion tones played with pitchbend. Chapter 6 contains the analyses of multiphonics, which are a more complex and nonlinear phenomenon than the preceding single tones because they have two or more pitches sounding simultaneously. Chapter 7 discusses the analyses of the musical excerpts and the role of the airways in a musical performance context. Chapter 8 discusses the implications of this research for clarinet performance and the relevance of these findings for the musician. Finally, Chapter 9 summarizes the conclusions.

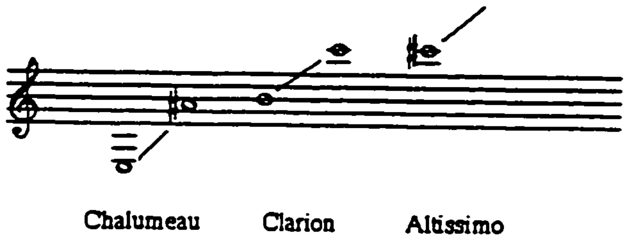


Figure 1.1: Registers of the clarinet.

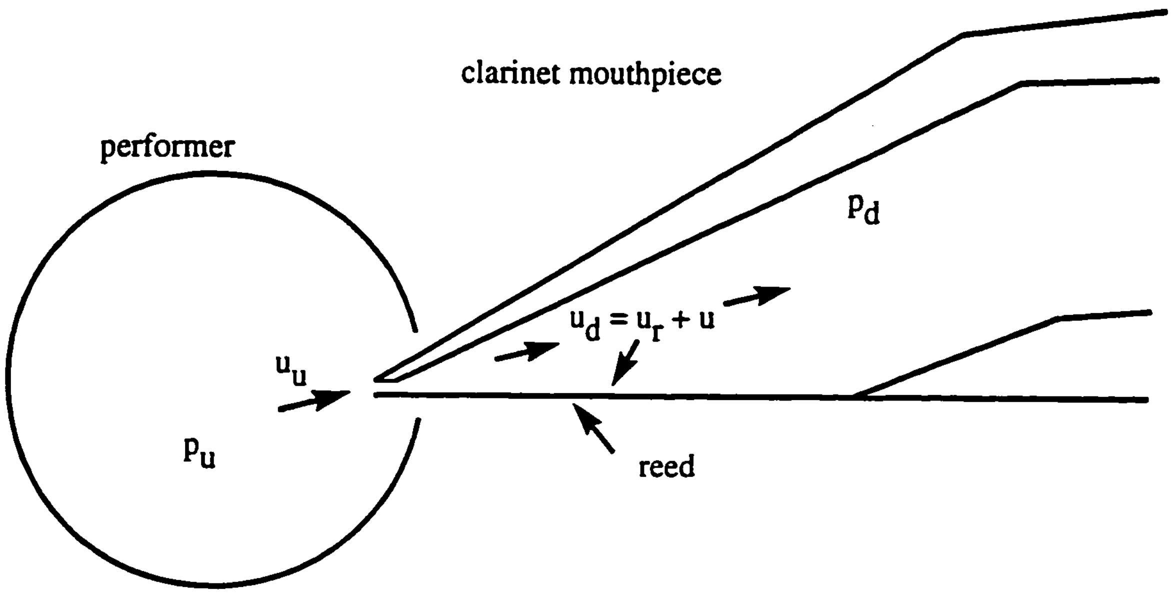
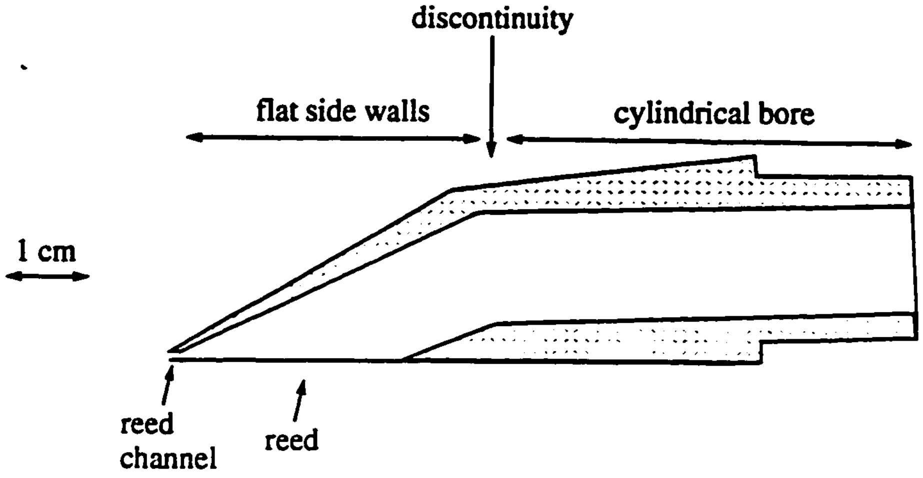
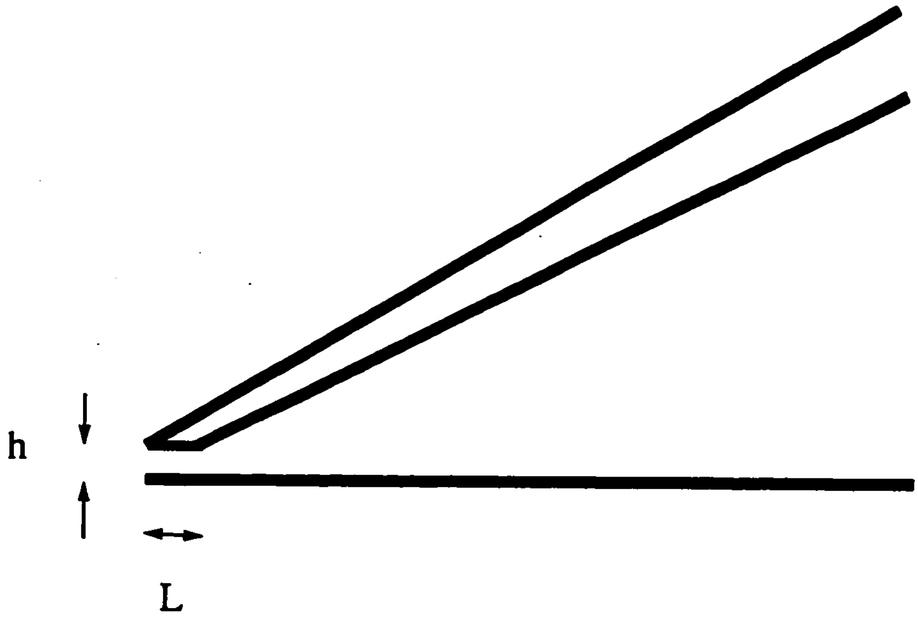


Figure 1.2: Pressures and flows for the mouth and clarinet mouthpiece.



(a) Geometry.



(b) Close-up of reed channel.

Figure 1.3: The clarinet mouthpiece.

Chapter 2
MEASUREMENT METHODS

The experimental data consist of pressure and impedance measurements. The data necessary for the indirect measurement of the upstream impedance Z_u are the pressures inside the mouth and the mouthpiece and the impedance of the instrument. A direct measurement of the upstream impedance must also be made in order to compare it with the calculated Z_u. The methods used to measure these quantities will be explained, and the musical phenomena that were studied and the performers who played them will be briefly described.

2.1 Pressure Measurements

Figure 2.1-a shows the set-up used to measure the pressure in the performer's mouth and in the mouthpiece. The mouthpiece was a Buffet model 125G. The pressure was actually measured at two positions in the mouthpiece (1 and 2 in the Figure) in order to determine which pressure would be more appropriate to use for the indirect upstream impedance measurement. Two holes were drilled approximately 2 cm apart on the top side of the mouthpiece. The hole at position 1 was through the cylindrical part of the mouthpiece, and the hole at position 2 was closer to the lips and through the baffle. The hole through the baffle was 2.7 cm from the mouthpiece tip as measured from the center of the hole along a line parallel to the clarinet air column, and the second hole was 4.6 cm from the mouthpiece tip. The two holes were positioned on either side of the bore discontinuity where the side walls change from straight to cylindrical.

The three pressure transducers used were piezoresistive pressure transducers manufactured by Endevco with sensitivities of 18–30 μV/Pa. They are designed to withstand the high pressures that can occur in the mouth and mouthpiece. Two transducers were inserted into the two holes in the mouthpiece until they were flush with the interior surface, and then the space between the mouthpiece hole and the transducer was sealed with wax to prevent leaks. A third transducer with a small plastic sleeve around it was inserted into the corner of the performer's mouth by taping it to the side of the mouthpiece to measure the mouth pressure. An attempt was made to angle the mouth transducer away from the reed tip so the measurement would not be affected by three-dimensional flow effects near the reed tip. The tip of the transducer was probably within one centimeter of the reed tip, although this was not possible to measure once the mouthpiece was placed in the performer's mouth. A one-centimeter distance is acoustically negligible for frequencies for which this represents less than $\lambda/8$, or for $f < 4300$ Hz. The signals from two of the transducers were fed into the signal conditioner (Figure 2.1-b), which applied a gain, and into the Digital Ears, a 16 bit analog-to-digital converter (ADC) with a 20 kHz lowpass input filter capable of measuring both AC and DC signals. The Digital Ears sampled the signals at a rate of 44.1 kHz, and the data were stored as NeXT sound files. The high sampling rate gives good resolution in the pressure spectra when large FFT sizes are used, and the 16 bit ADC has a signal-to-noise ratio of approximately 85 dB.

Since the Digital Ears had only two inputs, the pressures at only two of the three transducer positions could be measured simultaneously. In the interest of time, it was decided that two transducer configurations would be used. In the first, the pressures were measured at the two positions in the mouthpiece. In the second, the pressure was measured in the mouth and at the mouthpiece position farthest from the reed tip (position 1). This mouthpiece position was chosen because pilot data showed that there was less flow noise at this position, and acoustically it is at the same location as the other mouthpiece position for $1/8\lambda \leq 3$ cm, or for $f \leq 2100$ Hz. (See Section 4.1.)

It was necessary to calibrate the signals stored in the sound files in order to obtain absolute pressure readings because the Digital Ears applied an unknown gain. A sine wave of known RMS voltage amplitude from an oscillator was fed into the Digital Ears and recorded. From this measurement the calibration from ADC units to voltage was calculated. The sensitivities of the transducers and the gain setting of the signal conditioner were then used to convert the voltage to pressure. This calibration factor from ADC units to pressure was applied to all measurements taken with that setting of the Digital Ears gain knobs.

2.2 *Impedance Measurements*

The method used to measure the impedance was a one-microphone technique developed by Keefe et al. [52]. In this method, source and microphone probes (Figure 2.2-a) are threaded through a small piece of foam that is inserted into the entryway of the air column to be measured. The foam expands to provide a leak-free seal. The source emits a broadband chirp, and the microphone picks up the response, which is sent to a computer. The source/microphone system can be represented as an equivalent circuit (Figure 2.2-b) with a Thevenin pressure and impedance. These Thevenin parameters are calculated in a calibration procedure with closed cylindrical tubes. The responses of the calibration tubes are fit to a model by a least-mean-squares optimization of the Thevenin parameters. Once these parameters are known, an unknown impedance may be calculated from its impulse response. This method works well for tubes with unknown cross-sectional areas.

The hardware for the impedance measurements is shown in Figure 2.2-a. The source was an Etymotic ER-3A source, and the microphone was an Etymotic ER-7C pressure transducer. An Ariel Proport 16-bit converter served as the digital-to-analog and analog-to-digital interface between the transducers and the Ariel 16C DSP card in the Pentium computer.

The calibration tubes were brass cylinders closed at one end with diameters of 0.485 cm. The calibration tubes should have cross-sectional areas that are close to the input area of the unknown impedance that will be measured. In this case, the input area corresponds to the reed opening that couples the clarinet and the airways. The tubes should then have a diameter that is small compared to the clarinet bore. Since a tube of the same diameter must serve as a coupler both to the instrument and to the airways when measuring their impedances, a tube with a small diameter also simplifies geometrical constraints, as described below in the section on measuring the upstream impedance.

In order to obtain a good calibration, the chirp stimulus must be designed to give a flat pressure response over the desired frequency range when emitted in one of the calibration tubes. The chirp used for these measurements had a frequency range of 50-5500 Hz. It was sampled at a rate of 11.025 kHz and contained 4096 points, for a chirp duration of 0.37 seconds and a frequency resolution of 2.7 Hz. To calculate the Thevenin parameters, the least-mean-squares error was minimized over the frequency range 50–5300 Hz, which gave a good fit between model and data over 40–5300 Hz, and therefore the calibration is good over this frequency range.

The same chirp was used to make the measurements on both the instrument and the airways. When measuring the impedance of the instrument, the response to eight chirps was averaged to obtain the response that was used to calculate Z_d, but only a single chirp was used for the upstream measurements because it was difficult for the performer to keep the airways still for much longer. This lack of averaging decreased the signal-to-noise ratio of the upstream measurements. In addition, the physiological system of the airways is inherently noisier than the inside of a clarinet, especially at low frequencies up to about 300 Hz, and so one would expect the upstream measurements to be noisier than the instrument measurements.

Ideally, the calibration tubes should have the same cross-sectional dimensions as the reed tip opening coupling the airways and the clarinet. However, the calibration tubes have circular cross-sections, and the reed tip opening is rectangular, with additional openings on the sides through which air can flow. In addition, the diameters of both the airways and the clarinet grow very quickly to much larger diameters (1.5 cm in the main clarinet bore). There was some concern that using small-diameter, cylindrical calibration tubes to measure the impedance of the airways and the clarinet would not give accurate measurements. To investigate this concern, a calibration was performed using the small 0.485 cm diameter tubes, and then the impedances of two closed brass cylinders of diameters 1.27 cm and 2.54 cm were measured. The small foam tip holding the probes that fit inside the 0.485 cm calibration tubes was coupled to the large diameter brass cylinders by means of a brass plate that was sealed to the end of the brass cylinder with a smaller cylinder positioned in the center into which the foam tip could be inserted with a leak-free fit and flush with the inner surface of the brass plate. Figures 2.3 and 2.4 show the measured and predicted impedances (imaginary part) for the closed brass cylinders with diameters of 1.27 cm and 2.54 cm. There is excellent agreement up to 4000 Hz for the 1.27 cm diameter tube, which is about the size of a clarinet bore. The agreement for the 2.54 cm diameter tube is also fairly good below 1000 Hz. The calculated diameter, estimated from the real part of the impedance (Keefe et al. [52]) was 1.29 cm for the 1.27 cm tube and 2.80 cm for the 2.54 cm tube. The discrepancies for the 2.54 cm tube at high frequencies can be corrected with the addition of an inertance term $j\omega I$ to the model (Figure 2.5). This inertance term is due to evanescent modes (Keefe and Benade [45]) in the larger diameter tube that were not accounted for in the calibration with the smaller diameter tubes. The fit is optimized for an inertance value of $I = \rho \delta l / S = 30$ g cm^4, which gives an end correction of $\delta l = 1.28$ cm, or $\delta l = 1.01a$, where a is the radius of the tube. It is concluded that this impedance measuring technique is valid for measuring the impedance of clarinet-sized bores when the system is calibrated with much smaller diameter tubes.

2.2.1 Instrument Impedance (Z_d) Measurement

The set-up to measure the impedance of the clarinet is shown in Figure 2.6. An adapter was constructed that allowed the source and microphone to be attached in a tight seal to the mouthpiece tip. It is similar to a design used by Backus [4]. A brass plate was sealed airtight to the reed window of the mouthpiece with wax. If this seal is not airtight, then leaks will cause the low frequency peaks to decrease in magnitude. Near the tip of the mouthpiece, a hole was drilled in the plate and a small cylinder inserted flush with the interior surface of the plate. The small foam tip containing the the source and microphone was inserted into the cylinder until even with the interior edge. A possible problem with this design is that the microphone probe tube, which extends out of the foam slightly, might be too close to the mouthpiece baffle. This is remedied by positioning the tube farther from the mouthpiece tip. As long as the distance over which the probe is moved is less than 1/8 the wavelength of the highest frequency measured, the results will be effectively the same. At 5000 Hz, 1/8 of a wavelength is 0.86 cm, which is more than enough to move the microphone to a favorable location.

In order to examine the effect of the transducer position on the measurement more closely, the impedance was measured for various positions along the length of the reed window. Figure 2.7 shows the impedance measurements on a Buffet R-13 for the fingering for $G4$ at the extrema of the distance covered: 0.49 cm and 2.70 cm as measured from the mouthpiece tip to the center of the source. The two largest impedance peaks at low frequencies changed very little over the entire distance. The largest peak at 360 Hz stayed within 20 CGS ohms of the value at 0.49 cm, while the next largest peak at 1070 Hz dropped by 50 CGS ohms over the entire distance. The highest frequency peaks began to decrease at 1.35 cm. The maximum distance from the tip that the probes can be placed and still make an accurate measurement of the impedance up to 5000 Hz is in the range 0.90-1.35 cm, which is close to the value of

0.86 cm estimated above. For subsequent measurements of Z_d, the transducers were placed at approximately 0.7 cm from the tip.

2.2.2 Direct Measurement of the Upstream Impedance (Z_u^o)

The upstream impedance that was measured directly will be referred to as Z_u^o in order to distinguish it from the upstream impedance Z_u measured indirectly by means of the continuity of flow equation. The superscript "o" refers to the one-microphone method used. The set-up to measure the upstream impedance is shown in Figure 2.8. This set-up couples the transducers to the performer's airways and allows the performer to create an airtight seal while forming a performance-like embouchure and airway shape. This adapter is similar to the one used for measuring instrument impedances, but the transducers are pointing in the reverse direction. The cylinder containing the foam tip is slightly recessed to minimize the chance of the tongue touching the microphone probe. The remainder of the reed window is closed with a plastic plate and sealed with wax. The clarinet mouthpiece is attached to the body of a clarinet by means of a T-joint that replaces the barrel. Clarinetists reported that having a real clarinet to finger while forming an embouchure for a particular note made the task easier and more realistic. The wires leading to the source and microphone preamplifiers were strung through the arm of the T-joint since they were not long enough to fit through the entire clarinet.

In addition, a small air tube was strung through the T-joint and the mouthpiece alongside the transducers so that the end of the tube was at the mouthpiece tip. The tube had an outer diameter of 0.43 cm and an inner diameter of 0.30 cm. This was the air tube that allowed the performer to exhale in order to keep the glottis open. The performer was then able to form a natural embouchure with no tubes inserted in the corner of the mouth, and blowing on the measurement mouthpiece gave a sensation similar to actual playing, although this "instrument" had a "resistance" (in the words of performers) that was constant across the pitch range, whereas the "resistance" of actual clarinets varies.

Two known sources of error contribute to uncertainty in the direct measurement of the upstream impedance and limit the accuracy. A large part of the uncertainty comes from the set-up used to measure the upstream impedance. The measurement cannot be made during performance, but instead the performer must pretend to play a specific tone with no feedback from the instrument and with a mouthpiece that has been altered from normal playing conditions, e.g., with a plastic plate instead of a cane reed. Thus the expertise of the performer is essential in order to reproduce the airway configuration for a reliable measurement. In addition, the measurement must be made with only one chirp, of duration 1/3 second, because it is difficult for a performer to maintain a constant physiological state of the vocal tract for an extended period of time. Normally, the impedance would be calculated from an average of several chirps, so this lack of averaging gives a very low signal-to-noise ratio.

2.2.3 Indirect Measurement of the Upstream Impedance (Z_u)

For the musical phenomena studied, the upstream impedance was measured indirectly using the continuity of flow equation and measurements of the downstream impedance and the mouth and mouthpiece pressures. This section describes the calculation method used to obtain the upstream impedance from the pressure and instrument impedance data. The calculation method for noisy data using cross-spectral averaging is also described.

Calculation Method

The upstream impedance Z_u was measured indirectly using Equation 1.31 on short-time sections of N samples of the pressure time series. N ranged from $2^{11} = 2048$ to $2^{15} = 32768$ depending on the particular case at hand and was chosen to allow a large FFT size and still provide sufficient time resolution between sections. The sections were overlapped by half the length of a complete section in order to increase the time resolution.

The pressure p_u was the pressure measured in the mouth, and the pressure p_d was the pressure measured in the mouthpiece at position 1 (Figure 2.1). Position 1 was chosen rather than position 2 closer to the reed tip because there was very little difference in the spectral peak magnitudes between the two positions and the flow noise was lower at position 1, as discussed in Section 4.

The downstream impedance Z_d was the instrument impedance, measured near the tip of the mouthpiece, as shown in Fig 2.6. Since Z_d is defined in terms of p_d, ideally p_d should be measured at the same location as Z_d, but this was not possible. The distance between the locations at which p_d and Z_d were measured produces a phase shift between these two quantities that would not be present if they were measured at the same location. For example, for $f = 2200$ Hz, this distance, which was approximately 3.9 cm, corresponds to $\lambda/4$, and the same signal measured at the two positions would be 90 degrees out of phase. This phase shift is negligible for frequencies for which the distance is less than $\lambda/8$, or for $f < 1100$ Hz. This frequency range can be increased further to 1500 Hz, introducing only minimal error. Therefore the indirect measurement of Z_u using the measured quantities p_d and Z_d in this experimental set-up will be considered valid only up to 1500 Hz, and results involving the indirect measurement of Z_u will only be shown up to 1500 Hz.

Another source of error in Z_u arises from the fact that Z_d was measured for an instrument that had not been warmed up, and p_u and p_d were measured under playing conditions, when the instrument was warmed up. The change in temperature of the instrument and the air inside the instrument will increase the speed of sound, and the resonance and playing frequencies will also increase. Young [76] has shown that for an ambient temperature of 21 degrees Celsius the playing frequency of the clarinet increases approximately 10 cents as the instrument warms up. This corresponds to a 0.6% frequency shift, which is negligible for the frequency range studied here.

Z_u was calculated at harmonic frequencies of the tone, i.e., at integer multiples of the fundamental frequency. At these frequencies there are peaks in the pressure spectra and so the calculations are not contaminated by noise. The fundamental frequency was calculated for each short-time section of the sound file using the algorithm of Brown and Puckette [18]. The initial and final transients of the tone were omitted, but an attempt was made to include as much of the tone itself as possible, as long as a fundamental frequency could be calculated for each section.

The fundamental frequency, and therefore the harmonic frequencies at which Z_u was calculated, varied slightly from section to section due to instability in the tone. Z_u was calculated at harmonics of the fundamental frequency for each individual section rather than for harmonics of a fixed frequency for all sections because the fundamental frequency gives the frequency of oscillation, and it is determined by the dynamics of the oscillation. Therefore, calculating Z_u at slightly different frequencies for each section is justifiable since Z_u is calculated at the frequency of oscillation at that particular moment in the time series.

To calculate Z_u for each short-time section, the data were windowed with a Hanning window, and the pressure spectra p_u and p_d were calculated by means of an N-point FFT. The instrument impedance Z_d and the pressure ratio p_u/p_d were interpolated at each harmonic frequency with a four-point interpolation, and these values were used in Equation 1.31 to find Z_u. The pressure ratio p_u/p_d was interpolated over four points because the magnitude and phase of this ratio were smoothly continuous over this frequency range.

It was necessary to interpolate Z_u rather than simply calculate it at the nearest FFT bin frequency because for small FFT sizes, the bin frequency spacing could be a significant fraction of the full-width at half-maximum of the Z_d peaks. The full-width at half-maximum of the Z_d peaks ranged from 15 to 60 Hz. The FFT spacing between data points is equal to the sampling rate divided by the FFT size. For the pressure data, the sampling rate was 44100 Hz and the FFT size was variable. For an FFT size of 2048, the spacing between FFT bins would be 21.53 Hz, which was the largest FFT spacing used. This spacing constitutes a significant fraction of the Z_d peak widths, and non-interpolated Z_d values could produce large errors. Figure 2.9 shows Z_u vs. frequency for one 2048-sample section of the pressure time series of a $G4$ tone from the Brahms excerpt calculated with and without interpolation. A 2048-point FFT was used for this tone in order to obtain sufficient time resolution, and with this low FFT size this example illustrates the largest errors possible. For the "not interpolated" data. Z_u was calculated at the frequency of the nearest pressure FFT bin frequency, and therefore could be a maximum error of 21.53 Hz / 2 = 10.77 Hz from the actual harmonic frequency, which is a significant fraction of the Z_d peak widths. A 10.77 Hz error in the frequency could make a large error in the Z_d value and therefore in the calculated Z_u. From the data in Figure 2.9, the error is largest at the fundamental frequency for both magnitude and phase.

Indirect Z_u Measurement for Noisy Data: Cross-Spectral Averaging

Z_u was calculated for these tones using cross-spectral averaging due to unsteadiness in the tones. It was found that in certain instances, if a tone was unsteady or if the pressure spectra had a high level of noise, the usual method of calculating Z_u gave very noisy results that were difficult to interpret. In order to smooth the effects of noise in the calculated $|Z_u|$ for these cases, the method of cross-spectral averaging [15] was used. In this method, pressure spectra are calculated for smaller sections and are then averaged together. For example, a 32768-point section could be divided into 16 smaller sections, a 2048-point FFT calculated for each smaller section, and all 16 spectra averaged together.

These averaged auto-spectra are defined as the mean square value of the pressure spectra p_u and p_d:

$$\begin{aligned} G_{uu} &= < |p_u|^2 > \\ G_{dd} &= < |p_d|^2 > \end{aligned} \tag{2.1}$$

The cross-spectrum G_{du} is defined as the average product of the complex conjugate of p_d with p_u:

$$G_{du} = < p_d^* p_u > \tag{2.2}$$

The upstream impedance is then defined as

$$Z_u = -Z_d \frac{< p_d^* p_u >}{< |p_d|^2 >} = -Z_d \frac{G_{du}}{G_{dd}} \tag{2.3}$$

The magnitude $|Z_u|$ is

$$|Z_u| = |Z_d| \left| \frac{G_{du}}{G_{dd}} \right| \tag{2.4}$$

For example, for each 32768-point data section, 16 (non-overlapping) spectra were calculated using an FFT size of 2048. These 16 spectra were averaged together to find the auto- and cross-spectra. $|G_{du}/G_{dd}|$ and $|Z_d|$ were interpolated at multiples of the basis frequency for that section, and $|Z_u|$ was calculated from Equation 2.4.

The coherence C is defined as:

$$C = \frac{|G_{du}|^2}{G_{dd} G_{uu}} . \tag{2.5}$$

The coherence gives a measure of the noise present in the data. C will be equal to one for completely noise-free data and equal to zero for pure noise.

2.3 Musical Phenomena Studied

The upstream impedance was measured for several musical phenomena in order to study the role of the airways in each situation and to answer the questions set forth in Chapter 1. These phenomena include:

1. Single tones at a mezzo forte dynamic level over the entire pitch range of the clarinet.

2. Single tones at piano and forte dynamic levels.

3. Single tones played with an "open throat" and a "closed throat".

4. Clarion tones played without the register key.

5. Clarion tones played with pitchbend.

6. Multiphonics.

7. Musical excerpts.

The upstream impedance was measured directly for items 1 and 3 above and indirectly for all items.

2.4 Experimental Procedure

Pressure: For single tones and the multiphonics, the performer was instructed to play steady tones, with a mezzo forte dynamic level except for the tones played at piano and forte. A ten second recording of the AC and DC pressures was made, which included a moment of silence before the performer took a breath. The same measurement method was used for the excerpts as the performer played them.

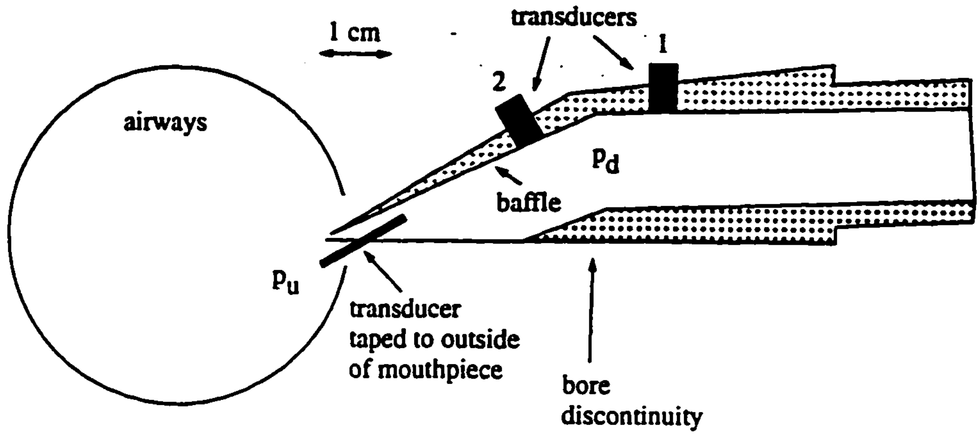
Z_d: The performer fingered each tone and held the instrument as steady as possible while the measurement was made. Z_d was measured for each fingering for which the pressure was measured.

Z_u^o: For each tone for which Z_u^o was measured directly, the performer first played the tone on an actual clarinet in order to become aware of the airway state. The performer then fingered the same tone on the measurement clarinet, took a breath, and began to blow through the measurement mouthpiece as though actually playing the tone. The experimenter sealed off the air tube, immediately took a measurement, and then opened the air tube. Two trials were made for each tone. Since this measurement relies on the expertise of the clarinetist in reproducing an airway configuration for a particular tone with no feedback from the instrument, it was necessary to use highly skilled (i.e., professional or advanced student) performers.

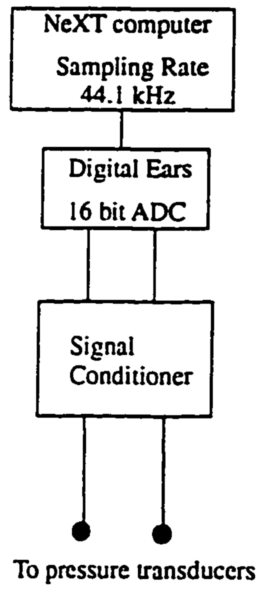
2.5 The Performers

The performers were three professional clarinetists (A, B, and C) and two amateurs at the level of advanced students (D and E). Performer A specializes in jazz and contemporary music and has played a major role in the development of multiphonic technique in the clarinet. B is a university clarinet professor with expertise in early clarinet performance. C is a member of a major symphony orchestra. D and E are both graduate students, but not clarinet majors.

For this study, performer A played multiphonics, and the other performers all played single tones at mezzo forte. In addition, B played tones at piano and forte, clarion tones without the register key, and clarion tones with pitchbend. C played musical excerpts. D played tones with an open and closed throat, clarion tones without the register key, and clarion tones with pitchbend.

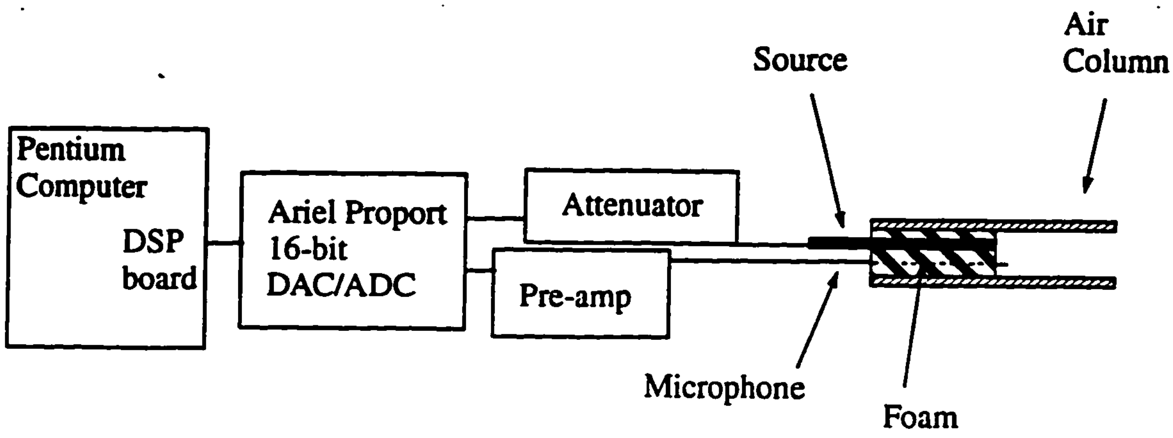


(a) Position of transducers.

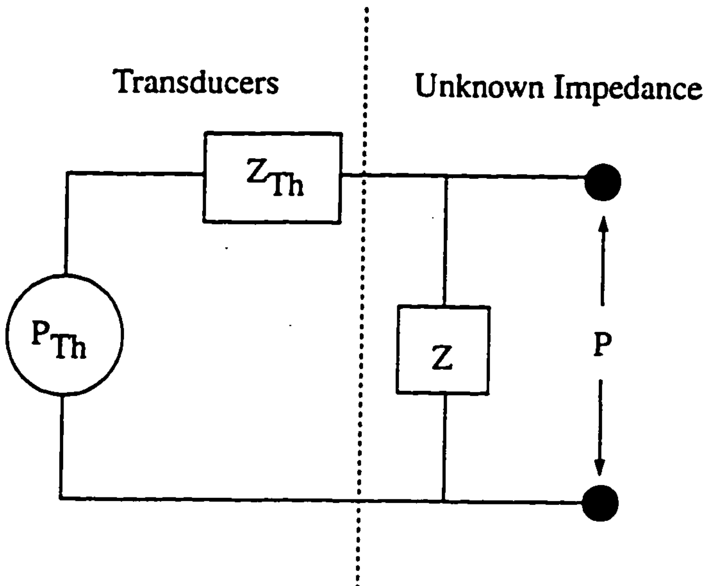


(b) Hardware.

Figure 2.1: Experimental set-up to measure the pressure in the mouth and in the mouthpiece.



(a) Hardware.



(b) Thevenin equivalent circuit.

Figure 2.2: Experimental set-up to measure impedance.

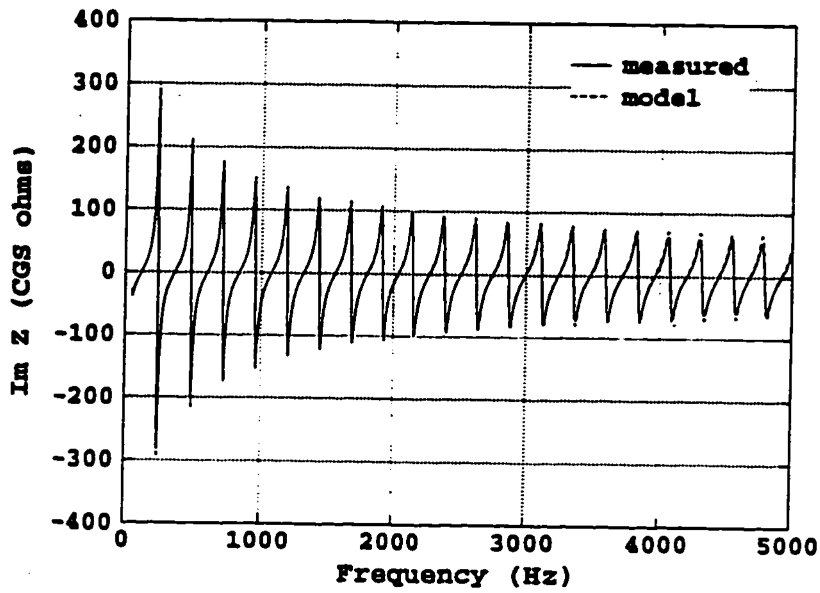


Figure 2.3: Measured and modelled ImZ for 0.5-inch diameter brass cylinder.

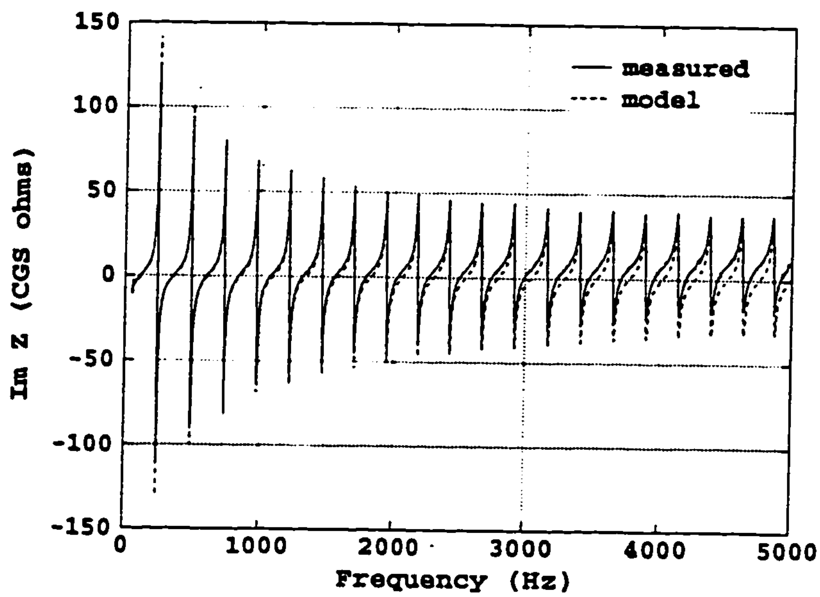


Figure 2.4: Measured and modelled ImZ for 1.0-inch diameter brass cylinder.

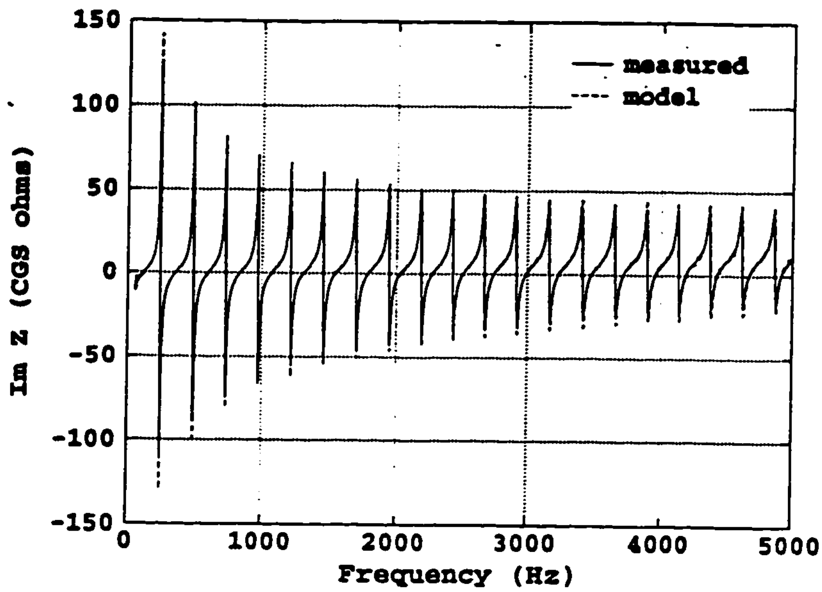


Figure 2.5: Measured and modelled ImZ for 1.0-inch diameter brass cylinder with inertance term added to model.

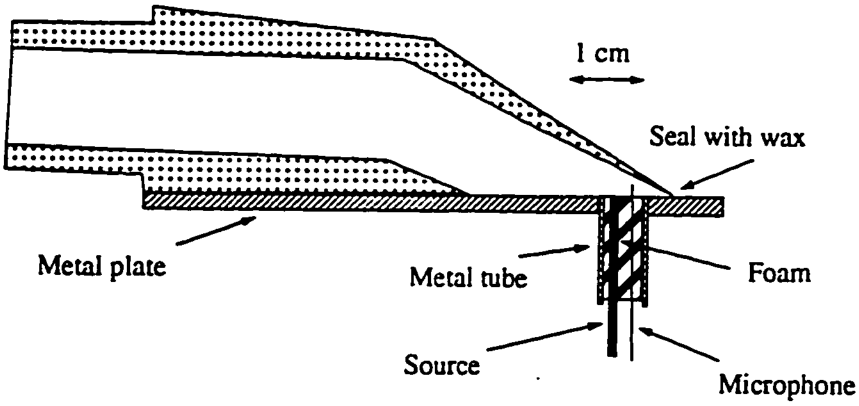


Figure 2.6: Experimental set-up to measure the impedance of the clarinet.

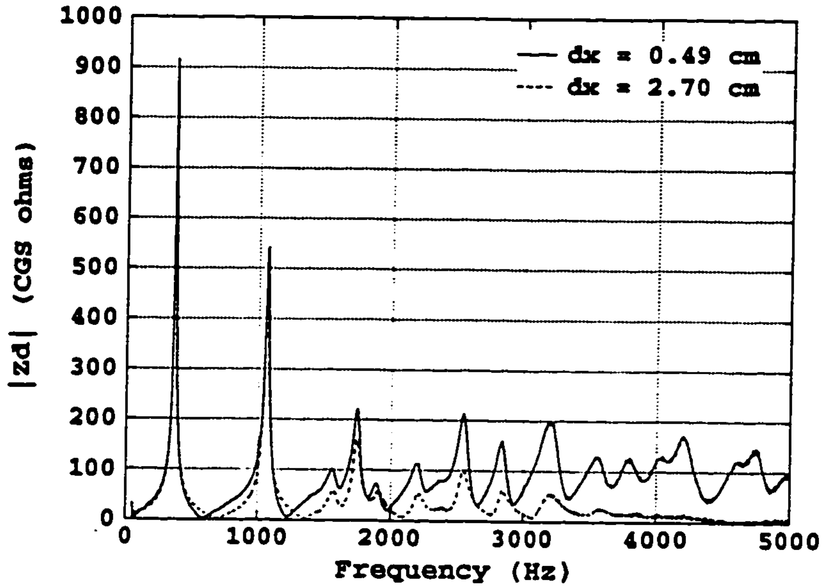


Figure 2.7: Instrument impedance $|Z_d|$ for $G4$ fingering. dx = distance between source transducer and mouthpiece tip.

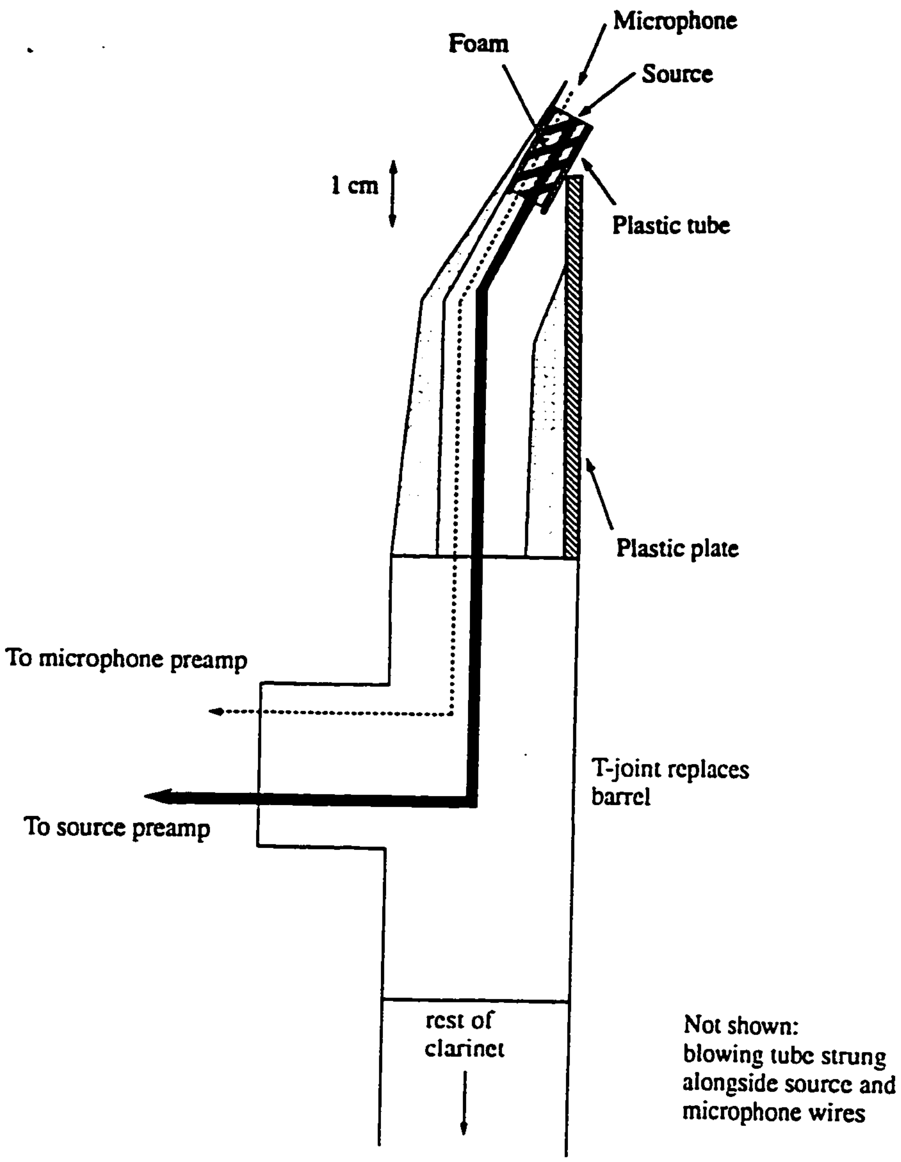
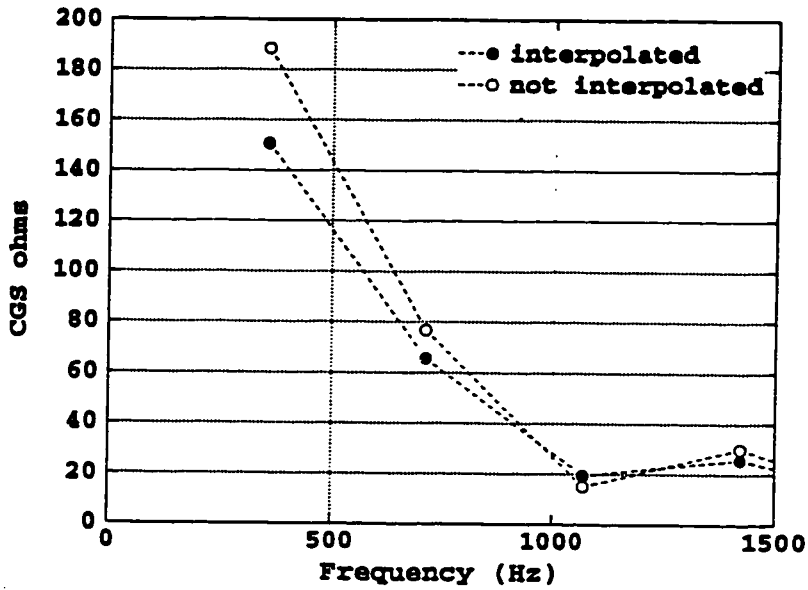
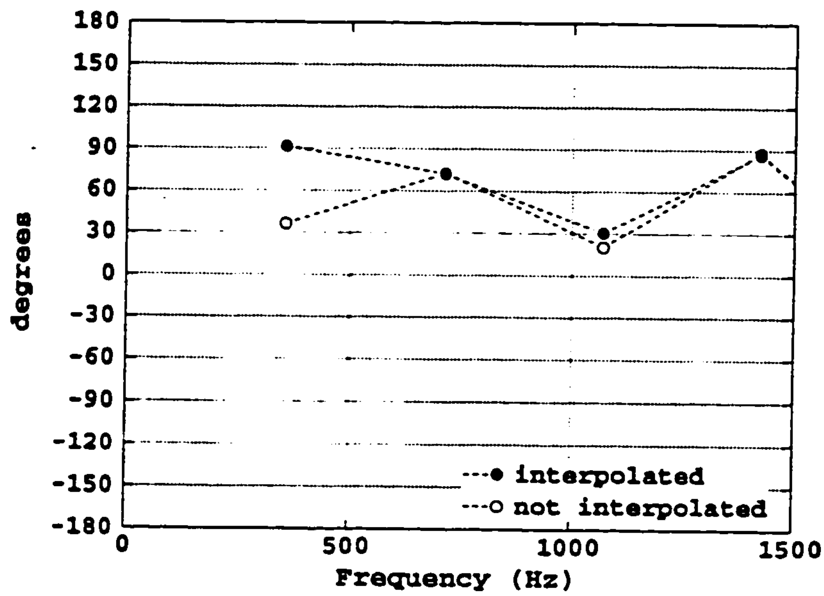


Figure 2.8: Experimental set-up to measure Z_u.



(a) Magnitude.



(b) Phase.

Figure 2.9: Z_u for $10-G4$ from Brahms excerpt, calculated with 4-point interpolation and without interpolation at nearest FFT bin frequency.

Chapter 3

RESULTS: SMALL-SIGNAL IMPEDANCE MEASUREMENTS

The study of wind instruments in musical acoustics has traditionally focused on the input impedance of the air column, since that determines the possible modes of the resonator. In this study, the impedances of the clarinet and the performer's airways were measured by means of a one-microphone method. The low-amplitude stimulus of this method gives the linear response of the air column to an excitation. This chapter presents the results of the clarinet and airway impedance measurements.

3.1 Instrument Impedance (Z_d)

The impedance of a Buffet R-13 clarinet was measured for 13 fingerings across the pitch range of the clarinet. Appendix B contains a compilation of the results and a brief discussion. This section will discuss the measurements as they relate to one of the musical phenomena studied (playing clarion tones without the register key), and the measurements will be compared to those of other researchers since instrument impedance has not been reported using this particular measurement technique.

3.1.1 Opening the Register Key

Figure 3.1 shows impedance curves for the chalumeau tone $A3$ and the corresponding clarion tone obtained by opening the register key, $E5$. The largest effect of opening the register key was to lower the magnitude of the first peak and to increase the frequency (Figure 3.1-a), so that the peak was no longer in harmonic alignment with the second peak, which stayed fairly constant along with most higher-frequency peaks. The phase at the first mode shifted accordingly (Figure 3.1-b). This illustrates the function of a properly placed register hole: it should bring the first mode out of harmonic alignment without affecting the second mode [8]. Although it is possible to play second-mode tones without using the register key by overblowing the first mode, these tones are much easier to play when the register hole is opened.

3.1.2 Measurements of Other Researchers

Measurements of instrument impedance for the clarinet have already been reported by Backus [4], Thompson [71], Hoekje [42], Gibiat and Laloë [32], and Benade and Keefe [11].

Thompson, and Benade and Keefe, reported uncalibrated impedance measurements. Thompson showed the instrument impedance up to 3000 Hz for three fingerings in the chalumeau register. They were similar to the measurements here except the high frequency peaks were not as pronounced. Benade and Keefe showed measurements on the both the Buffet and NX clarinets up to 2000 Hz for the fingerings from $E3$ to $C5$. The main difference between their data and those here is that for tones in the lower clarion register, the first peak was the largest in their data, but the second peak was the largest in the data here.

Backus measured Z_d up to about 2000 Hz on a plastic Bundy clarinet using the capillary tube method. The measurements reported here are similar in magnitude and peak structure to those of Backus, with only slight variations.

Hoekje used an impulse response technique with a piezo-electric disc as a flow source. He reported the impedance curve for $C4$ up to 2500 Hz. It was similar to the measurement reported here except that the first peak was 650 CGS ohms rather than the 900 CGS ohms here.

Gibiat and Laloë (GL) reported the impedance of a Noblet clarinet for one fingering ($E3$) using the two-microphone-three-calibration method. In this method, the mouthpiece is replaced by a cylinder of equivalent volume and a measurement head is attached to the other end of the cylinder. In order to compare their results with those measured here with the one-microphone method, a cylindrical piece of wood tubing replaced the mouthpiece. It had an inner diameter equal to the entrance diameter of the clarinet barrel (15 mm) and a length of 65 mm, for a volume of 11.5 cm^3, which was approximately the measured volume of the mouthpiece, 11.2 cm^3. The open end of the cylinder was sealed with a brass plate that had a cylinder protruding from the outside. The foam tip was pushed into the cylinder until it was flush with the inner surface. In this way, the impedance could be measured in the same configuration as

GL, but with a different measurement method.

Figures 3.2 and 3.3 show measurements of the impedance for the fingering $E3$ using the one-microphone method and a mouthpiece (Figure 3.2) and using the one-microphone method with the cylindrical tube replacing the mouthpiece (Figure 3.3). This is a comparison of the impedance measured in the two configurations using the same measurement method. The axis scales are identical to those used by GL in their paper. The y-axis is unitless and is impedance divided by $\rho c/S = 22.6$ CGS ohms, where ρ is the density of air, c is the speed of sound, and $S = \pi(1.5\text{cm}/2)^2 = 1.8\ \text{cm}^2$ is the area of the entryway. The main difference between the two measurements was that for frequencies greater than about 1000 Hz, the peak magnitudes were reduced by half for the measurement with the cylinder. Several other fingerings across the range of the instrument were also measured, and for all fingerings except $E3$, the cylinder measurement gave lower peak values for all peaks, including the lowest-frequency one.

The replacement of the mouthpiece with a cylindrical tube makes the entryway of the air column more cylindrical and less conical, which implies that the mode ratios should increase for the cylindrical tube [8]. The ratio of the tenth mode frequency f_{10}^z to the first mode frequency f_1^z was calculated for the cylinder and the mouthpiece configurations. The frequencies of the first and tenth modes were interpolated to 0.1 Hz from the positive-slope zero crossings of the reactance. The reactance of the mouthpiece configuration appeared to have an inertance term since the levels of the peaks and dips increased with frequency, and therefore an inertance $j\omega I$ with $I = 0.0025\ \text{g cm}^4$ was subtracted from the reactance of the mouthpiece configuration before the zero-crossings were interpolated. The frequency of the first mode with the mouthpiece was $f_1^z = 150.8$ Hz and was $f_1^z = 150.0$ Hz with the cylinder. The frequency of the tenth mode was $f_{10}^z = 2387.3$ Hz with the mouthpiece and $f_{10}^z = 2429.8$ Hz with the cylinder. The mode ratio was $f_{10}^z/f_1^z = 15.83$ with the mouthpiece and $f_{10}^z/f_1^z = 16.20$ with the cylinder. Thus, the substitution of a cylinder for the mouthpiece does have the effect of increasing the mode ratios.

The data in Figure 3.3 can be compared to the data reported by GL to make a comparison of two different methods using the same configuration. The lowest-frequency peak is 25% lower in magnitude for the one-microphone technique, but the high frequency peaks and the phase are similar. The difference could be the result of a leak in the clarinet, or could be due to the differences between individual instruments. Gibiat [31] has reported that there is a wide variation among different instruments. A third possibility is that replacing the mouthpiece of a clarinet, or any other instrument, with a cylindrical tube produces errors that can be significant, in this case an error in the magnitude of the first modal peak.

3.1.3 Conclusions

The one-microphone technique gives reliable impedance measurements for clarinets that are comparable to those measured by other researchers. The variations that do exist could be due to differences among individual instruments. There are minor differences in peak magnitudes and mode ratios with the results of Gibiat and Laloë, who replaced the mouthpiece with a cylinder and used the two-microphone-three-calibration method to measure the impedance.

3.2 Direct Measurement of Upstream Impedance (Z_u^o)

Previous measurements of the upstream impedance (Gupta et al. [35], Benade [7], Hoekje [42]) have been for airway configurations for vowels and not for actual performance conditions. With this one-microphone technique, it was possible to measure directly the upstream impedance for airway configurations for actual clarinet performance. The upstream impedance of three performers was measured for several tones over the range of the instrument. These measurements will be compared among performers and with measurements obtained by Benade and Hoekje for vocal tract configurations of vowels.

3.2.1 Results for Three Performers

Z_u^o was measured using the direct method described in Section 2.2.2 for each of three performers for several tones across the range of the instrument. The general characteristics of the measured Z_u^o will be discussed for each performer.

Performer B

Z_u^o was measured with performer B for the following eleven tones: $E3$, $A3$, $C4$, $E4$, $G4$, $B4$, $E5$, $G5$, $B5$, $E6$, and $G6$. Figure 3.4-a shows $|Z_u^o|$ up to 5000 Hz for the tone $G5$ and illustrates some of the typical features of $|Z_u^o|$ for this performer. There was usually a noisy peak at 200–250 Hz, as shown in Figure 3.4-b, which tended to stay under 100 CGS ohms for all tones. For all tones, there was also a single peak in the frequency range 400–1100 Hz. This peak had an amplitude ranging from 20 to 100 CGS ohms, with the exception of $E6$ for which it had an amplitude of 220 CGS ohms. There was no clear trend of peak frequency with pitch for this peak, but the peak frequency was the greatest for tones in the altissimo register. In addition to this single peak, there were miscellaneous peaks above 2000 Hz, but often they varied in magnitude and frequency from one measurement trial to the next. If there were strong high frequency peaks, they usually fell in the range 3000–4000 Hz, as shown in this example. Between the peaks, $|Z_u^o|$ stayed relatively low: less than 10 CGS ohms.

Figure 3.5 shows the phase of Z_u^o for this measurement. The phase is equal to +90 degrees before each resonance, crosses zero at the resonance frequency and is equal to -90 degrees after the resonance, which agrees with Gupta et al. Except for some noise, the phase stays within ± 90 degrees. This is expected since the airways are a lossy system, and so the real part of the impedance should be positive.

Performer C

Z_u^o was measured with this performer for the four tones $E3$, $C4$, $G5$, and $E6$. Figure 3.6 plots $|Z_u^o|$ for the tone $G5$ and shows the features common to all four tones. There was a noisy peak at 200–250 Hz. Except for $E6$, there was a resonance of less than 50 CGS ohms at 700–800 Hz. The resonance at 700–800 Hz was the strongest for $G5$, which has a fundamental at 698.5 Hz. There was also a single resonance of 30–130 CGS ohms at 2200–2600 Hz that was strongest for the two lowest tones, $E3$ and $C4$. Between the peaks $|Z_u^o|$ was less than 10 CGS ohms.

Performer D

Z_u^o was measured for the same 11 tones from $E3$ to $G6$ that were measured for Performer B. Figure 3.7 shows $|Z_u^o|$ for $G5$ and illustrates the common features. There was a noisy peak in the range 200–250 Hz for all tones. There was a single peak that ranged from 800 to 1100 Hz, with an amplitude of 20–70 CGS ohms. There was no clear trend of peak amplitude or frequency with pitch for this peak. All tones had one or two peaks in the frequency range 2000–3000 Hz, with miscellaneous peaks at higher frequencies. From $G4$ up, there was a single peak in the frequency range

2300–2500 Hz that reached amplitudes of up to 130 CGS ohms. Between the peaks, $|Z_u|$ stayed less than 10 CGS ohms.

3.2.2 Comparison of the Three Performers

The measured Z_u^o of all three performers had several characteristics in common, but there were also some differences. The commonalities included:

1. A low level of $|Z_u^o|$ between peaks ($|Z_u^o| \leq 10$ CGS ohms).
2. A single, noisy peak less than 100 CGS ohms at 200–250 Hz. The source of the noise is probably physiological since the calibration of the impedance system was good down to 40 Hz.
3. A single peak less than about 200 CGS ohms in the range of 400–1100 Hz, of variable frequency and amplitude.
4. No peaks in the range 1000–2000 Hz, except for possibly the peak of 3. above.

These consistencies among the three performers appear to be general characteristics of Z_u^o for expert clarinetists, although the investigation of this assertion is beyond the scope of this study.

The main difference among the three performers concerns the high frequency peaks. Two performers (D and C) had a single strong peak at 2200–2600 Hz. The other performer (B) had a strong peak in this range for some of the measurements, but more often had peaks at higher frequencies, usually 3000–4000 Hz. These high frequency peaks could contribute to subtle differences between performers.

A second difference between performers B and D was that B varied one peak over the range 400–1100 Hz, whereas D varied the peak only over 800–1100 Hz. Whether this was simply due to error from lack of feedback from the instrument or a genuine difference in performers cannot be determined. Performer C varied the peak over 700–800 Hz, but Z_u^o was only measured for four tones for this performer.

3.2.3 Repeatability

This direct measurement of the upstream impedance gives results that have a fair degree of repeatability. Figure 3.8 shows another measurement of $|Z_u^o|$ with performer B for the tone $G5$, which can be compared with Figure 3.4. The two measurements were made on different days. The peak at 620 Hz remained constant in height and frequency. The main discrepancies were in the higher-frequency peaks. Both measurements had two peaks in the range 3000–4000 Hz, but with different heights and frequencies. In general, the upstream impedance measurements were repeatable, with differences in performer variability that may be due to the lack of feedback from the instrument.

Quality Factor of $|Z_u^o|$

The quality factor Q of a resonance is defined as $Q = f/\Delta f$, where f is the frequency of the peak and Δf is the full-width at half-maximum. For the measured Z_u^o of all three performers, Q was in the range 5–13 for the peak in the range 400–1100 Hz, and $Q = 23$–30 for peaks at higher frequencies. In comparison, Q for the Z_d peak at the fundamental frequency ranged from 12 to 26. The ratio of the quality factor Q_d of the downstream peak at the fundamental frequency to the quality factor Q_u of the upstream peak in 400–1100 Hz for the same tone ranged from 1 to 5, although it was usually around 4. Thus the airway resonances have slightly more damping than the instrument resonances.

3.2.4 Comparison with Results of Other Researchers

Direct Measurements of upstream impedance for vocal tract configurations for vowels have been reported by Benade [7] and Hoekje [42]. They both used an impulse response technique to measure $|Z_u^o|$ that uses a piezoelectric disc as a flow source and an electret microphone to measure the pressure response. They reported $|Z_u^o|$ up to 2500 Hz for vocal tract shapes of various vowels.

Benade [7] showed uncalibrated $|Z_u^o|$ for three vowels: AH, EH, and IH. For all three there was a peak at 200 Hz, which agrees with the measurements reported here. In addition, for all three vowels he found a large, broad peak in each of the ranges 810–920 Hz and 1170–1510 Hz, whereas there was only one rather small peak in the frequency range 400–1100 Hz in the measurements here. The overall appearance of Benade's $|Z_u^o|$ curves also differs. Figure 3.9-a shows $|Z_u^o|$ up to 2500 Hz for the tone $E5$ measured on performer D using an "open throat", which clarinetists claim to be desirable, and with a $\log_{10}$ scale for $|Z_u^o|$, which is the format of Benade's graphs, although he reported only relative values for $|Z_u^o|$. The level is fairly low and there are no broad peaks, unlike Benade's measurements. However, when $|Z_u^o|$ was measured for the same tone, but with the performer creating a "closed throat" condition (see Section 5.4), the resulting $|Z_u^o|$ (Figure 3.9-b) was very similar to what Benade measured. There were two broad, strong peaks in frequency ranges close to what Benade found.

The high frequency peaks and dips of Benade's measured upstream impedance became less pronounced at higher frequencies, and he attributed this to the reflection properties of the lungs. He reported no peaks in the range 1500–2500 Hz. The measurements reported here do show peaks above 2000 Hz that were often quite strong, greater than 100 CGS ohms, with high Q's.

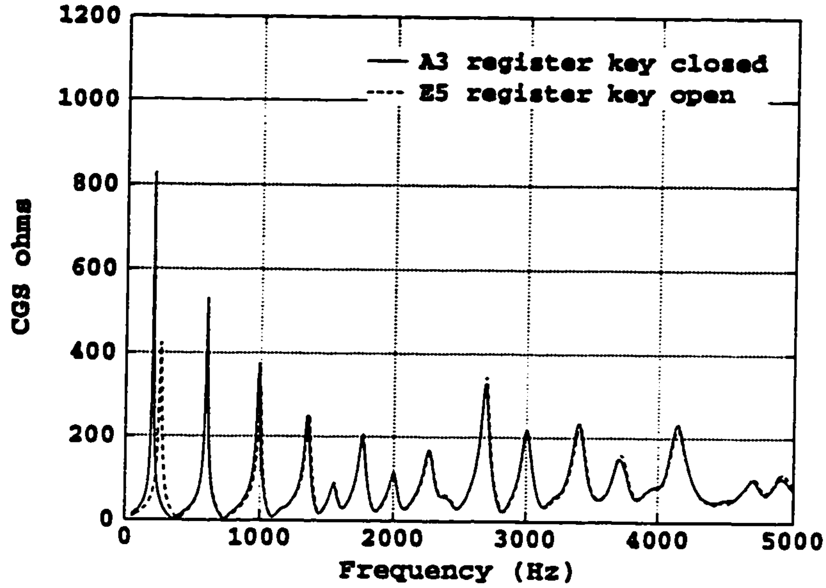
The peaks and dips of Benade's $|Z_u^o|$ were superimposed on a broad hump centered on 1000 Hz. He interpreted this as a broad hump in the wave impedance itself, which implied a constriction near the input end of the airways. None of the measurements reported here showed such a broad hump (Figure 3.9-a was typical), and it was not apparent in Hoekje's [42] measurements. For measurements with the "closed throat" configuration, such a hump could be obscured by the rise in $|Z_u^o|$ at low frequencies. One possible explanation for the absence of this hump is that the glottis was more open for the measurements here than for Benade's measurements. This would remove a constriction in the airways, which Benade claimed as the cause of his hump in the wave impedance.

Hoekje [42] reported $|Z_u^o|$ for vocal tract configurations for four vowels corresponding to tongue positions ranging from low to high. His measurements showed a peak at 200–250 Hz, with a maximum height of 70 CGS ohms, and another peak at 500–1000 Hz, but which had an amplitude twice as large as the peaks here. In addition he found a third peak for three of the vowels at 1725–2050 Hz, which is absent from these measurements.

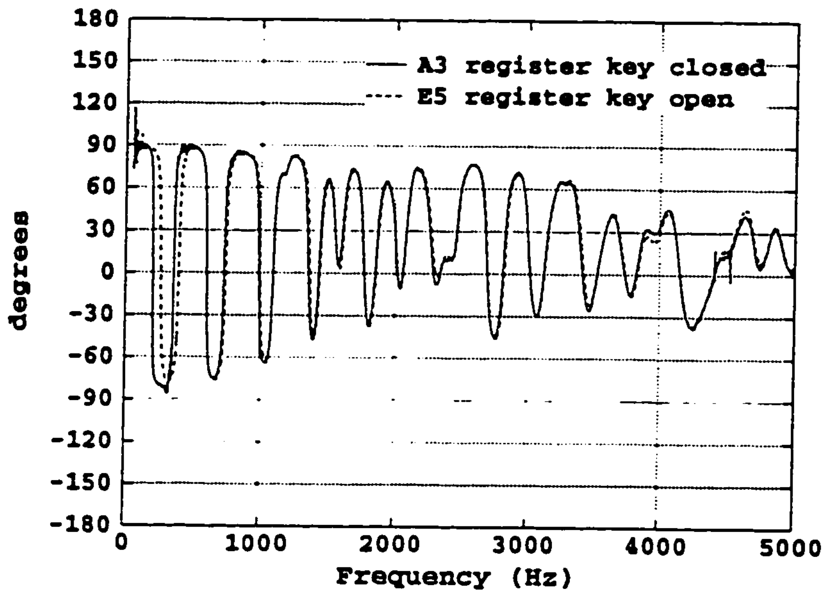
Although there are some similarities between the data of Benade and Hoekje with the measurements reported here, differences remain and are most likely due to the fact that they were measuring Z_u^o for vocal tract configurations of vowels, whereas the data here is intended to simulate actual clarinet playing. In addition, the glottal opening may have been more constricted for Benade's measurements. An implication is that vocal tract configurations for actual clarinet playing, while possibly similar to those for vowels, are not identical and can be quite different, which contradicts the teaching practices of some teachers who tell students to think of certain vowels for different registers. Further study is needed to clarify this matter.

3.2.5 Conclusions

From these measurements of the upstream impedance Z_u^o, it can be concluded that the performer can exert an influence in the ranges 200–250 Hz, 400–1100 Hz, and possibly also in 2000–3000 Hz and higher by varying the resonance peaks in these ranges. The range 400–1100 Hz happens to correspond to the clarion and altissimo registers of the clarinet, but could also influence the upper harmonics of tones in the chalumeau register. The peak amplitudes ranged mostly from 20 to 100 CGS ohms, but occasionally increased above 200 CGS ohms.

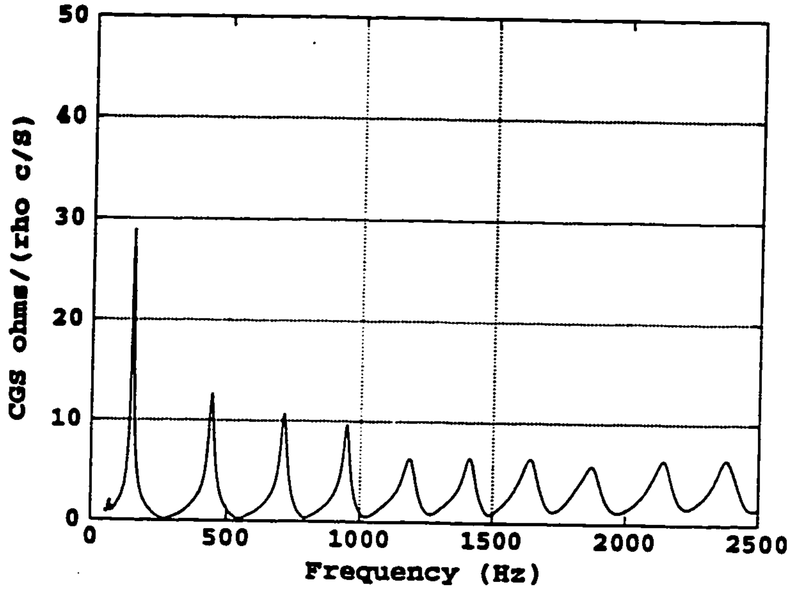


(a) Magnitude.

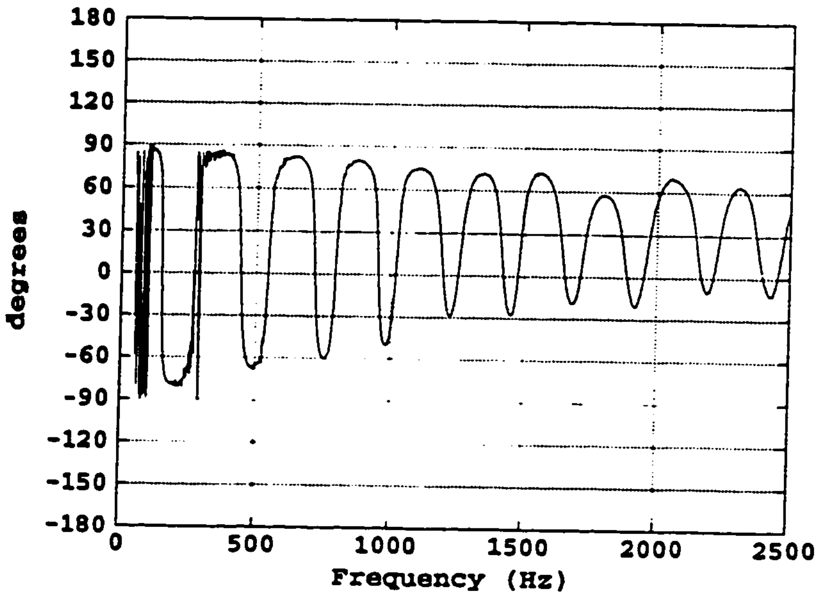


(b) Phase.

Figure 3.1: Instrument impedance Z_d for fingerings with and without the register key: $A3$ and $E5$.

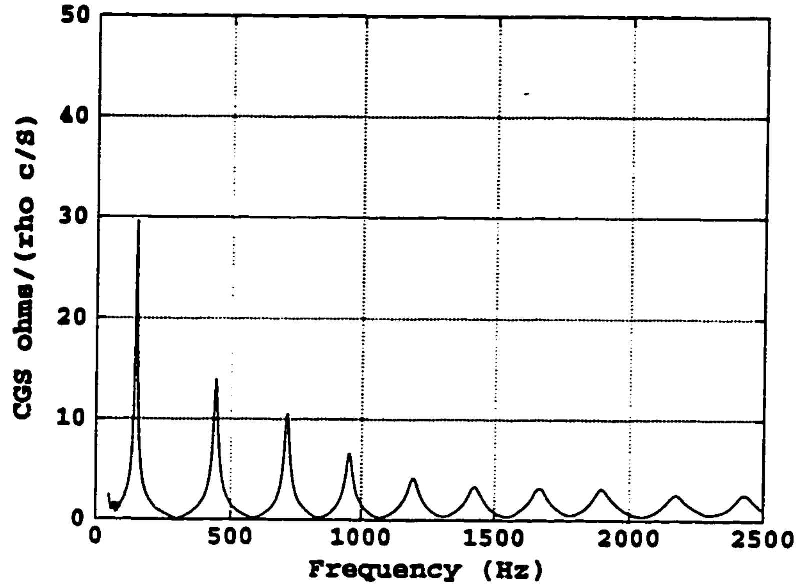


(a) Magnitude.

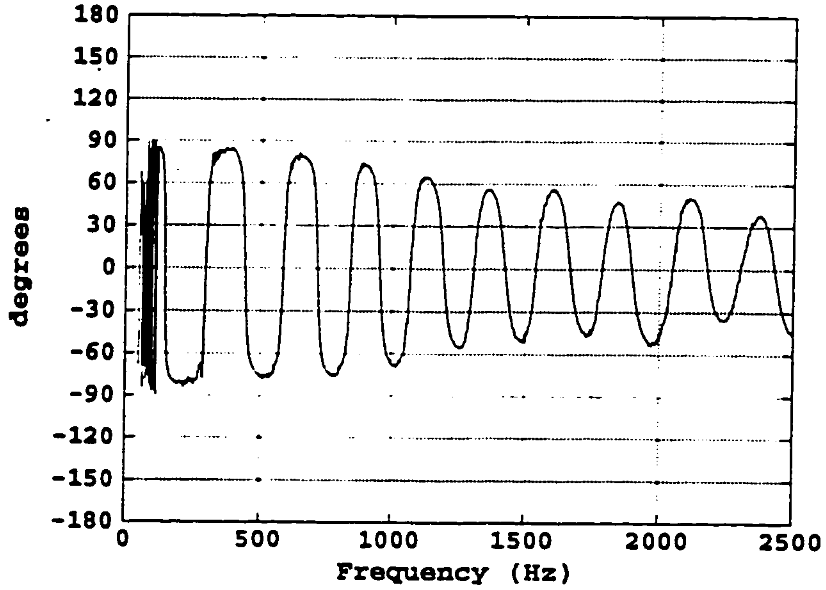


(b) Phase.

Figure 3.2: Instrument impedance Z_d for $E3$ measured with the mouthpiece.

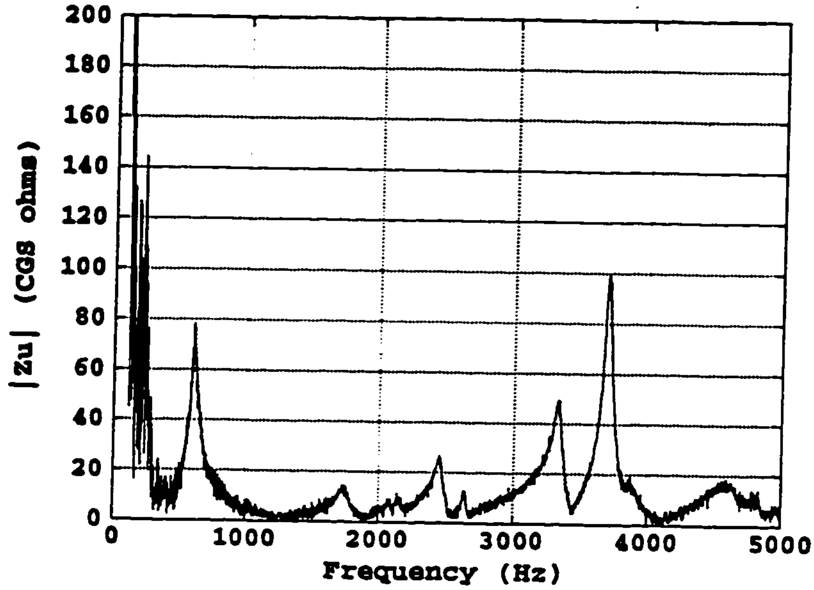


(a) Magnitude.

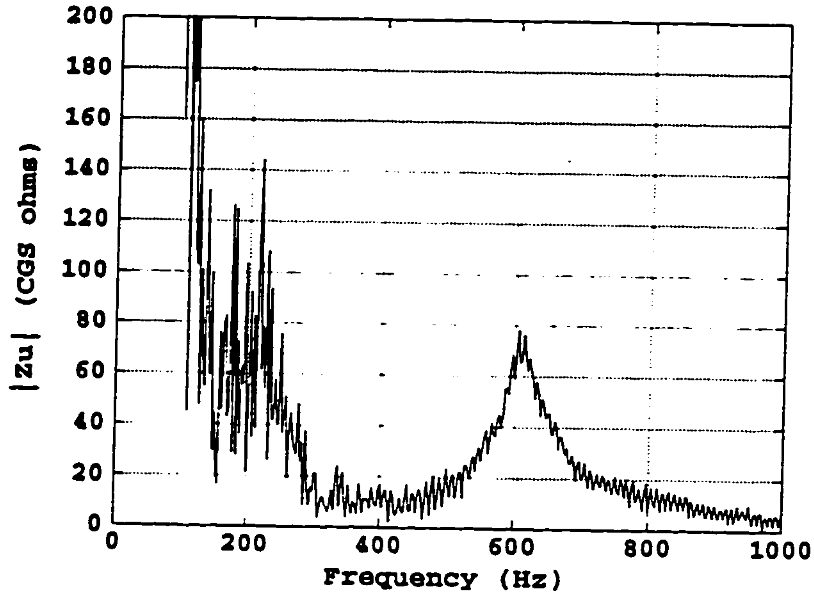


(b) Phase.

Figure 3.3: Instrument impedance Z_d for $E3$ with cylinder replacing mouthpiece.



(a) Up to 5000 Hz.



(b) Up to 1000 Hz.

Figure 3.4: Magnitude of upstream impedance Z_u^o for performer B for $G5$.

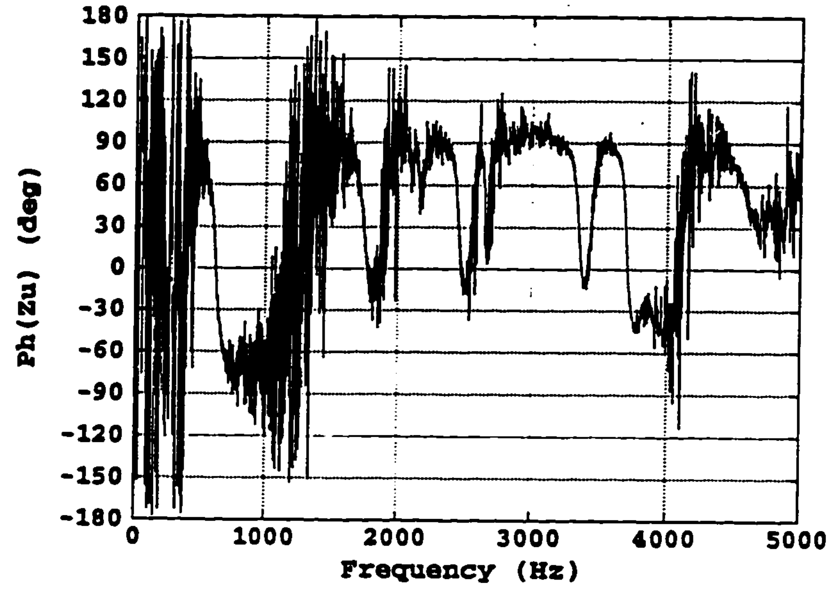


Figure 3.5: Phase of upstream impedance Z_u^o for performer B for $G5$.

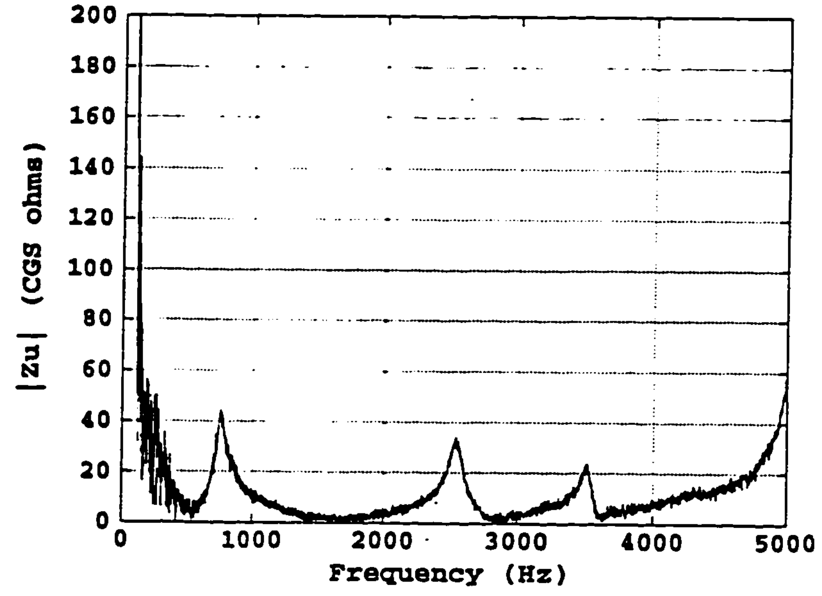


Figure 3.6: Magnitude of upstream impedance Z_u^o for performer C for $G5$.

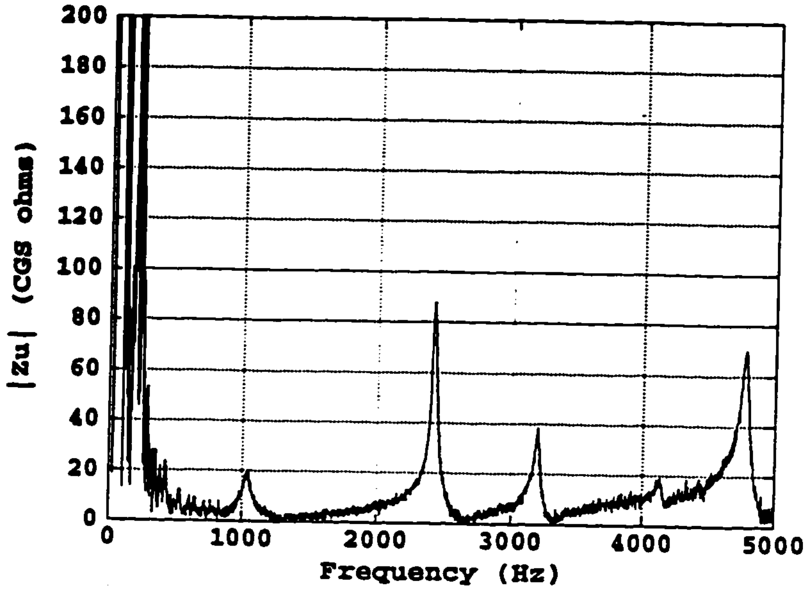


Figure 3.7: Magnitude of upstream impedance Z_u^o for performer D for $G5$.

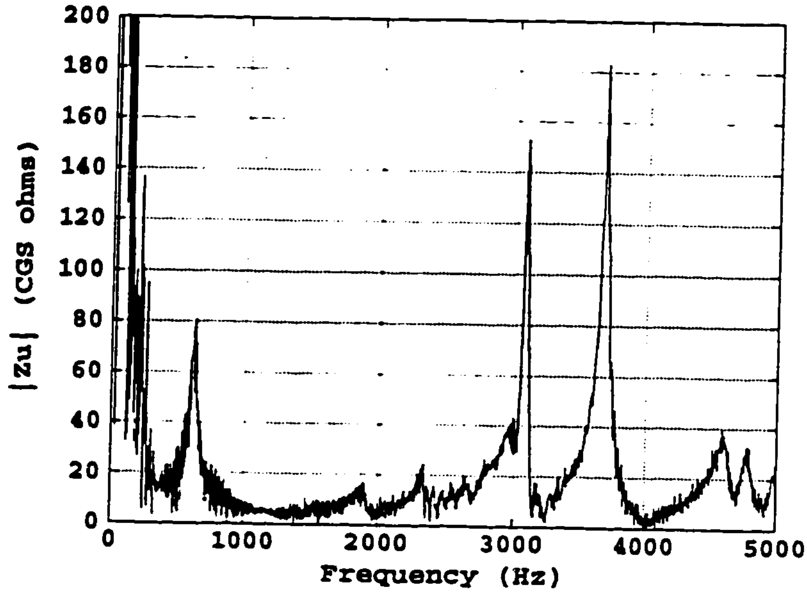
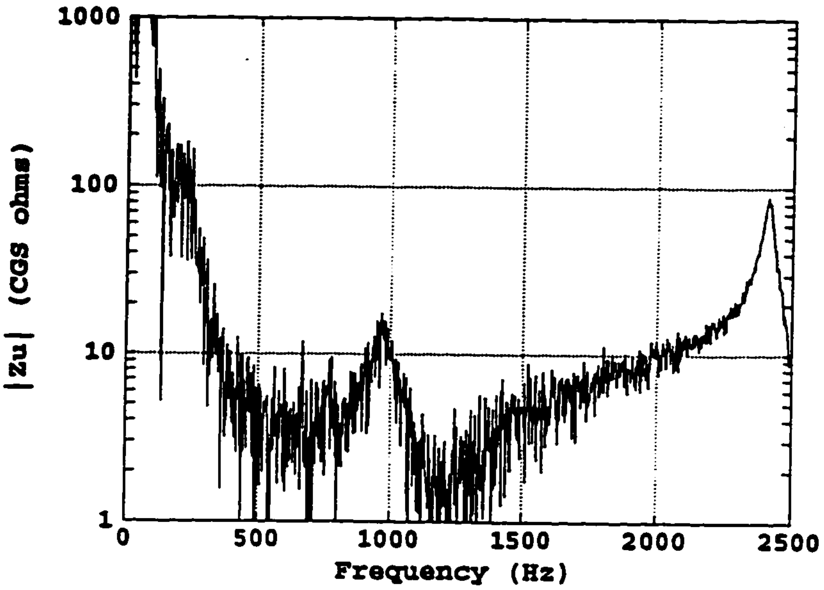
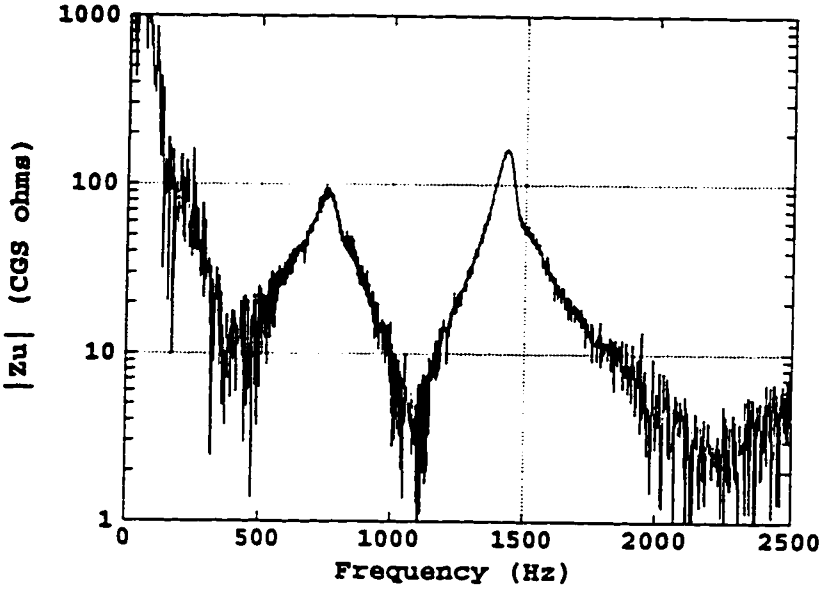


Figure 3.8: Repeatability of direct upstream impedance measurement, for performer B for $G5$ on a different day from Figure 3.4.



(a) "Open" throat.



(b) "Closed" throat.

Figure 3.9: $|Z_u^o|$, on a $\log_{10}$ scale, for the tone $E5$ (performer D), played with an "open throat" and a "closed throat".

Chapter 4

RESULTS: UPSTREAM AND DOWNSTREAM PRESSURE MEASUREMENTS

The indirect measurement of the upstream impedance required the pressures in the mouth and mouthpiece. The mouthpiece pressure was measured at two positions to determine if there were differences, caused perhaps by differences in the hydrodynamics at the two positions, that would favor one position over the other in the indirect upstream impedance measurement. Pressure spectra were calculated from the time series at each position by means of a Fast Fourier Transform (FFT), after a Hanning window had been applied to the data. The following sections will discuss various aspects of these pressure measurements: The comparison of the pressure spectra at the two mouthpiece positions will tell if there are nonlinear flow effects present that affect the standing wave pattern, and if one position is preferred for the indirect upstream impedance measurement. The noise floor of the pressure spectra will be examined to determine how it is affected by instrument resonances, and more importantly for this work, by airway resonances. The DC pressures at each position will be measured from the pressure spectra. They are relevant to this work since the continuity of flow equation is valid in a linear framework with small-amplitude reed vibrations, which are determined by the DC pressures. Once the DC pressures are found, it is easy to test for flow into the mouth by examining the mouth and mouthpiece pressure waveforms.

4.1 Comparison of Two Mouthpiece Positions

The pressure was measured at two positions in the mouthpiece in order to determine which one would be more appropriate to use for the indirect measurement of Z_u. The different mouthpiece geometries at the two positions could influence the hydrodynamics and produce different pressure spectra at each position. If hydrodynamic effects are significant, then using the instrument impedance measured under small-signal conditions would not be appropriate in the linear continuity of flow equation. In this section, a quantitative comparison between the pressure spectra will be made using the linear transfer function between the two mouthpiece positions.

4.1.1 Transfer Function

The linear transfer function between two positions in the mouthpiece can be used to characterize the differences between the pressure spectra at these two positions. In the absence of nonlinear flow effects, the pressure spectra will be due only to the pressure standing waves in the bore. For a cylindrical-bore instrument like the clarinet, the pressure standing waves are approximately either cosine or sine waves. The odd harmonics are cosine waves (Figure 4.1-a), and the pressure at position 2 is greater than the pressure at position 1. The opposite is true for the even harmonics, which are sine waves (Figure 4.1-b). This generalization holds true for positions that are less than approximately $\lambda/2$ from the reed tip, where λ is the wavelength of the standing wave. Since the acoustic standing wave varies along the bore, the pressure spectrum will also vary.

If there is nonlinear flow, the standing wave pattern will be altered, and this will produce additional differences in the pressure spectra. If the standing wave pattern can be removed, then the remaining differences due to nonlinear flow can be studied. One way to remove the standing wave pattern is to measure the linear transfer function T between the two positions. A small-amplitude signal is emitted at the reed tip. If the pressure in the bore at the two positions is p_1 and p_2, then the measured signals will be

$$v_1 = S_1 p_1 \tag{4.1}$$

$$v_2 = S_2 p_2 \tag{4.2}$$

where S_1 and S_2 are the sensitivities of the respective measuring systems. The linear transfer function T between the pressures at the two positions is then

$$T = \frac{p_2}{p_1} = \frac{S_1}{S_2}\frac{v_2}{v_1} \tag{4.3}$$

The magnitude $|T|$ is

$$|T| = \frac{S_1}{S_2}\left|\frac{v_2}{v_2}\right| \tag{4.4}$$

The phase $\Phi(T)$ is

$$\Phi(T) = \Phi(v_2) - \Phi(v_1) \tag{4.5}$$

where $\Phi(v_1)$ and $\Phi(v_2)$ are the phases of v_1 and v_2. Then, if the pressures measured at the two positions for any large flow, for example as during actual playing, are p_1 and p_2, multiplying p_1 by T will give a pressure p_1' that can be compared to p_2 with no standing wave effects:

$$|p_1'| = |T||p_1| \tag{4.6}$$

$$\Phi(p_1') = \Phi(T) + \Phi(p_1) \tag{4.7}$$

The pressures p_2 and p_1' will be identical and equal to the standing wave pattern at position 2 if there are no nonlinear flow effects.

The transfer function T is dependent upon the air column that follows the mouthpiece, and therefore varies with different fingerings. This can be proven from the transmission line equation relating the pressure and flow at position 2 with the pressure and flow at position 1:

$$\begin{pmatrix} p_2 \\ u_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} p_1 \\ u_1 \end{pmatrix} = \begin{pmatrix} Ap_1 + Bu_1 \\ Cp_1 + Du_1 \end{pmatrix} \tag{4.8}$$

The ABCD matrix [47] transforms the pressure and flow at position 1 to the pressure and flow at position 2 and is analogous to an acoustical scattering matrix.

The pressure at position 2 is

$$p_2 = Ap_1 + Bu_1 = p_1(A + BZ_1) \tag{4.9}$$

where Z_1 is the impedance looking down the air column from position 1. Z_1 will be different for different fingerings, and the linear transfer function, calculated by

$$T = \frac{p_2}{p_1} = A + BZ_1, \tag{4.10}$$

will vary with the fingering. T must be measured for each fingering and then applied to pressures measured under actual playing conditions using that fingering. Note that the $ABCD$ matrix is independent of the reed and the airways, and therefore T is is constant under both performance and nonperformance conditions.

4.1.2 *Measurements*

The pressure was measured at positions 1 and 2 in the same mouthpiece shown in Figure 2.1-a. They were separated by a distance of 1.9 cm and the one nearest the reed tip was 2.7 cm from it. Position 1 was in the uniform, cylindrical portion of the bore, and position 2 was in the nonuniform portion of the bore. The two positions were separated by the sharp edge discontinuity indicated by the arrow in Figure 1.3-a. The reed channel height h and length L were approximately $h = 0.5$ mm $\pm$ 0.2 mm and $L = 1.1$ mm $\pm$ 0.1 mm, and $L/h = 2.2$. These are the equilibrium values; h will vary during the course of an oscillation. The differences in the pressure standing wave at these two positions could be affected by the nonlinear flow effects both at the reed tip and at the bore discontinuity. Although these pressures measured at the mouthpiece wall are not the jet pressure, if a jet exists, they are relevant to sound production since it is the wall pressure (at the position of the reed) that generates the force on the reed.

The transfer function between positions 1 and 2 was measured using the set-up in Figure 4.2. The reed window of the mouthpiece was sealed by a brass plate that had a hole near the reed tip. The Etymotic source probe, fitted into a foam tip, was inserted into the hole, forming a tight seal. A low-amplitude, swept sine wave from a lock-in amplifier was transmitted by the source transducer into the mouthpiece. The pressure at each mouthpiece position was measured one at a time by an Endevco transducer inserted into the bore and flush with the inner wall. The output signal was sent through a signal conditioner and then back to the lock-in amplifier. The sine wave was swept from 50 to 6000 Hz with a sweep rate of 64 samples/second over a duration of 40 seconds, for a frequency resolution of 2.3 Hz/sample. The linear transfer function was measured in this way for the fingerings for $C4$ and $G4$.

The pressure response at the two positions was measured while the performer played the tones $C4$ and $G4$ using the set-up in Figure 2.1-b. The performer held each tone as steady as possible for 6–8 seconds at a mezzo forte dynamic level. The pressures were sampled at a rate of 44.1 kHz and stored as NeXT sound files.

4.1.3 *Results*

The transfer function T was calculated from Eqns. 4.4 and 4.5, where the sensitivities S_1 and S_2 include the gain of the signal conditioner and the sensitivity of the transducer. The magnitude and phase of T are shown in Figure 4.3 for the fingering $C4$ up to 2000 Hz. Only the results for $C4$ will be presented here, but the results for $G4$ were similar. The solid line is the measured linear transfer function. Below 200 Hz, the transfer function is noisy in both cases, and those data are not shown.

The pressure spectrum was calculated at each mouthpiece position for 32768-sample sections of the pressure time series, overlapped by 16384-samples. A fundamental frequency was also calculated for each 32768-sample section. For each section the magnitude and phase of the transfer function T and the pressure spectra at both positions were interpolated at multiples of the fundamental frequency using a four-point interpolation. The interpolated points of the transfer function magnitude and phase are shown as the dots connected by dashed lines in Figure 4.3. The dot at the lowest frequency is at the fundamental frequency of the tone, which was 234 Hz for $C4$. At this frequency $|T| \approx 1$ and $\Phi(T) \approx 0$ for both tones. For the first few lowest modes, $|T| \approx 1$ for odd harmonics and differs from 1 at even harmonics. This is because even harmonics have a node at the reed tip (Figure 4.1-b), and the pressure at nearby points is changing faster than if there were an antinode at the tip. Therefore there is a greater difference between the two positions for even harmonics and the transfer function is larger. This holds true only for wavelengths λ such that $\lambda/8 <$ 5 cm, the distance from the reed tip to the farthest mouthpiece position, or for $f <$ 860 Hz.

For both tones, the linear transfer function magnitude $|T|$ had a dip and then a large peak just above the second harmonic frequency, which can be explained as follows. At the second harmonic frequency, there was a node at the reed tip. The dip just above the second harmonic happened as this node that was at the reed tip passed through position 2. At this frequency, p_2 was near zero and p_1 was larger than zero, so $T = p_2/p_1$ was small and therefore had a dip. The peak just above that dip happened as the node was passing through position 1. At this frequency, p_1 was near zero and p_2 was larger than zero, so $T = p_2/p_1$ was larger and therefore had a peak. The node moved down the air column as the frequency increased until there was an antinode at the reed tip again, which happened at the third harmonic frequency. This situation occurs whenever there is a node at the reed tip, and therefore after every even harmonic, and this is evident in the graph of $|T|$, although it was less prominent at higher frequencies. The wavelengths corresponding to the frequencies of the dip and peak differed by 4 cm at 500 Hz and 2 cm at 1000 Hz for $C4$. This is approximately the distance between the two mouthpiece positions. The difference between the wavelengths is larger at lower frequencies. The difference between this and the true distance (about 2 cm) is probably not due to nonlinear effects since the excitation level was low, but might be due to the fact that the mouthpiece is not exactly a cylinder. Since this is a function of a node passing through the two mouthpiece positions, it is dependent on the air column. For the tone $G4$, which used a different fingering, the peak/dip pairs occurred at 800 Hz and 1500 Hz.

A large peak in the phase of T occurred between each dip and peak in $|T|$. The full-width at half-maximum points of the phase peak coincided with the frequencies of the dip and the peak in $|T|$, and the phase peak itself was between the dip and the peak in $|T|$, so that the largest phase difference between the two mouthpiece positions occurred when the node was halfway between them. At this point, the pressures at the two positions were equal in amplitude, but had opposite phases, so that the phase of T went through a 180 degree change at this frequency.

The pressure standing wave effects were removed from position 1 using Eqn. 4.6 and Eqn. 4.7 in order to obtain the adjusted pressure p_1'. Figure 4.4 shows the magnitude and phase of the difference $p_2 - p_1'$ for one 32768-sample section of the $C4$ pressure time series. This difference should be zero (in both magnitude and phase) if only linear standing waves were present. However, there was a difference of about 45–55 Pa in magnitude at the first harmonic for both tones. All other harmonics had much smaller differences (~10 Pa). The largest differences in phase occurred at the even harmonics for both tones. These differences tended to remain steady in both magnitude and phase for the entire duration of both tone.

Figure 4.5 represents the magnitude of the difference $p_2 - p_1'$ as a percentage of the magnitude of p_1'. This ratio is plotted as a function of frequency for the same 32768-sample section shown in Figure 4.4. For both tones, the largest percent differences occurred at the even harmonics because the mouthpiece pressure is low for the lowest even harmonics in clarinet tones. The difference for $C4$ was approximately 110%, 20%, and 30% at the 2nd, 4th, and 6th harmonics, respectively. For $G4$, the difference was approximately 35% and 65% at the 2nd and 4th harmonics. This percent difference tended to remain steady, except for the fourth harmonic of $G4$, which increased to 140–160% during the tone. The percent difference at the odd harmonics was about

4% for $C4$ and was 4%, 7%, and 10% at the 1st, 3rd, and 5th harmonics of $G4$.

4.1.4 Discussion

The mouthpiece pressure within a few centimeters of the reed tip had contributions that were not explained by linear acoustics. There were differences in the mouthpiece pressure spectra between two positions along a clarinet mouthpiece, after standing wave effects had been removed. There was a difference of 45–55 Pa at the first harmonic of both tones that were measured, and the difference was less than or equal to 10 Pa at the other harmonics. The largest percent differences were at the even harmonics and ranged from 20% to 160%, while the percent differences at the odd harmonics ranged from 4% to 10%. This contradicts Van Zon et al. [77] who said that the pressure variations along the mouthpiece bore were less than 3% of the total variation.

The pressure in the mouthpiece is not due to the standing wave alone, although the magnitude pressure differences are small. These small pressure differences may indicate that the instrument impedance Z_d has a small nonlinear component, which may produce errors when a linear measurement of Z_d is used to find the upstream impedance Z_u from the indirect measurement using the continuity of flow equation under playing conditions. The pressure at either mouthpiece position would be suitable to use in the indirect measurement of Z_u, and nonlinearities in Z_d are a possible source of error at both positions. Errors are likely to be greater at the even harmonics, where nonlinear flow effects are relatively larger.

4.2 Pressure Spectra Noise Floor

The pressure time series were measured with the Digital Ears 16-bit analog-to-digital converter, which has a signal-to-noise ratio of approximately 85 dB. This is sufficient to detect the noise floor of the measured pressure spectra. This noise floor is not the level of the electrical and computational noise, but actually the flow noise associated with the sound generation process.

Figure 4.6 shows the mouthpiece pressure spectrum measured at position 1 (far from the reed tip) for the chalumeau tone $A3$, calculated from a 262144-(2^{18}-) sample

FFT. The odd harmonic peaks are the largest, which is expected since the clarinet can be considered a cylinder closed at one end, and the first few strongest odd harmonics correspond to the lowest-frequency instrument impedance peaks, shown as the dashed line above the spectrum. The largest peak is about 160 dB, and the peaks above 3000 Hz are between 80 and 100 dB. The level of the noise floor was 60–90 dB, higher than the noise level during a measurement of silence, which was 45–55 dB. The noise floor had a negative slope for frequencies less than about 2–3 kHz. Above this frequency range, the noise floor was approximately flat.

Figure 4.7 shows the mouthpiece pressure spectrum measured at position 2 (close to the reed tip) for the tone $A3$, calculated from a 262144-sample FFT. This measurement was simultaneous with the measurement in Figure 4.6. The peak magnitudes are similar for both mouthpiece positions, and the small differences that do exist have been examined in Section 4.1. The noise floor was similar to that for position 1, with a negative slope up to about 2–3 kHz and then a flat noise level, but the overall level was 5–10 dB greater at position 2, indicating stronger flow noise at the position closer to the reed tip.

Figure 4.8 shows the mouth pressure spectrum for $A3$, calculated from a 262144-sample FFT. This measurement was not simultaneous with the two mouthpiece measurements. The first few odd harmonics are about 20 dB lower than in the mouthpiece. The largest peak is about 140 dB. The noise floor in the mouth tended to be flat and at about the same level as in the mouthpiece above 2–3 kHz.

The hydrodynamic processes that are present affect the mouthpiece pressure closest to the reed the most strongly and also affect the pressure 5 cm downstream, although the effect has diminished. They affect the mouth pressure the least, although they are still present since the noise floor is higher during performance than during silence.

The dashed curve in Figure 4.6 shows the instrument impedance for the fingering $A3$ on the same frequency scale as the pressure spectrum below. In the mouthpiece, the noise floor rose on either side of pressure peaks that aligned with instrument impedance peaks, for frequencies less than the cut-off frequency of the instrument, which is about 1500 Hz for the $B\flat$ clarinet. Sound was generated not just at harmonic frequencies, but also at nearby frequencies where the instrument impedance was relatively large. This information can be used to deduce the existence of upstream resonances, assuming that upstream impedance peaks also cause the noise floor to rise in the mouth. For example, in the mouth pressure (Figure 4.8), the noise floor rose around the third pressure peak near 600 Hz, which indicates that there is an upstream impedance peak at this frequency.

Instrument impedance peaks also appeared to cause the noise floor to rise even when there was no harmonic frequency nearby. Figure 4.9 shows the mouthpiece pressure at position 1 for the tone $E5$. There were peaks in the noise floor at 250, 1000, and 1330 Hz that were about 15 dB above the overall noise level. All three of these peaks correspond to nonharmonic peaks in the instrument impedance, which is plotted above the pressure spectrum. The pressure spectrum was enhanced at these peak frequencies even though they were not aligned with harmonic frequencies of the tone. Evidence for these pressure peaks at nonharmonic frequencies has been found by other researchers from the analyses of pressure waveforms. Using the norm difference method, Schumacher [64] observed fluctuations at the frequency of the lowest impedance peak of the French horn, and Schumacher and Chafe [63] found a strong third subharmonic for the tone $F5$ on the clarinet, also corresponding to the lowest instrument impedance peak. Keefe [50] proposed that the low frequency structure of these norm difference results was due to these Z_d resonances that were not involved in the regime of oscillation. The data presented here provide evidence for this assertion.

The alignment of low-amplitude peaks in the mouthpiece pressure noise floor with instrument impedance peaks implies that peaks in the mouth pressure noise floor could correspond to peaks in the upstream impedance. This can be used as another way to study the influence of the airways on sound production.

4.3 DC Pressures

The piezoresistive pressure transducers permitted the measurement of DC as well as AC pressures in the mouth and mouthpiece. The DC pressures are of interest because their difference will set the operating point of the reed, which will determine whether or not the reed closes against the lay of the mouthpiece. The linear framework of the indirect measurement of Z_u assumes that the reed does not close. The DC pressures are thus related to the degree of nonlinearity present in the oscillation.

4.3.1 Results

The DC pressure was calculated for single, normal tones played at a mezzo forte dynamic level across the frequency range of the clarinet at both mouthpiece positions and in the mouth. The DC pressure for each tone was obtained from a 262144-(2^{18}-) sample FFT on the corresponding pressure time series. The zero point of the DC pressure was calculated using an 8192-sample FFT on a section of silence at the beginning of the time series. This zero point was subtracted from the DC pressure of the tone spectrum to obtain the values shown in the following graphs. A different zero point was calculated for each tone because it tended to drift slowly with time for all three transducers.

Figures 4.10–4.12 show the DC pressure in cm H_2O vs pitch frequency, where 1 cm H_2O = 98.07 Pa, for mouthpiece position 1 (far from the tip), mouthpiece position 2 (nearer to the tip), and the mouth, respectively. The DC pressure is expressed in cm H_2O because physiological measurements of DC pressure are often expressed in cm H_2O. Note that the vertical axes in the three plots differ because the DC mouth pressure was much larger than the DC pressure at position 1, which was much larger than the DC pressure at position 2. At the mouthpiece position farthest from the reed tip (Figure 4.10), the DC pressure ranged from 0.05 to 1.2 cm H_2O and decreased with frequency. This was most apparent for the three measurements done with subject B, who played much louder than the other subjects.

At the mouthpiece position nearest to the mouth (about 2 cm closer than mouthpiece position 2), the DC pressure varied randomly between -0.2 cm H_2O and +0.2 cm H_2O (Figure 4.11). The standard deviation of the DC zero point variation with time was 0.007–0.042 cm H_2O for all three transducers, and so the pressures measured at this position were the actual DC pressures and were not due to the variation of the zero point.

The pressure at mouthpiece position 2 was much smaller than at mouthpiece position 1 because position 2 was near the reed tip, which is a region of high velocity, and the distance between 1 and 2 was less than the acoustic wavelengths of the pitch frequency range shown. The expected decrease in DC pressure between these two positions can be estimated from Bernoulli's law (assuming a laminar, inviscid flow model), which says that $p + \rho v^2$ should remain constant as the cross-sectional area of the bore changes. ρ is the density of air (0.00117 g/cm^3), and v is the air velocity, which at low frequencies (or zero frequency, for the DC pressures here) can be approximated as the constant volume flow u_0 divided by the area at the mouthpiece position. The constant volume flow u_0 was estimated from the data of Backus [3] for a reed opening of 0.04 cm, as $u_0 = 300$ cm^3/sec. The cross-section of the mouthpiece at position 1 was a circle of diameter 1.5 cm, and the cross-section at position 2 was approximately a rectangle of dimensions 1.4 cm by 0.8 cm. The values for $p + \rho v^2$ ranged from 0.08 to 1.23 cm H_2O at position 1 and from -0.11 to 0.29 cm H_2O at position 2. According to Bernoulli's law, the values of these ranges should be equal. While they do overlap, there is some disagreement at the extremes. The large variation could be due to uncertainties in the flow estimate and the area of the bore.

In the mouth (Figure 4.12), the DC pressure ranged from 30 to 65 cm H_2O and decreased with frequency. These pressures are much larger than the DC pressures in the mouthpiece, which were about 1 cm H_2O at the most. Again, the decrease with frequency was most apparent with the measurements of performer B and not so apparent with the other two performers, who were playing more softly.

Performer B played two tones (*C4* and *G5*) at piano and forte dynamic levels. The DC pressures for these tones will give an estimate of the range of pressures possible. Figures 4.13–4.15 show the DC pressures for tones played at mezzo forte across the range of the clarinet and for the two tones played at piano and forte. Figure 4.13 shows two measurements of the DC pressure at mouthpiece position 1, Figure 4.14 shows one measurement at mouthpiece position 2, and Figure 4.15 shows one measurement of the mouth pressure. Except for mouthpiece position 2, where the DC pressure again showed no clear trend with respect to frequency, the DC pressure increased with increasing dynamic level, and the variation was larger for the lower tone.

4.3.2 Discussion

The only researchers who reported DC mouthpiece pressures were Kobata and Idogawa [54], who measured the mouthpiece pressure at the wall by inserting a transducer through a hole in the mouthpiece wall at a distance of 34 mm from the mouthpiece tip along a line parallel to the air column, approximately at mouthpiece position 1 here but slightly closer to the tip. They measured mouthpiece pressures of 300–350 Pa (3.1–3.6 cm H_2O), much larger than the pressures shown in Figure 4.10.

The DC pressure in the mouth has been more commonly measured. Stone [69] measured DC mouth pressures ranging from 38 cm H_2O for lower tones to 20 cm H_2O for higher tones, values that are a little lower than those reported here. Bouhuys [17] measured 60 cm H_2O for a fortissimo low tone and 48 cm H_2O for a fortissimo high tone, which agree with the data of performer B quite well. Kobata and Idogawa [54] reported the blowing pressures used for their artificially-blown clarinet, which would correspond to the mouth pressure. They used a blowing pressure of 7.1 kPa (72 cm H_2O) to produce an $E3$ and pressures ranging from 3.7 to 11.2 kPa (38–114 cm H_2O) to produce various other tones using an $E3$ fingering. This range of blowing pressures is much larger than that in Figure 4.12, but the blowing pressure for $E3$ is only a little larger. This is consistent with the mouthpiece pressures measured by Kobata and Idogawa, which were also larger than the ones measured here.

The minimum mouth pressure for performer B for the piano tones was about 40 cm H_2O and was 30–40 cm H_2O for all performers. This minimum blowing pressure is limited by the threshold blowing pressure necessary to produce a tone. Backus [2] measured threshold blowing pressures ranging from 15 to 28 cm H2O for reed openings of 0.010–0.035 cm. These threshold values are slightly less than the minimum blowing pressures measured here.

4.4 Flow into the Mouth

The expected direction of the flow is from the mouth into the mouthpiece due to the large DC pressure in the mouth. However, if the pressure difference across the reed $p_u(t) - p_d(t)$ is less than zero for any part of the cycle, then there will be flow from the mouthpiece into the mouth. The data of Kobata and Idogawa [54] showed no evidence of flow into the mouth, but they did not have simultaneous measurements of the mouthpiece AC and DC pressures. Since the measurements reported here were simultaneous, the actual pressure difference across the reed $p_u(t) - p_d(t)$ could be calculated. The mouthpiece pressure used in the calculation was that at position 1, farthest from the reed tip, so that the nonacoustic contribution to the pressure can be neglected. The DC zero point of each transducer, calculated from the silence at the beginning of the sound file, was subtracted from the pressure waveform, and the pressure difference was calculated for 11 normal tones, played by two different performers. Figure 4.16 shows $p_u(t) - p_d(t)$ for a mezzo forte $E5$ played by performer

B, and it shows the typical variation range of this difference. For all the tones tested, the pressure difference was positive, and therefore there was no evidence of flow from the mouthpiece into the mouth.

4.5 *Conclusions*

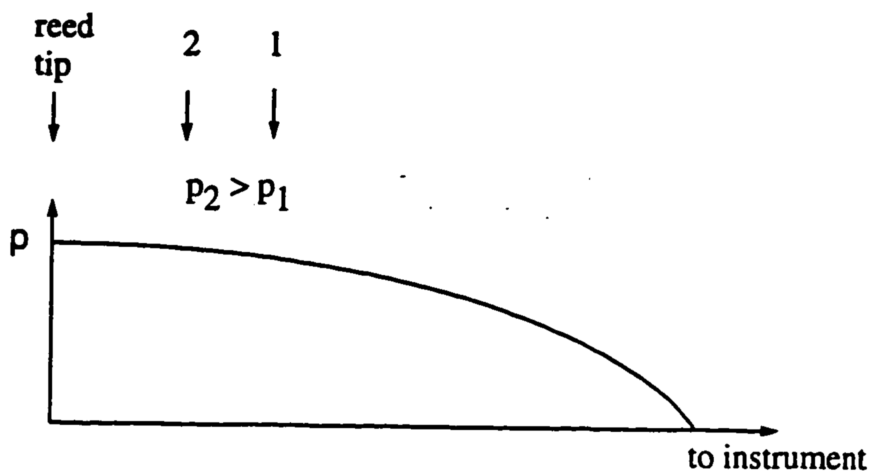
The pressure spectra noise floor is higher at the mouthpiece position closer to the tip, indicating stronger flow noise at this position. The noise floor tends to rise near instrument impedance peaks, even at nonharmonic frequencies. Similar rises in the mouth pressure noise floor appear to indicate the presence of upstream impedance peaks.

From the comparison of the pressure standing wave at the two mouthpiece positions, it was found that the magnitude of the pressure differences at the two positions is quite small, but the percentage difference can be large at the even harmonics. This implies that nonlinear flow processes have a larger effect at the even harmonics.

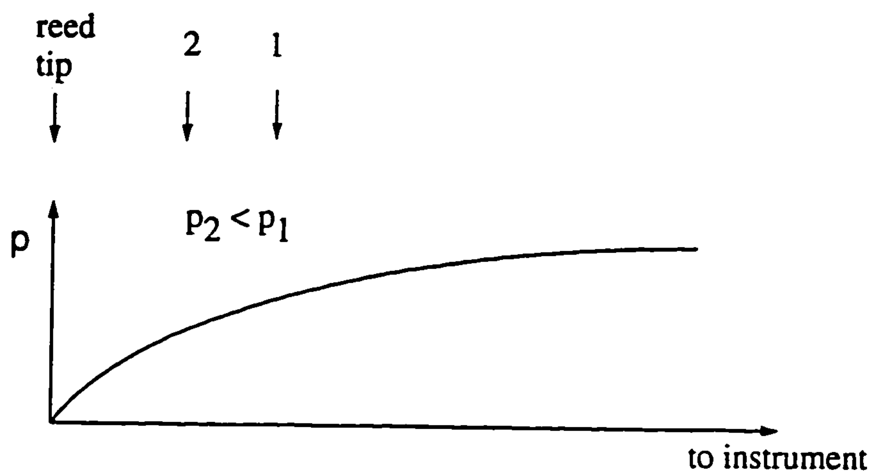
The DC pressures measured here agree with previous measurements. The mouthpiece pressure at the position closest to the reed tip was smaller than at the position farther from the reed tip and showed no trend with frequency.

The difference between the mouth and mouthpiece pressure waveforms showed no evidence of flow into the mouth.

The actual differences between the pressures at the two mouthpiece positions are small. Although the percentage differences at even harmonics can be large, the magnitude differences are small. In view of this result and the fact that the noise floor is lower at position 1, the pressure at position 1, farthest from the mouthpiece tip, was chosen to be used for the indirect measurement of Z_u. This indirect measurement is from a model based on acoustics rather than hydrodynamics, and it is preferable to use a mouthpiece position where the hydrodynamic effects are minimized. Possible problems due to flow effects might still be evident at even harmonics, where positions 1 and 2 showed the largest differences, but these flow effects will be minimized by using position 1 farthest from the tip.



(a) Odd harmonics.



(b) Even harmonics.

Figure 4.1: Pressure standing waves along the clarinet mouthpiece.

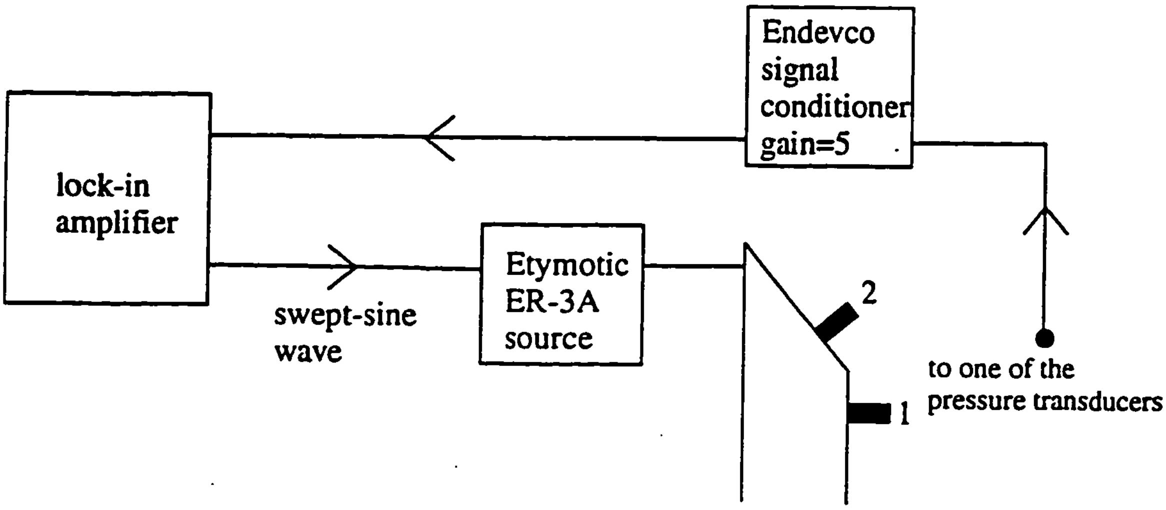
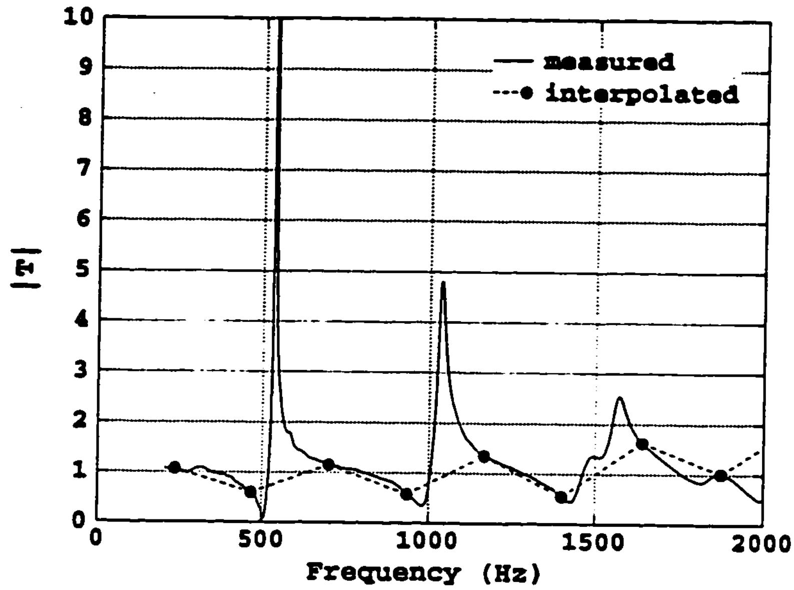
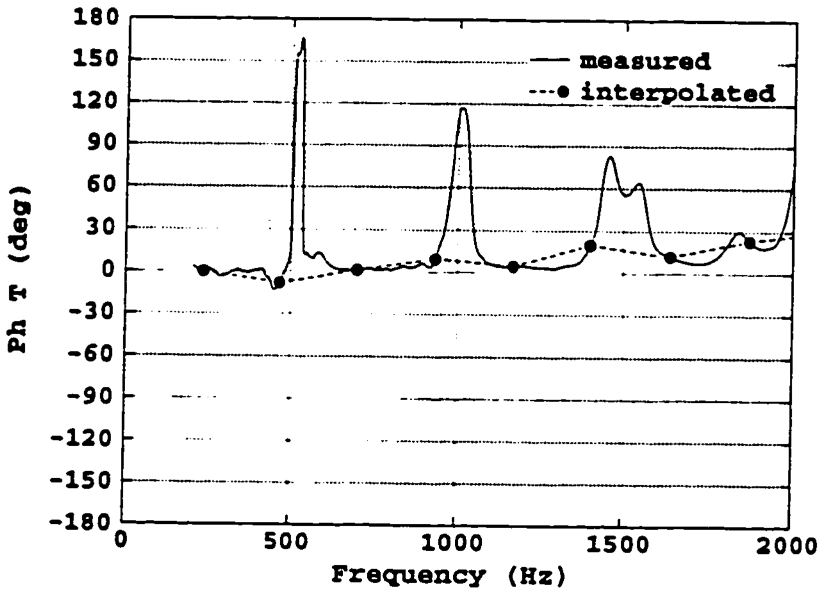


Figure 4.2: Experimental set-up for measuring the transfer function.

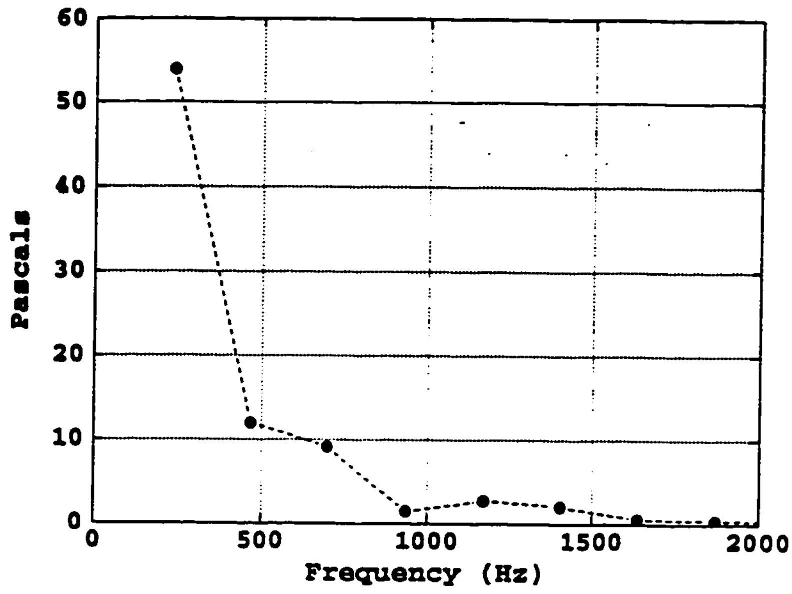


(a) Magnitude.

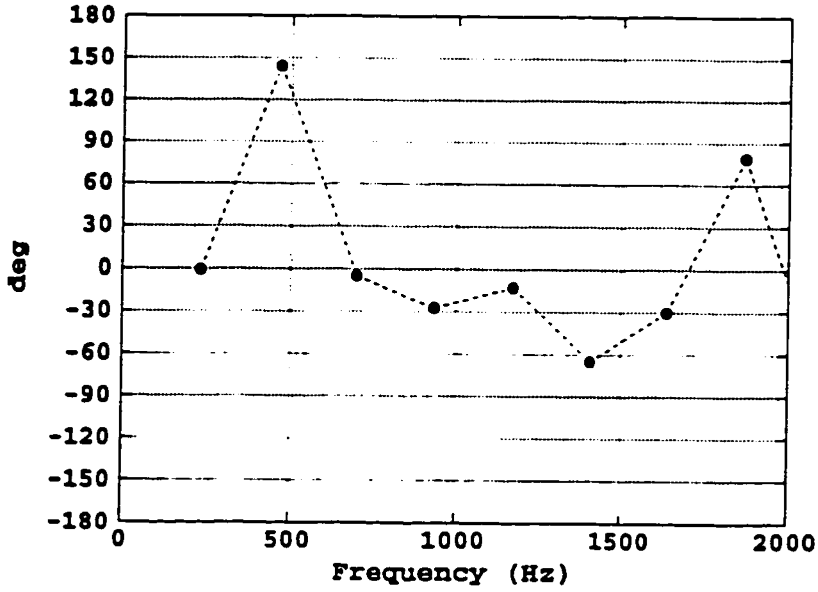


(b) Phase.

Figure 4.3: Transfer function T for $C4$.



(a) Magnitude.



(b) Phase.

Figure 4.4: Pressure difference $p_2 - p_1'$ between the two mouthpiece positions, without standing wave effects, for $C4$.

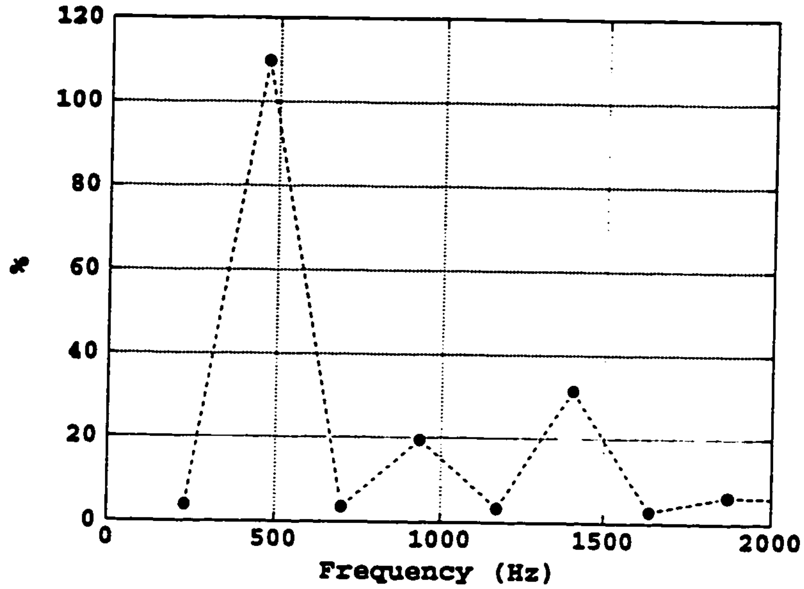


Figure 4.5: Pressure difference $|p_2 - p'_1|$ between the two mouthpiece positions as a function of frequency for $C4$, expressed as a percentage of the adjusted pressure $|p'_1|$, for the harmonics below 2000 Hz.

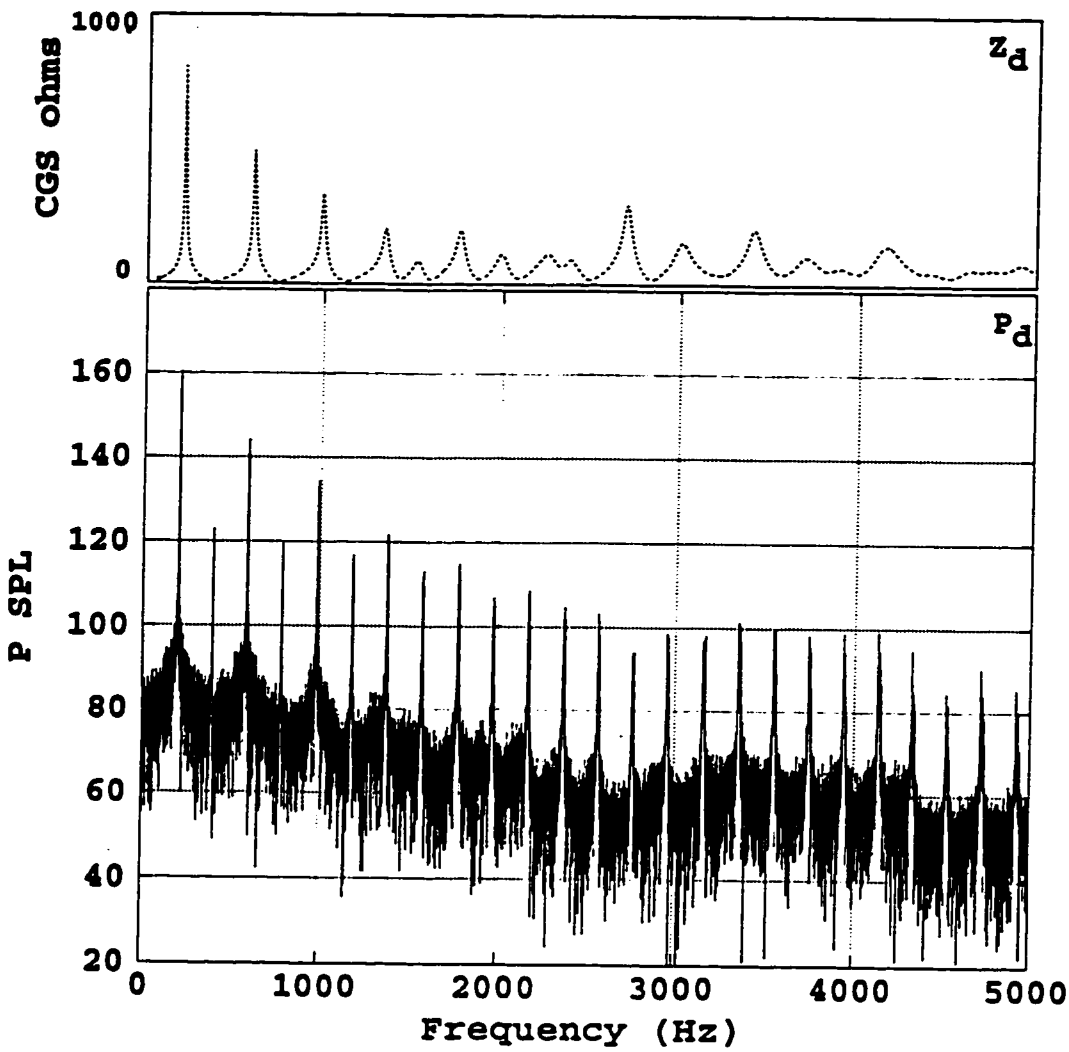


Figure 4.6: Mouthpiece pressure at position 1 (far from the tip) for A3. The dashed line plotted above is the instrument impedance for A3.

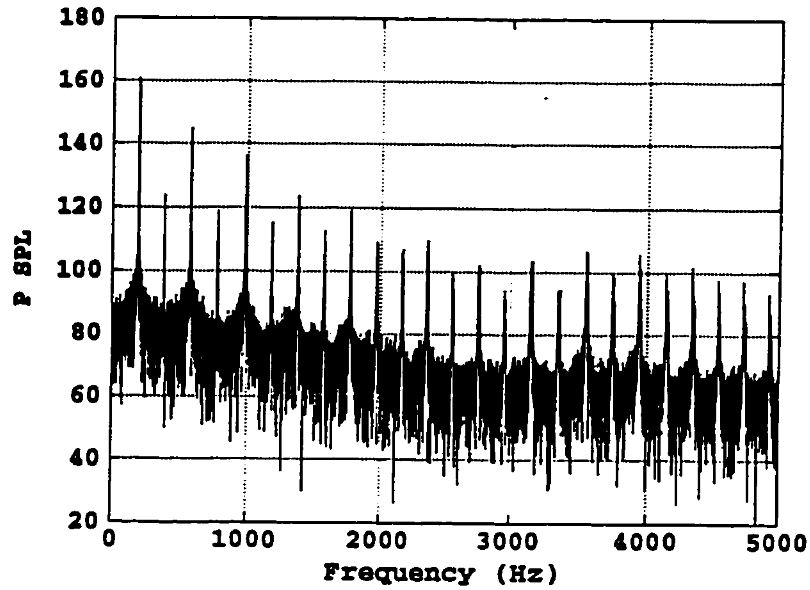


Figure 4.7: Mouthpiece pressure at position 2 (near the tip) for A3.

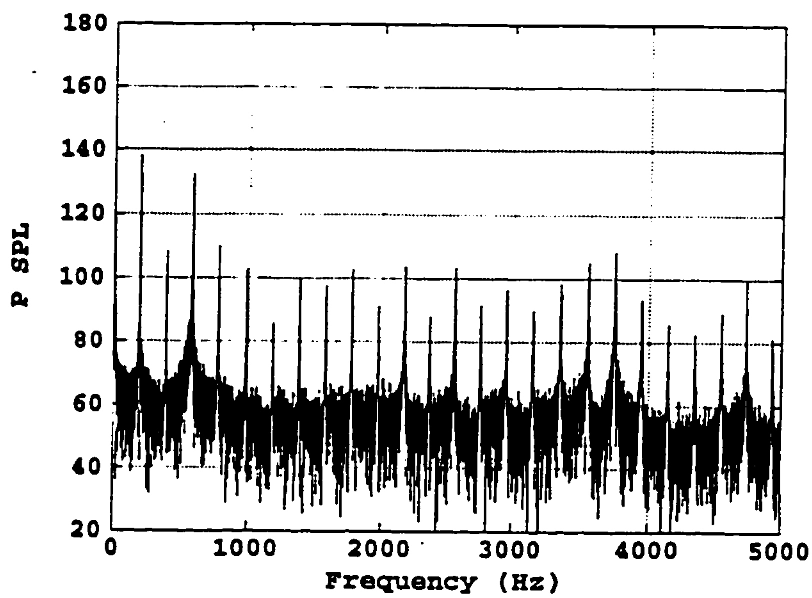


Figure 4.8: Mouth pressure for A3.

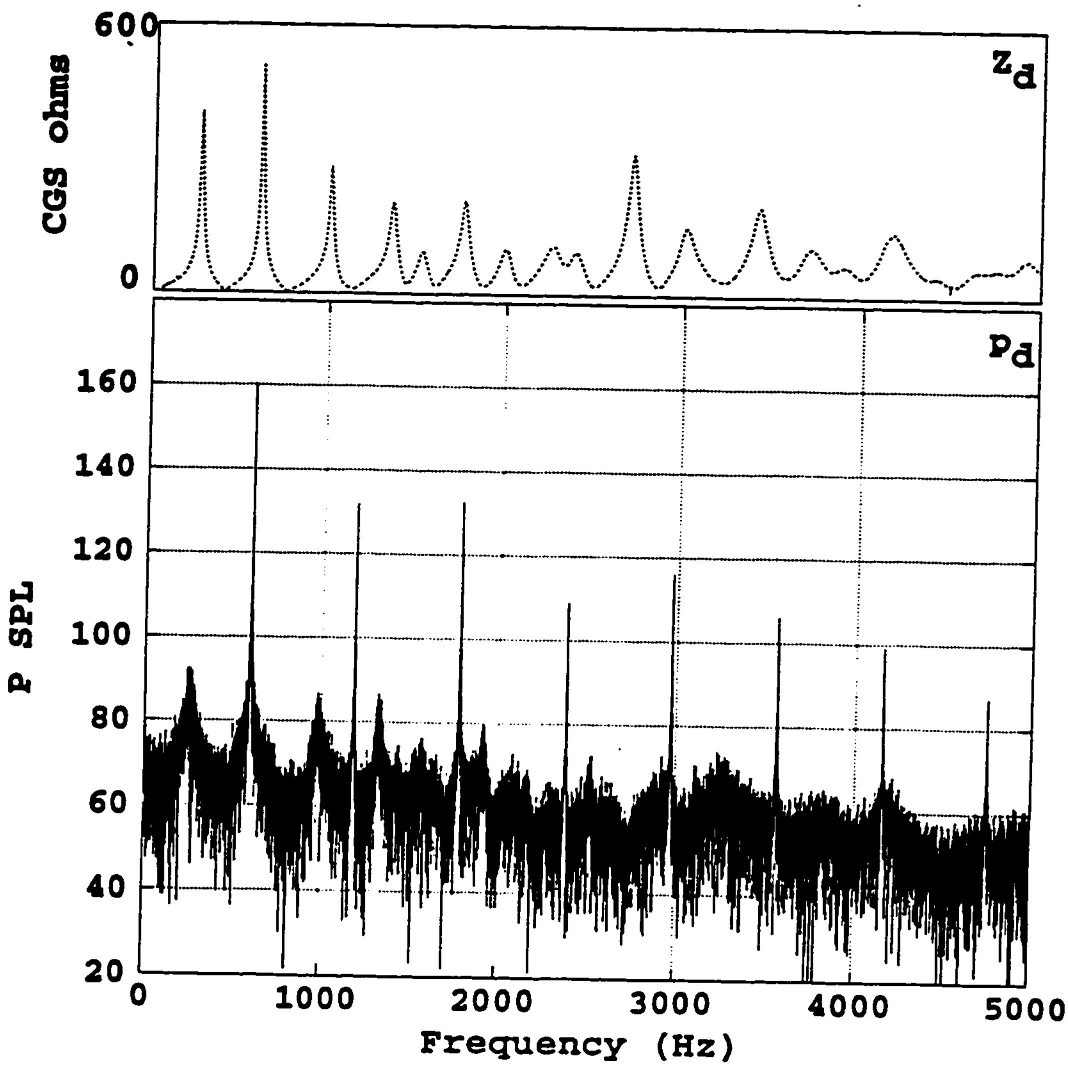


Figure 4.9: Mouthpiece pressure at position 1 (far from the tip) for $E5$. The dashed line plotted above is the instrument impedance for $E5$.

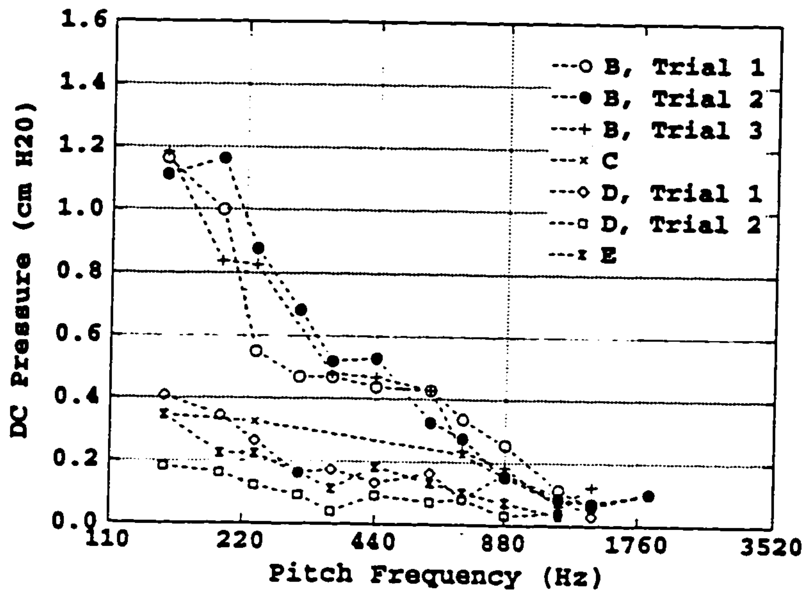


Figure 4.10: DC pressure at mouthpiece position 1 (far from the tip) for various performers.

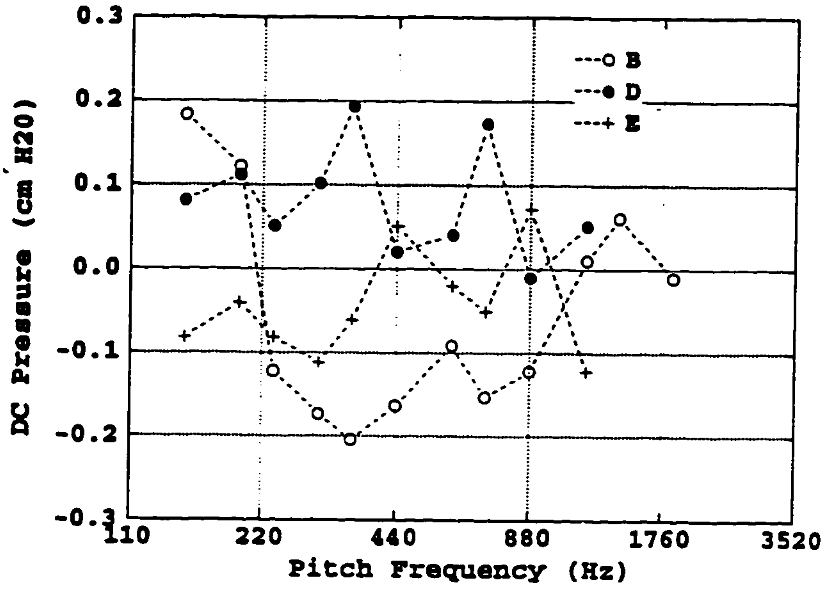


Figure 4.11: DC pressure at mouthpiece position 2 (near the tip) for various performers.

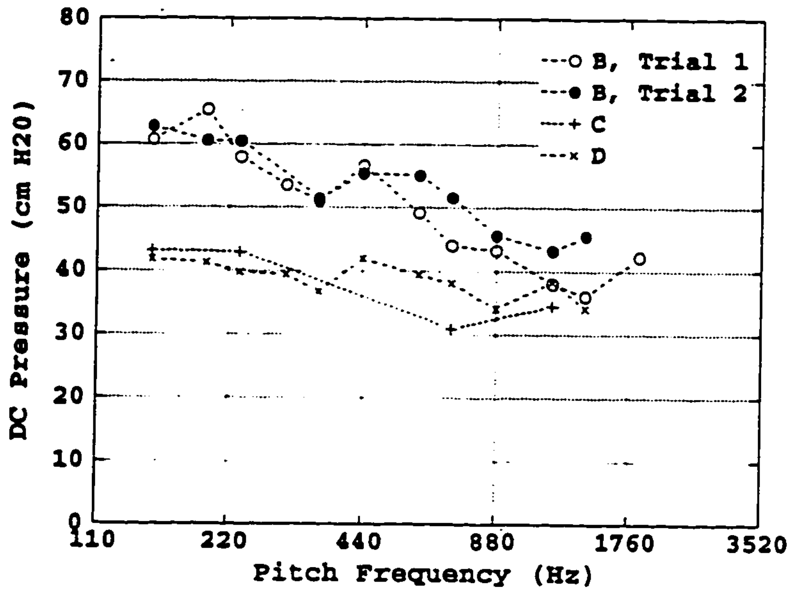


Figure 4.12: DC pressure in the mouth for various performers.

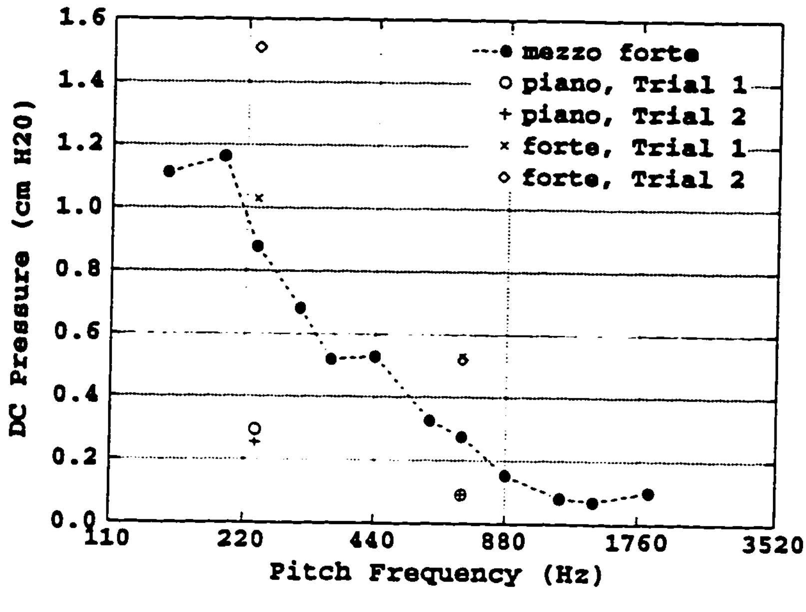


Figure 4.13: DC pressure measured at mouthpiece position 1 (far from the tip) for different dynamic levels.

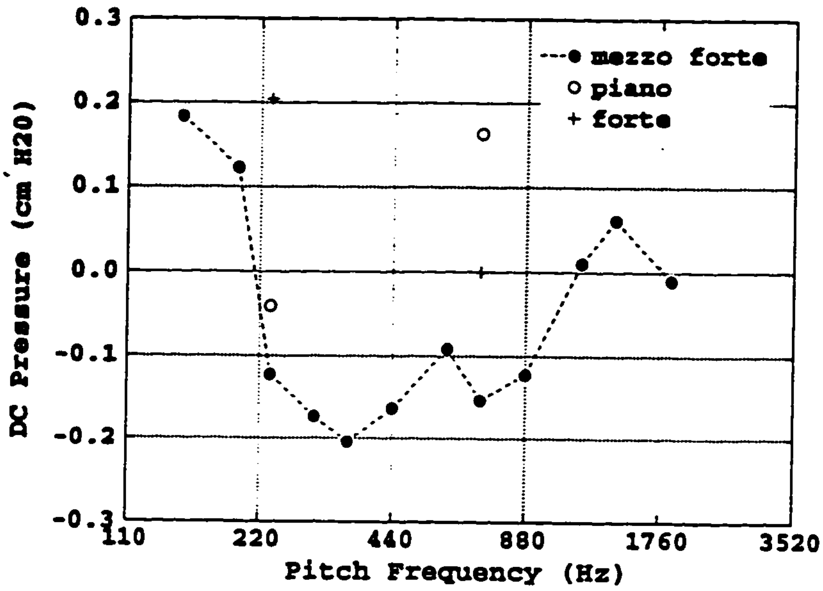


Figure 4.14: DC pressure measured at mouthpiece position 2 (near the tip) for different dynamic levels.

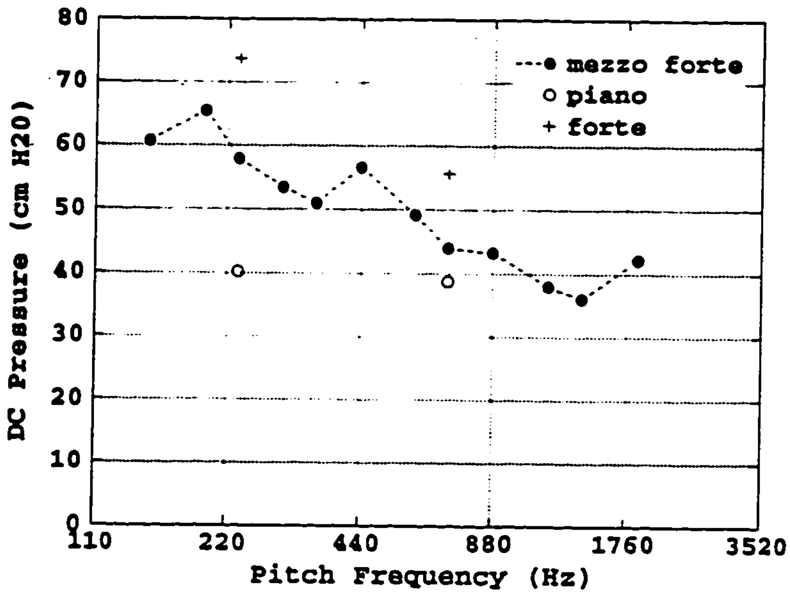


Figure 4.15: DC pressure measured in the mouth for different dynamic levels.

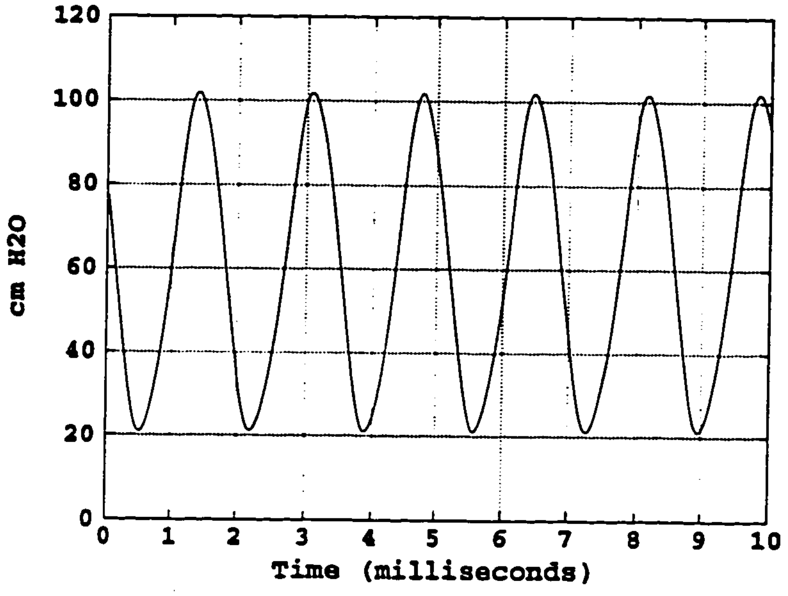


Figure 4.16: $p_u(t) - p_d(t)$ for the tone $E5$.

Chapter 5

RESULTS: UPSTREAM IMPEDANCE FOR SINGLE TONES

This chapter compares the direct and indirect measurement of the upstream impedance for normal tones in order to verify the indirect method. Then, the upstream impedance obtained by the indirect measurement is used to examine the role of the performer's airways for the following single tones: tones played at various dynamic levels, tones played with an open and a closed throat, clarion tones played without the register key, and clarion tones played with pitchbend.

5.1 *Comparison of the Direct and Indirect Measurements of the Upstream Impedance*

The indirect method of measuring Z_u was verified by comparing Z_u calculated from the continuity of flow equation (Eqn. 1.31) with Z_u^o measured directly with the one-microphone technique. Since the continuity of flow equation assumes a linear model of impedance, it applies only to linear oscillations. However, the pressure oscillation of a clarinet is never strictly linear due to the nonlinear flow-control properties of the reed, which come from the restriction of the reed motion by the lay of the mouthpiece in one direction and by the performer's lip in the other direction. This nonlinear reed motion produces pressure oscillations at harmonic frequencies of an initial pressure component through harmonic generation. As the reed amplitude increases at higher dynamic levels, the reed eventually closes completely against the lay of the mouthpiece, and the sound generation process is then highly nonlinear due to this discontinuity in the reed displacement. When the reed closes, the assumption of linearity is no longer valid, and therefore the indirect measurement of Z_u should only be used for tones for which the reed does not close completely.

A measurement of the reed tip displacement would show if the reed is closing completely against the lay. However, since pressure variations were measured in this study but not reed displacement, a criterion must be defined for reed tip closure that can be determined from pressure measurements alone. Two papers report simultaneous measurements of reed displacement and pressure: Backus [2] and Kobata and Idogawa [54]. Backus measured mouthpiece pressure, and Kobata and Idogawa measured mouth and mouthpiece pressures. Neither paper gave a criterion for reed tip closure from the pressure alone. At low reed amplitudes the reed motion will not be significantly restricted by the lay, but at higher amplitudes when a greater length of the reed contacts the lay, one might expect an asymmetry in the mouth or mouthpiece pressures to appear. The data presented in these two papers showed that the mouthpiece pressure waveform was usually symmetric about its average value, regardless of the reed displacement amplitude. The mouth pressure waveforms measured by Kobata and Idogawa were asymmetric for all cases that they showed. Thus the asymmetry in the reed displacement for large-amplitude reed motion does not appear as a corresponding asymmetry in the mouthpiece pressure waveform, and the mouth pressure waveform can be asymmetric even for low-amplitude reed displacement. Low-amplitude mouthpiece pressures usually corresponded to low-amplitude reed motion, although this was not the case for one of the more complex oscillation states studied by Kobata and Idogawa.

From the available data, there is no clear criterion for determining reed tip closure from pressure measurements alone. The tones most likely not to have reed displacement so large that the reed tip closes against the lay are normal tones with lower-amplitude mouthpiece pressure waveforms, and therefore the indirect measurement method for Z_u will be tested using such tones.

5.1.1 Data

Figures 5.1, 5.2, and 5.3 show mouthpiece pressure waveforms for tones in the chalumeau, clarion, and altissimo registers, respectively, that had low-amplitude mouthpiece pressure waveforms. The DC component of the mouthpiece pressure has not been subtracted from these waveforms. Each Figure shows waveforms from two tones, one played by performer B and one played by performer D. Figure 5.1 shows waveforms for the chalumeau tone $G4$, Figure 5.2 shows the clarion tone $G5$, and Figure 5.3 shows the altissimo tone $E6$. The peak-to-peak amplitudes of these waveforms ranged from just under 4000 Pa to just over 8000 Pa. The amplitudes of all mezzo forte tones played by the performers ranged from 1800 Pa to 16000 Pa, so the six tones analyzed here represent the low-amplitude range. For both performers, the amplitudes were largest in the chalumeau register (Figure 5.1) and smallest in the altissimo register (Figure 5.3). Although all the waveforms are relatively low-amplitude, none are clearly sinusoidal. They all have upper harmonics strong enough to be visible in the pressure waveforms and therefore are not strictly linear.

The upstream impedance measured directly and indirectly will be presented for each of these six tones. A comparison of these two measurements of the upstream impedance will test the validity of the indirect measurement, which uses the continuity of flow equation and a linear systems impedance model. These tones were chosen because they are most likely to have reed motion that does not close against the reed and therefore approximate the assumption of linearity.

5.1.2 Results

Figure 5.4 shows the magnitude and phase of the upstream impedance vs. frequency, up to 1500 Hz, for the chalumeau tone *G4* played by performer B. The dashed curve is the instrument impedance, Z_d. The solid, noisy curve is the direct measurement of the upstream impedance, Z_u^o. The open circles are the values of the indirectly measured Z_u at harmonics of the fundamental frequency. For the indirect measurement, Z_u was calculated at harmonic frequencies for 32768-sample sections of the pressure time series, overlapped by half that size. The plotted points of Z_u are the values of the indirectly measured Z_u averaged over all the 32768-sample sections of the pressure time series. The error bars shown in the graph represent the standard deviation about the average value of Z_u at each harmonic frequency. The vertical dashed lines mark the harmonic frequencies.

The magnitude of the upstream impedance (Figure 5.4-a), which is plotted on a logarithmic scale, showed good agreement between the two methods at the first and fourth harmonics (350 Hz and 1400 Hz), where the impedance was very low. At the second and third harmonics (700 Hz and 1050 Hz) the magnitude from the indirect measurement was 10-20 CGS ohms larger than the direct measurement. The values at these frequencies might be brought into agreement if the peak in Z_u^o at 600 Hz were moved up in frequency slightly. The phases of the impedances are shown in Figure 5.4-b. The direct measurement was noisy and so it is difficult to make an accurate comparison. At the first, second, and fourth harmonics, the phase from the indirect measurement was at +90 degrees, which agreed with the direct measurement at the first and fourth harmonics but not at the second harmonic, although at the second harmonic, the phase of Z_u was equal to the phase of Z_d. Again, the phases at the second harmonic could be brought into agreement if the peak in Z_u^o is moved up in frequency. At the third harmonic, the phase of Z_u was nearly -180 degrees (or +180 degrees, if the phase is wrapped around). Since the airways are a dissipative system, the phase should be between -90 degrees and +90 degrees.

The same chalumeau tone played by performer D showed similar disagreement (Figure 5.5). For this tone, the magnitudes (5.5-a) agreed at the first and third harmonics, but not at the second and fourth harmonics, where the indirect measurement gave larger values by about 20 CGS ohms. The phases (5.5-b) from the indirect measurement were larger than +90 degrees at three harmonics. At the second harmonic, the phase differed by about 60 degrees.

Clarion tones showed better agreement between the two upstream impedance measurements. Figure 5.6 shows the results for the clarion tone $G5$ played by performer B. The magnitudes (5.6-a) had excellent agreement at both the first and second harmonics (700 Hz and 1400 Hz). The phase (5.6-b) agreed at the second harmonic, with a value of about +90 degrees. There was disagreement in the phase at the first harmonic, but this could possibly be corrected if the peak in Z_u^o at 600 Hz were moved up in frequency slightly. The indirect phase value was nearly equal to the phase of Z_d at that frequency.

Figure 5.7 shows the same clarion tone played by performer D. The magnitude (5.7-a) differed by only a few CGS ohms at the first two harmonics. The phase at both harmonics (5.7-b) was about +90 degrees for the indirect measurement, but the direct measurement was noisy and a comparison is difficult to make. The upstream impedance measured indirectly was nearly in phase with Z_d at the two harmonics.

Figure 5.8 plots the results for the altissimo tone $E6$ played by performer B. The magnitude (5.8-a) differed by about 60 CGS ohms at the first harmonic (1200 Hz). The phase from the indirect measurement (5.8-b) was aligned with the phase of Z_d, but did not agree with the phase of Z_u^o. The discrepancies in both magnitude and phase could be eliminated if the peak in Z_u^o at 1100 Hz were moved up in frequency.

For the same altissimo tone played by performer D, the magnitude (5.9-a) was in agreement, but the phase of Z_u^o (5.9-b) was too noisy to make a comparison, although the phase of Z_u at the first harmonic was aligned with the phase of Z_d.

5.1.3 Discussion

From this data, the direct and indirect upstream impedance measurements agree better in magnitude than in phase. The magnitude was in greatest disagreement for the chalumeau tones. The phase of the direct measurement was often too noisy to make an accurate comparison with the indirect measurement. This was due to the direct measurement being the result of only a single chirp response, which was not averaged.

For one chalumeau tone ($G4$ played by B) and one altissimo tone ($E6$ played by B), both the magnitude and phase could have been brought into agreement if the peak in the direct measurement had been moved up in frequency. In these cases, it is possible that the performer did not reproduce the airway configuration accurately for the direct measurement, which is likely due to the fact that the performer was receiving no feedback from the instrument and so had to rely on physiological memory to perform the task. This could cause errors in the magnitude and frequency of peaks measured with the direct method.

Both chalumeau tones presented had phase values from the indirect measurement that were outside the range of -90 to +90 degrees, which is the expected range for a dissipative system like the airways. These values were almost all in the range +90 to +180 degrees. In fact, the phase of Z_u was usually outside of the expected range at some harmonic for tones across the chalumeau register and for the tone $B4$, the lowest tone of the clarion register. There are several possible explanations for these unphysical phase values.

One explanation is that they are errors due to low magnitude values at those frequencies. If the magnitude is low, then there will be more uncertainty in the phase value and the error bar should be larger. However, the phase values greater than +90 degrees had small error bars, and they were not always low-magnitude points.

Another possible explanation is that the effect of using a cold measurement of Z_d in the indirect measurement of Z_u under playing conditions is to increase the phase above +90 degrees. As the instrument warms up, the resonances increase in frequency and the phase of the Z_d curve also shifts up in frequency. Since the phase increases below a resonance, the effect of using a cold measurement of Z_d will be to give phase values that are too negative, which is not the case for the data here. If the data were corrected for this temperature effect, the phases would become even more positive. This also does not explain why these phase errors are seen only for chalumeau tones. The use of a cold measurement of Z_d does not account for these phase values.

A third possible explanation for these phase values is that they are genuine, and that the upstream impedance is different under playing conditions, compared to the conditions of the direct measurement. Phase values outside the range -90 to +90 degrees imply that the airways have a negative resistance, or in other words they are acting as a sound energy generator. Research on horn playing by Dejonckere et al. [24] has shown that the glottis vibrates at the fundamental frequency, or at a multiple or submultiple of the fundamental, during horn playing. The amplitude of the vibration was larger at higher dynamic levels, that is, at higher pressure levels. The phase values measured indirectly for the upstream impedance for clarinet playing would agree with the explanation that the glottis is acting as a generator during performance, but not during the direct measurement when no sound is being produced. These values were seen in the lower pitch range of the clarinet, where generally higher pressures are used to play these tones, which agrees with the finding of Dejonckere et al. that glottal vibrations increase at higher pressures.

A fourth explanation is that the instrument impedance Z_d has a significant non-linear component under playing conditions that is not included in the small-signal measurement of Z_d used to calculate Z_u in the indirect method. In Section 4.1 a comparison of the pressures at two positions along the mouthpiece bore under playing conditions showed that there were contributions that could not be explained by linear acoustics, and this could lead to errors in Z_u if a linear measurement of Z_d is used to find Z_u.

The final possible explanation is that the reed is closing completely against the lay of the mouthpiece for these tones, and the linear systems assumption is no longer valid. These low-register tones had the largest mouthpiece pressure waveform amplitudes and are therefore the tones most likely to have the reed closing completely against the lay. One problem with a decisive judgment on this explanation is that there is no reliable way to determine if the reed closes completely, given pressure measurements alone.

The data in this study would support any of the last three explanations: the glottis is acting as a generator, or Z_d is nonlinear, or the assumption of linearity is no longer valid for these tones, and it is not possible to come to a definitive conclusion with this data alone. Measurement of glottal vibrations would confirm the first explanation, but the validity of the assumption of linearity would still be questionable. At this point a conclusion cannot be made.

The indirect method can be used to measure the upstream impedance for tones in the clarion and altissimo registers. The magnitude was more reliable than the phase, which was often difficult to determine from the direct measurement. Tones in the chalumeau register had phase values from the indirect measurement that cannot be decisively explained, but there was more agreement between the magnitudes, although the agreement was not as good as in the rest of the pitch range.

5.2 Regeneration Calculations

Once the upstream impedance is determined, it can be included in the regeneration equation via the dissipative admittance Y in order to see if the inclusion of the upstream admittance helps to satisfy the regeneration conditions. This section will describe the regeneration calculations and present an example of the calculations for a single, normal tone.

5.2.1 Calculations

According to regeneration theory, the generator admittance Y_G and the dissipative admittance Y must satisfy the regeneration equation (Eqn. 1.15) in order to sustain an oscillation. (The subscript n in Eqn. 1.15 will be suppressed in the rest of the dissertation.) Y is the total admittance of the instrument, airways, and reed system and is the inverse of the impedance in Eqn. 1.28. The generator admittance Y_G is calculated from Eqn. 1.13, with the parameters listed in Table 5.1.

The reed admittance was calculated as the inverse of the impedance in Eqn. 1.25. Figure 5.10 shows the real and imaginary parts of the reed impedance calculated with the parameters in Table 5.1. In the linear theory, the reed is assumed to be a simple harmonic oscillator with only one resonance. The lack of knowledge about the reed and the variability of its parameters with playing conditions introduce uncertainties into the calculation. For example, the reed is assumed to have only one resonance, but experiments have shown that it might actually have multiple resonances (Keefe and Waeffler [46], Hoekje and Roberts [41]). The reed resonance is adjustable over a range of frequencies (Thompson [71]), but here it is taken as fixed at 2500 Hz. The reed closing pressure p_c varies from reed to reed (Worman [75]), but here it is taken as 6000 Pa for all calculations, which is about the mid-value of the range that Worman gives. The effective dynamic reed area S_r has never been measured and always estimated. An attempt was made to measure a value for S_r (see Appendix C), but unrealistically large values were obtained, and the value of 0.73 cm^2 was chosen, in accordance with Thompson [71]. The values for these parameters are probably reasonable, and in any case the results are not very sensitive to their exact values.

The quantities that were varied from tone to tone were the DC blowing pressure p_0 and the upstream and downstream impedances. The DC blowing pressure was taken as the DC pressure during the tone, as calculated from the upstream pressure spectra (see for example Figure 4.12). The downstream impedance was the measured instrument impedance, and the upstream impedance was the indirect measurement of Z_u, calculated at harmonic frequencies and averaged over the entire tone duration.

5.2.2 Results

Results will be presented for the tone $G5$ played by performer B used in the previous section to demonstrate the indirect measurement of Z_u. Figure 5.11 presents the results of the regeneration calculations for this tone. The dashed curve is the negative of the generator admittance ($-Y_G$). The solid curve is the dissipative admittance Y_{dr} that includes only the downstream system and the reed; the upstream admittance is omitted from Y_{dr}. The linear regeneration condition states that an oscillation can be sustained at frequencies where $-Y_G$ intersects the dissipative admittance. The intersections of the dashed and solid curves show the possible frequencies where oscillations can be sustained in the absence of the airways. The solid dots show the values of the dissipative admittance Y when the upstream admittance is included. Since the upstream admittance was only calculated at harmonic frequencies of the tone, the dissipative admittance Y can only be shown at harmonic frequencies, which are marked by the vertical dashed lines.

The real part of the admittances (Figure 5.11-a) shows whether energy is generated or dissipated at each harmonic frequency when Y_g is evaluated at the measured blowing pressure. If $Re(-Y_G)$ is greater than $Re(Y)$, then energy is generated, but if $Re(Y)$ is greater, then energy is dissipated. So, for example, energy is generated at the first harmonic and dissipated at the second harmonic. The airways have virtually no effect at the first harmonic, but they decrease energy dissipation slightly at the second harmonic.

The imaginary part of the admittances (Figure 5.11-b) determines the playing frequency. Ideally, $Im(-Y_G)$ should be equal to $Im(Y)$ at harmonic frequencies, and so it is desirable to have $Im(-Y_G)$ and $Im(Y)$ as close as possible to each other. In this example this condition is most closely satisfied at the first harmonic, and the airways have very little effect at that frequency. At the second harmonic, the airways help satisfy the condition just slightly better, but $Im(-Y_G)$ and $Im(Y)$ still do not come close to intersecting.

In the linear theory, $-Y_G$ and Y should be equal at each frequency, but once the nonlinear interaction between the different harmonic components is taken into account, the resulting oscillation is actually a compromise between all components. For the real part of the admittances, this means that the energy generated at one frequency can go to feed an oscillation at another frequency where energy is being dissipated, and there does not have to be exact equality at all harmonic frequencies. Likewise, the playing frequency is determined by an optimization at all harmonic frequencies and equality of the imaginary parts does not have to be exact.

In this example, the airways had very little effect, and this is probably due to the low level of $|Z_u|$. The dashed curve in Figure 5.6-a plots Z_d, and the magnitude of Z_u is low relative to that of Z_d. Even though the performer has aligned a Z_u peak near the first harmonic, the actual value of Z_u at the first harmonic is not large enough to have a significant effect.

5.3 Tones Played at Different Dynamic Levels

As the dynamic level changes from piano to forte, the blowing pressure increases, and the amplitude of the reed vibration becomes larger. At low dynamic levels the reed is operating in a small-amplitude regime, but at higher dynamic levels the reed motion becomes increasingly nonlinear. Since the indirect measurement of Z_u assumes that the reed motion is linear, the Z_u for tones played at different dynamic levels will show how this linear measurement holds up under nonlinear conditions.

5.3.1 Data

The upstream impedance Z_u was measured for two tones, $C4$ and $G5$, played by performer B at three dynamic levels: piano, mezzo forte, and forte. No attempt was made to ensure a consistent sound intensity level, and so these dynamic levels represent only the performer's musical interpretation of them.

5.3.2 Results

The mouthpiece pressure waveforms for $C4$ had peak-to-peak amplitudes of 6000 Pa, 11000 Pa, and 14000 Pa at piano, mezzo forte, and forte, respectively. The mouthpiece pressure waveforms for $G5$ had smaller amplitudes at all three dynamic levels, with peak-to-peak amplitudes of 2500 Pa, 7000 Pa, and 9000 Pa at piano, mezzo forte, and forte, respectively. Results will be presented for the written tone $C4$ (sounding frequency 233 Hz), but results for both $C4$ and $G5$ were usually similar. Instances where the results differed for the two tones will be noted.

Figure 5.12 shows Z_u for $C4$ at the three dynamic levels and Z_d for the $C4$ fingering. There were two measurements at mezzo forte. The dashed lines mark the harmonic frequencies of the piano tone, which were slightly higher than for the mezzo forte and forte tones. The magnitude of Z_u (Figure 5.12-a) tended to be higher overall for the piano tone and lower for the forte tone. The difference in $|Z_u|$ between piano and forte at the first and third harmonics was 10–20 CGS ohms and was less than 10 CGS ohms at the second harmonic. $|Z_u|$ for the mezzo forte tones was not as consistent and could be larger or smaller than $|Z_u|$ for both the piano and forte tones.

The phase of Z_u (Figure 5.12-b) increased from piano to forte for the first three harmonics, and became greater than 90 degrees for the first and third harmonics at mezzo forte and forte dynamic levels. The large error bars associated with Z_u at the fifth and sixth harmonics could be due to the low magnitudes of those points. At the first and third harmonics, Z_u and Z_d were in phase for the piano tone, but were out of phase for the higher dynamic levels.

The tone $G5$ had similar changes in magnitude but not in phase. $|Z_u|$ decreased as the dynamic level increased, as for $C4$, and the difference in $|Z_u|$ between piano and forte was about 30 CGS ohms. However, the changes in the phase were in the opposite direction from those of $C4$. The phase decreased by 20 to 30 degrees as the dynamic level increased and was never outside of ± 90 degrees.

5.3.3 Discussion

Compagno [22] used a laryngoscope to observe the vocal tract changes for tones of different dynamic levels and for tones played with crescendo and decrescendo. He found that as the dynamic level increased from piano to forte, the glottal opening increased and the larynx ascended. An increase in the glottal opening, as observed by Compagno for an increase in dynamic level, would decrease the wave impedance of the airways and cause a decrease in the level of Z_u. Therefore, from Compagno's data, $|Z_u|$ should decrease as the dynamic level increases. This agrees with the data presented here. The magnitude of the upstream impedance decreased slightly (10–30 CGS ohms) as the dynamic level increased from piano to forte. However, the magnitude for the mezzo forte tones was not consistent and could take on values close to those of the piano or forte tones. Whatever changes in the glottal opening or larynx position that may be taking place between different dynamic levels apparently have a small effect on the magnitude of the upstream impedance.

Although the changes in magnitude were similar for both tones that were measured, the phase changes were in opposite directions, and this is not easily explained. The pressure amplitudes for $G5$ at mezzo forte and forte were comparable to those for $C4$ at piano and mezzo forte, but the phase of Z_u decreased for $G5$ while it increased for $C4$. It is possible that the reed was closing for the $C4$ oscillation, and then the phase values greater than +90 degrees for $C4$ may indicate that the assumption of linearity is not valid for this tone.

On the other hand, as noted in Section 5.1 comparing the direct and indirect measurements of the upstream impedance, phase values greater than +90 degrees could also be due to glottal vibrations, which would increase with increasing pressure levels. However, such phase behavior occurred only for $C4$ and not for $G5$, even at comparable mouthpiece pressure levels. More data is needed to determine the explanation for these phase values.

5.4 *Tones Played with an Open and a Closed Throat*

Many performers believe that an open throat is necessary for a good tone quality. The upstream impedance for tones played with an open and a closed throat could tell us why an open throat is better. For example, an open throat could produce resonances that stabilize the tone better than the resonances of a closed throat.

5.4.1 *Performer's Observations*

Data were taken for several tones that performer D played with an "open" and a "closed" throat. Exactly what an "open" and a "closed" throat were was not specifically described, but the performer believed that the "open" throat produced the better tone. The performer stated that the open throat tones had a warmer, fuller, more mellow sound, and the closed throat tones sounded brittle and shrill. The performer also thought the closed throat tones sounded constricted and tense, but added that might just be how the airway feels rather than how the resulting tone sounds. The closed throat tones had a slightly higher sounding frequency than the open throat tones.

5.4.2 *Results*

All of these tones had low-amplitude mouthpiece pressure waveforms (peak-to-peak amplitudes less than about 5000 Pa), and so it is appropriate to use the indirect method to measure Z_u. The results for the tone $D5$ will be presented.

Figure 5.13 shows the directly measured Z_u^o, the indirectly measured Z_u up to 1500 Hz, and the measured Z_d for the tone $D5$ played with an open throat. Figure 5.14 shows the same quantities for the tone played with a closed throat. The upstream impedance Z_u^o that was measured directly with the one-microphone technique (the solid line in the graphs) was consistently different for the two throat conditions for all pitches measured, and these differences are illustrated by this example. For this performer, the overall level of the measured $|Z_u^o|$ was larger with the closed throat and was comparable to the level of $|Z_d|$, whereas the level of $|Z_u^o|$ for the open throat was much lower than $|Z_d|$. For open throat tones, this performer had one small peak of 20–30 CGS ohms around 1000 Hz and a single peak of 40–100 CGS ohms in the range 2–3 kHz. For the closed throat tones, there was a large peak of 150–250 CGS ohms in 500–1000 Hz that was often split into two peaks, as in Figure 5.14-a. There was also a peak of 40–180 CGS ohms in 1–2 kHz and no peaks in 2–3 kHz.

The Z_u measured directly that is shown in Figures 5.13 and 5.14 was calculated for 32768-sample sections, overlapped by 16384 samples, and averaged across the entire tone. The error bars give the standard deviation about the average. The Z_u^o measured directly and the Z_u measured indirectly agreed quite well for the open throat, except for the phase at the first harmonic, which was probably an error due to the low magnitude at that frequency. There was somewhat more disagreement for the closed throat. This is not surprising since clarinetists are not accustomed to playing with a closed throat, and therefore when asked to reproduce a closed throat during the direct measurement without any feedback from the instrument, the error will likely be larger.

As mentioned in Section 3.2.4, the upstream impedance measured by Benade [14] for vowels was more similar to the closed throat upstream impedance measured here, but Hoekje's [42] measurements (also for vowels) were more similar to the open throat measurements here. The airway configuration for Benade's measurements was probably more constricted than that for these or Hoekje's measurements.

5.4.3 Discussion

The upstream impedance for an open throat had sharply tuned resonances with a low level of impedance between the peaks. A closed throat had broader and larger upstream impedance peaks for all tones. Since the theory predicts that a large value of Z_u at harmonic frequencies stabilizes the tone, this implies that a tone played with a closed throat should actually be more stable than a tone played with an open throat, and yet it is the open throat that clarinetists claim produces a better tone quality.

One explanation is that the broad, strong peaks of the closed throat impedance tend to disrupt the harmonic alignment of impedance peaks that makes it easy to play a tone. For example, the broad peak in Figure 5.14 between the first two harmonics, which is probably several peaks closely spaced, is not tuned to any harmonic frequency and does not facilitate sound production. The diminished oscillation stability could result in a poorer tone quality.

5.5 Clarion Tones Played without the Register Key

The tones of the second (clarion) register of the clarinet are normally played with the register key. Opening this hole displaces the first mode so that it is no longer in harmonic alignment with the second mode (see Figure 3.1, and the second mode easily sounds. It is possible to play clarion tones without using the register key, but more effort is required on the part of the performer. Johnston et al. [44] predicted from Benade's [7] theory that the airways could produce this effect if there is an upstream resonance aligned with the second instrument mode. According to this prediction, the upstream impedance should be large at the fundamental frequency when playing a clarion tone using the fingering for the corresponding chalumeau tone.

5.5.1 Data and Calculations

Performers B and D played the pitches $E5$, $G5$, and $B5$ without using the register key. Both performers began $E5$ with the register key and then released the register key once the tone had begun because it was too difficult to begin the tone without the register key. Performer B also began $G5$ in this manner. The performers were instructed to hold the tones as steady as possible.

The upstream impedance Z_u for the clarion tones played without the register key was calculated using cross-spectral averaging (Section 2.2.3) due to unsteadiness in the tone. For each 32768-sample section of the pressure time series, the spectra of 16 non-overlapping 2048-sample sections was averaged. and Z_u was calculated at integer multiples of the fundamental frequency of the 32768-sample section. Z_u was calculated in this manner for consecutive 32768-sample sections, overlapped by 16384-samples, in order to obtain Z_u as a function of time.

5.5.2 Results

Figure 5.15 shows the phase and magnitude of Z_u up to 1500 Hz for three tones played by performer D: for the chalumeau tone $C4$, for the tone $G5$ played without the register key (the same fingering as for $C4$), and for $G5$ played normally (with the register key). The solid line plots Z_d for the fingering of $C4$, which was used for the tone $C4$ itself and to play $G5$ without the register key.

At the fundamental frequency of the clarion tone, the magnitudes of the upstream impedance for the two clarion tones and the chalumeau tone were all within 30 CGS ohms (Figure 5.15-a). $|Z_u|$ for the clarion tone played without the register key was 15 CGS ohms larger at this frequency than $|Z_u|$ for the chalumeau tone. This was typical of the other tones that were examined. When the clarion tone was played with the chalumeau fingering, $|Z_u|$ increased by 10–40 CGS ohms compared to the chalumeau tone for all tones except two: for one tone $|Z_u|$ increased by 60 CGS ohms and for another $|Z_u|$ decreased by 20 CGS ohms. These values are still relatively small compared to the value of $|Z_d|$ at that frequency. For the example shown, $|Z_d|$ was 370 CGS ohms at the fundamental frequency of the clarion tone, and $|Z_u|$ for the clarion tone played without the register key was only 8% of this value, up from 4% for the chalumeau tone.

It was possible to calculate Z_u for the clarion tone without the register key at the fundamental frequency of the chalumeau tone, even though this was not at a harmonic frequency of the clarion tone. As discussed in Section 4.2 there is a small peak in the mouthpiece pressure noise floor at the frequency of the first instrument mode for clarion tones. The coherence C at this peak frequency was 0.5 or higher, so Z_u could be measured indirectly at this frequency using cross-spectral averaging. The triangle in Figure 5.15-a shows the value of $|Z_u|$ for the clarion tone without the register key at the fundamental frequency of the chalumeau tone. It is approximately 30 CGS ohms lower than $|Z_u|$ for the chalumeau tone. For all tones, when the clarion tone was played with the chalumeau fingering, $|Z_u|$ at the fundamental frequency of the chalumeau tone decreased by up to 40 CGS ohms compared to the chalumeau tone.

Figure 5.15-b plots the phase for the data shown in Figure 5.15-a. The phase of Z_u for the clarion tone played without the register key is equal to the phase of Z_d at the fundamental frequency of the clarion tone. For all tones, the phase of Z_u was similar for the clarion tones played with and without the register key, and was equal to or slightly less than the phase of Z_d at that frequency. The phases for the chalumeau tone and the clarion tone played without the register key for the example in Figure 5.15-b are greater than +90 degrees. This might be due to the low magnitude of Z_u for these tones, but the error bar for the phase of the chalumeau tone is quite small, suggesting that it is not due to error associated with a low magnitude.

As noted in Section 5.1 chalumeau tones often had phase values greater than +90 degrees, which may be evidence that the assumption of linearity is not valid. This presents a problem in interpreting the phase data of the chalumeau tones. At the fundamental frequency of the clarion tone, all but one of the chalumeau tones had phases greater than +90 degrees. At the fundamental frequency of the chalumeau tone, half of the chalumeau tones had phases greater than +90 degrees. For the other half, the phase decreased by 40–80 degrees when the clarion tone was played without the register key, but it is not clear how reliable these values are since other tones appeared to have questionable values.

5.5.3 *Discussion*

The role of the airways in playing a clarion tone without the register key appears to be minor. Z_u was larger at the fundamental for the tone played without the register key than for the chalumeau tone played with the same fingering, but except for one tone, the difference was no larger than 40 CGS ohms, and in all cases $|Z_u|$ was still significantly lower than $|Z_d|$. Z_u was in phase with Z_d at the fundamental frequency for the clarion tones played with and without the register key.

Both Johnston et al. [44] and Sommerfeldt and Strong [66] found that their computer models could produce a clarion pitch with a chalumeau fingering when there was a strong upstream resonance at the fundamental frequency of the clarion pitch. Johnston et al. found that the peak ratio $|Z_u/Z_d|$ had to be in the range 0.2–5.0. This ratio was less than or equal to 0.25 for all tones studied here and was usually less than 0.15, smaller than the values of Johnston et al. Sommerfeldt and Strong had to increase the magnitude of the upstream resonance from 170 CGS ohms to 300 CGS ohms in order to produce the clarion tone. Although the measurements here show increases in $|Z_u|$ by a factor of three or more, $|Z_u|$ remains at a low level, less than 80 CGS ohms. If changes in the upstream resonance of the magnitude suggested by Sommerfeldt and Strong are responsible for this phenomenon, then the upstream resonance must not be tuned very closely to the fundamental frequency of the clarion tone.

Clarinetists have not written much about this effect, but performer B stated that he thought that biting harder and using more mouthpiece in the mouth were helpful. Clarinetist Charlie Neidich [58] has stated that changes in the embouchure cause this effect. He claims that the position of the teeth on the reed must be changed in order to produce different harmonics with the same fingering, and as the teeth are moved down the reed, higher partials are possible, which is in agreement with the statement of performer B.

Benade [8] suggested that the adjustment of the reed resonance frequency is responsible for this effect. By changing the reed resonance through embouchure adjustments, the modal peaks of the chalumeau fingering can be brought out of alignment, making it difficult to sound the chalumeau tone, and the clarion tone sounds instead. This is in agreement with the performers' statements above that the position of the lip on the reed is the cause of this effect.

Thompson [71] predicted that clarion tones can be played without the register key by aligning the reed resonance with a harmonic frequency of the clarion tone. Again, this would be accomplished by adjusting the embouchure, in agreement with performers.

There were small but consistent differences in Z_u between clarion tones played with and without the register key and the corresponding chalumeau tone at the fundamental frequencies of both the chalumeau and the clarion tone. There are two explanations for this. The first is that the airways do play a small but significant role when playing upper register tones without using the register key. The changes in Z_u at the fundamental frequencies of the chalumeau and clarion tones are in a direction that would aid production of the clarion tone, and these changes in the airways, perhaps in combination with embouchure changes, could produce the clarion tone. The other explanation is that this phenomenon is due mostly to adjustment of the reed resonance frequency, which is accomplished by changing the embouchure. Moving the lower lip farther down the reed will slightly change the airway shape and therefore the measured value of Z_u. If this is the case, then from the consistent changes in Z_u that were observed, it appears that the performers were making similar adjustments in embouchure, for example, by moving the lip farther down on the reed in order to play the overtone, as suggested by Neidich.

5.6 Clarion Tones Played with Pitchbend

Pitchbend, also called "lipping down" and "bending the note", is the technique of dropping the fundamental frequency of a tone below its usual value and is frequently used in jazz. Johnston et al. [44] noted that Benade's theory implied that a strong upstream resonance lower in frequency than the lowest instrument resonance could determine the playing frequency, and in this way the performer could lower the fundamental frequency. Several pitchbend tones were analyzed to determine if $|Z_u|$ was large at the fundamental frequency.

5.6.1 Data and Calculations

Performers B and D both played clarion tones with pitchbend. They were instructed to drop the sounding frequency as far down as they could comfortably hold it steady.

Z_u was measured for these tones using the indirect method and using cross-spectral averaging (Section 2.2.3) due to unsteadiness in the tones. For each 32768-sample section of the pressure time series, the spectra of 16 non-overlapping 2048-sample sections were averaged, and Z_u was calculated at integer multiples of the fundamental frequency of the 32768-sample section. Z_u was calculated in this manner for consecutive 32768-sample sections. overlapped by 16384-samples, in order to obtain Z_u as a function of time.

5.6.2 Results

Table 5.2 lists the tones played by each performer. the amount that they dropped the sounding frequency (in cents). and the range of the maximum value of $|Z_u|$ at the first harmonic for the pitchbend tone and for the normal tone. $|Z_u|$ at the first harmonic only is listed because there were no significant changes at other harmonic frequencies. In all cases the value of $|Z_u|$ for the pitchbend tones was much larger than for the normal tones.

The results for the tone $B5$ (Trial 2) played by performer D and the tone $B5$ (Trial 2) played by B will be presented. These two tones represent the extremes of the pitch drop range. The peak-to-peak amplitude of the mouthpiece pressure waveform was about 2000 Pa for the tone played by D and about 4000 Pa for the tone played by B. Both are relatively low-amplitude oscillations, and so the indirect method can be used to measure Z_u.

Figure 5.16 shows Z_u and Z_d as a function of frequency for the tone B5 (Trial 2) played by performer D. The performer dropped the fundamental frequency by 80 cents. The solid line is the instrument impedance Z_d, and the dots plot the value of Z_u as a function of time as the fundamental frequency was dropped. Only the value of Z_u at the first harmonic is shown since Z_u changed very little at the other harmonics.

Figure 5.16-a shows the magnitude of the impedances on a logarithmic scale. As the frequency dropped, $|Z_u|$ increased to about 90 CGS ohms. In contrast, $|Z_u|$ for the normal tone was 5–25 CGS ohms. The magnitude of Z_u approached that of Z_d at the final frequency. This is different from normal tones, where $|Z_u|$ stayed much less than $|Z_d|$ at the fundamental frequency. $|Z_u|$ reached its maximum value before the playing frequency had dropped to its lowest value. $|Z_u|$ then decreased, but the playing frequency remained relatively steady at its minimum value.

This behavior was typical of the pitchbend tones of both performers. Out of the eight tones, $|Z_u|$ increased at the beginning of the tone, and then reached a maximum somewhere during the frequency drop for five of the tones, at the frequency minimum for two of the tones, and after the frequency minimum for one of the tones. After reaching this maximum, $|Z_u|$ either decreased, remained constant, or a combination of both. Even though the fundamental frequency remained constant for all but one of the tones, $|Z_u|$ tended to decrease for most of the tones after reaching its maximum.

Figure 5.16-b shows the phase of the impedances. As the pitch dropped, the phase of Z_u increased from +90 degrees to between 120 and 150 degrees, which implies that the real part of Z_u was negative.

As the performer dropped the fundamental frequency, the performer created a large upstream resonance at this frequency, comparable in magnitude to the instrument impedance. The generator and dissipative admittances, Y_G and Y, were calculated to see how this large resonance at the fundamental frequency affected sound regeneration. Figure 5.17 plots Y_G, Y_{dr} (the dissipative admittance including the downstream and reed admittances and omitting the upstream admittance), and Y (the dissipative admittance including the upstream admittance) as a function of frequency for the data shown in Figure 5.16.

A closing pressure p_c of 3000 Pa was used for this calculation rather than the 6000 Pa of other calculations. The blowing pressures for this performer on the day of this recording were about one-third to one-half the pressures used on another day, probably due to the performer using a softer reed. The closing pressure p_c was therefore set to 3000 Pa for the regeneration calculations for this performer's tones on this day so that $Re(-Y_G)$ would not be negative at the fundamental frequency. It is difficult to say how the other reed parameters were changed by whatever reed the performer used, and so the resulting calculated values will only give an idea of the relative change of Y as the playing frequency dropped.

If embouchure adjustments are involved in pitchbend, then the reed parameters (p_c, H, S_r, f_r) as well as the blowing pressure could change with time as the playing frequency drops. All of these parameters would change the calculated admittances. The admittances shown here are calculated with these parameters held constant, and this will introduce some error into the results.

In Figure 5.17, Y is plotted as a series of dots, which represent the value of Y as a function of time, starting with the normal fundamental frequency and ending at the final, dropped frequency. The initial value of $Re(Y)$ is larger than $Re(-Y_g)$, and this is probably due to uncertainties in the parameters used to calculate Y_g. The real part of Y (Figure 5.17-a) decreased to about zero as the fundamental frequency dropped. All pitchbend tones that were studied had $Re(Y)$ equal to zero or slightly less than zero. Z_u changed in such a way as to decrease $Re(Y)$ and minimize losses at the fundamental. Figure 5.17-b shows the imaginary parts of the admittances. The imaginary part of Y decreased so that its final value intersected Y_G. Since the playing frequency is determined by the intersection of the imaginary parts of $-Y_G$ and Y, this means that the playing frequency will follow $Im(Y)$, and this is the source of the pitchbend phenomenon. The large Z_u resonance created by the performer has the effect of keeping $Im(Y)$ equal to $Im(-Y_G)$ and thereby controls the fundamental frequency of the tone.

Performer B also played the tone $B5$ with pitchbend, but with a much greater drop of 330 cents in the fundamental frequency. Figure 5.18 shows the magnitude and the phase of Z_u and Z_d as a function of frequency. The dots plot the change in Z_u with time as the playing frequency dropped. The magnitude of Z_u increased to 500 CGS ohms as the pitch dropped, which was much larger than Z_d at that frequency. The phase of Z_u tended to follow the phase of Z_d, so that the final phase value of Z_u was real and positive, although it went slightly negative during the pitch drop.

Figure 5.19 shows the generator and dissipative admittances for this $B5$ played by performer B, calculated with a closing pressure of 6000 Pa. The real part of Y

(Figure 5.19-a) decreased with time until it was zero and then it remained zero for the rest of the tone. The performer adjusted the airway resonance so that there was almost no dissipation of energy at the fundamental frequency. The imaginary part of Y (Figure 5.19-b) decreased until it reached $Im(-Y_G)$, and then it remained equal to $Im(-Y_G)$ as the playing frequency continued to drop. The behavior of Y for this tone was similar to Y for the tone show in Figure 5.17: the real part of Y decreased to practically zero, and the imaginary part of Y followed the imaginary part of $-Y_G$. In fact, all the pitchbend tones studied had this behavior, and there were no obvious, systematic differences that depended on the mouthpiece pressure waveform characteristics.

5.6.3 Discussion

Pitchbend tones are associated with a large value of $|Z_u|$ at the fundamental frequency, ranging up to almost 500 CGS ohms. The performer creates a large airway resonance below the frequency of an instrument resonance, and this large airway resonance controls the playing frequency. As the frequency drops, Z_u changes so that the real part of the total admittance Y decreases at the fundamental, thus decreasing energy dissipation, and the imaginary part of Y follows $Im(-Y_G)$ to control the sounding frequency.

These results confirm the prediction that a very large upstream resonance can drop the fundamental frequency of a tone below its usual value. $|Z_u|$ at the fundamental was much larger for pitchbend tones than for normal tones, and it was comparable to or much larger than $|Z_d|$ at the playing frequency. According to the theory, since the total impedance depends on $(Z_u + Z_d)$, if Z_u is greater than or equal to Z_d, the upstream system will have the greater influence on the oscillation, and for pitchbend tones, the result is that the oscillation frequency is determined by the airway resonance rather than the instrument.

Johnston et al. found effects such as pitchbend in their numerical model for peak values of Z_u and Z_d such that $|Z_u/Z_d| = 0.2$–5.0. The oscillation was based completely on the airways for the larger values of this ratio. Although the calculations here do not give $|Z_u|$ at the peak, they do give $|Z_u|$ at the fundamental frequency. The ratio $|Z_u/Z_d|$ was calculated for the pitchbend tones at the fundamental frequency of the dropped pitch, using the value of $|Z_d|$ at that frequency. This ratio ranged from 0.4

to 15 for all pitchbend tones, but was less than 0.1 for normal tones, in agreement with the numerical results of Johnston et al.

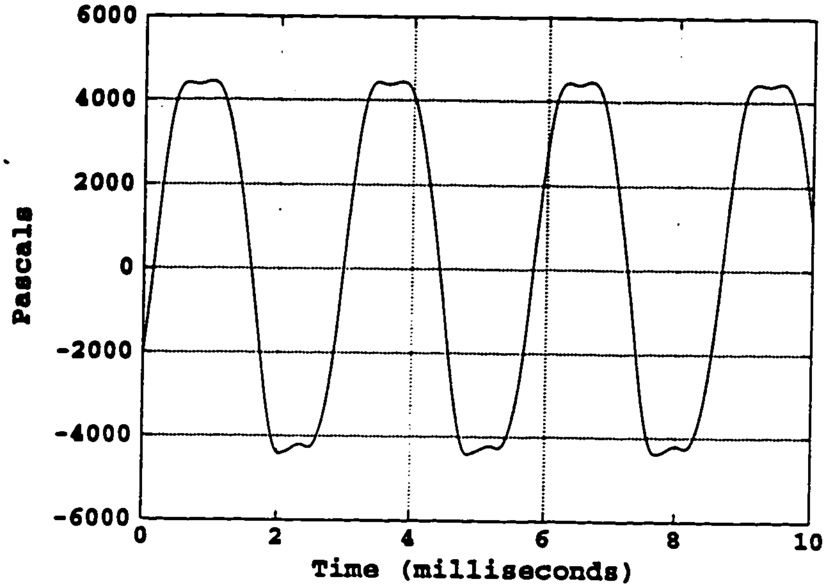
These results are in agreement with clarinetists, who claim that the shape of the oral cavity and embouchure adjustments can drop the playing frequency (Rehfeldt [60]). For the large frequency changes here, the airway resonance appears to be the predominant influence. Embouchure adjustments, which would have the effect of changing the reed resonance frequency, probably play a minor role, but they could be more important for small frequency changes such as those made in order to correct tuning [49]. The theory does not explain the details of the behavior of Z_u during and after the drop in fundamental frequency. Z_u tends to stabilize before the frequency does, but then once the frequency stabilizes, Z_u tends to decrease. These changes could be related to the performer's attempts to stabilize the oscillation.

Table 5.1: Parameters used in regeneration calculations.

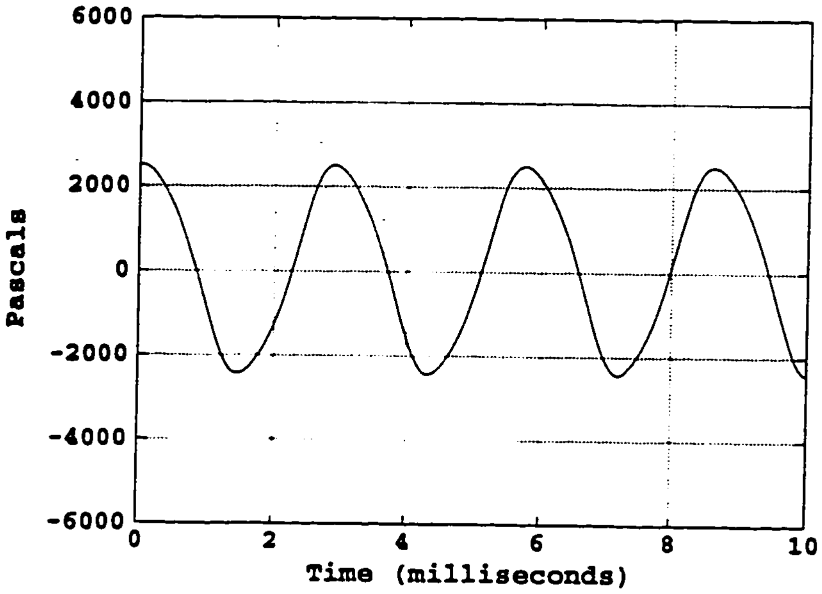
PARAMETER	DEFINITION	VALUE
For all tones:		
B	Bernoulli scaling factor	~ 1 (CGS)
ρ	density of air	0.00117 g/cm^3
w	reed channel effective width	0.8 cm (Keefe [49])
H	static reed opening	0.04 cm
μ	exponent of flow relation	2/3 (Backus [3])
ν	exponent of flow relation	4/3 (Backus [3])
f_r	reed resonance frequency	2500 Hz (Thompson [71])
Q_r	reed quality factor	3.0 (Worman [75])
p_c	reed closing pressure	60000 $dyne/cm^2$ (Worman [75])
S_r	effective reed area	0.73 cm^2 (Thompson [71])
Different for each tone:		
p_0	DC blowing pressure	
Z_d	downstream impedance	
Z_u	upstream impedance	

Table 5.2: Fundamental frequency drop and maximum value of Z_u at the fundamental frequency for pitchbend tones and range of Z_u at the fundamental frequency for corresponding normal tones.

Performer B			
Tone	Frequency Drop (cents)	Max Z_u (CGS ohms)	
		Pitchbend	Normal Tone
$E5$	-160	75–135	10–25
$G5$	-280	175–325	15–40
$B5$ (trial 1)	-190	200–225	20–55
$B5$ (trial 2)	-330	330–470	20–55
Performer D			
Tone	Frequency Drop (cents)	Max Z_u (CGS ohms)	
		Pitchbend	Normal Tone
$D5$	-75	120–180	5–10
$A5$	-80	60–125	5–25
$B5$ (trial 1)	-60	90–170	5–25
$B5$ (trial 2)	-80	35–90	5–25

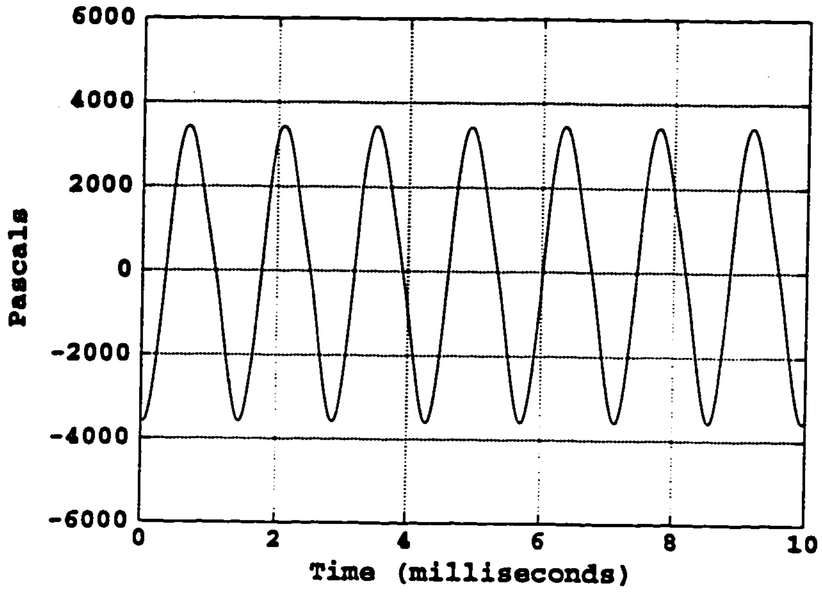


(a) Performer B.

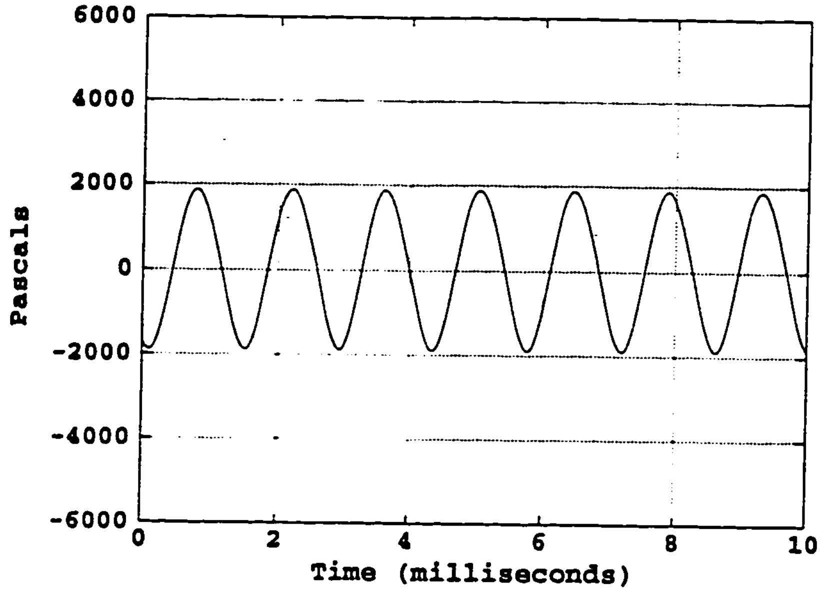


(b) Performer D.

Figure 5.1: Downstream pressure waveforms for $G4$.

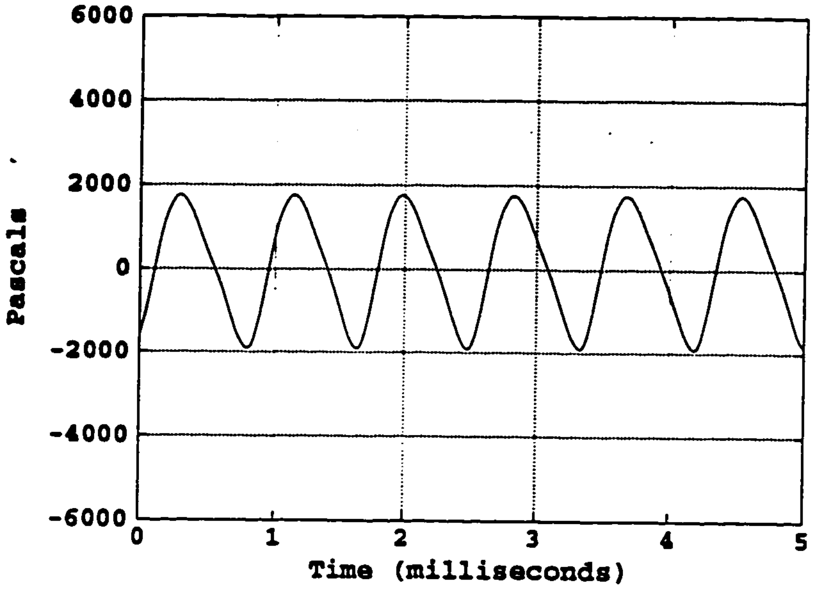


(a) Performer B.

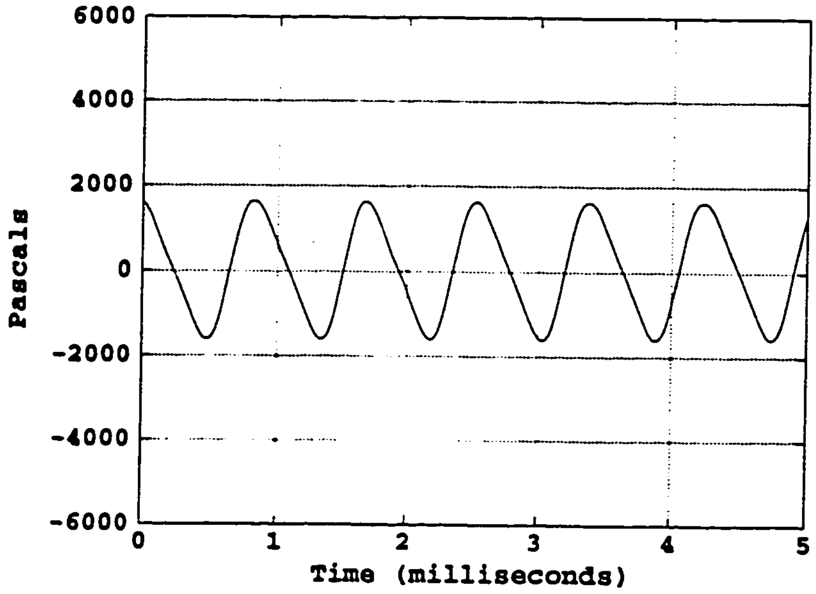


(b) Performer D.

Figure 5.2: Downstream pressure waveforms for $G5$.

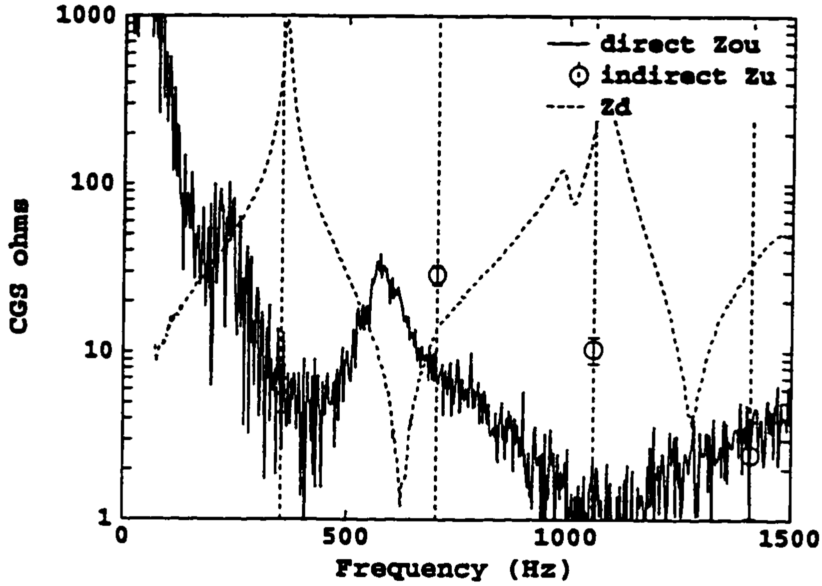


(a) Performer B.

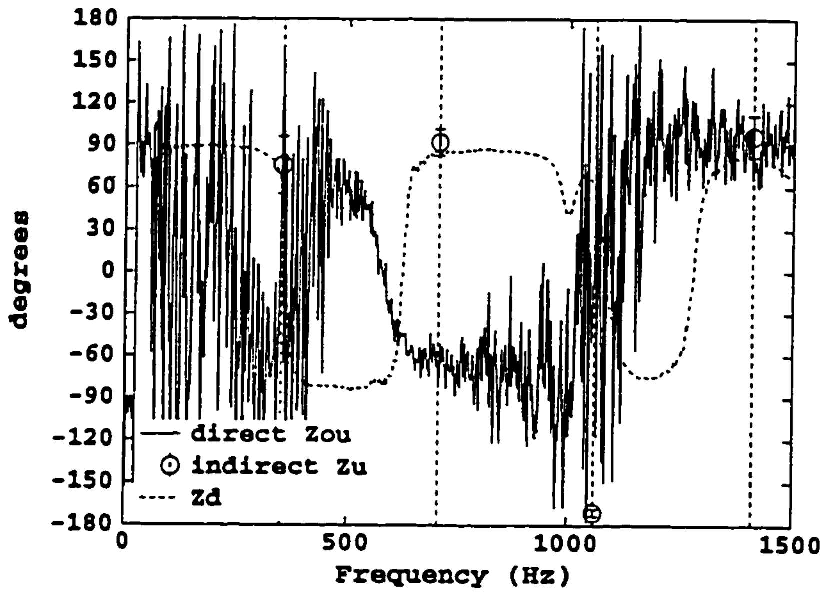


(b) Performer D.

Figure 5.3: Downstream pressure waveforms for $E6$.

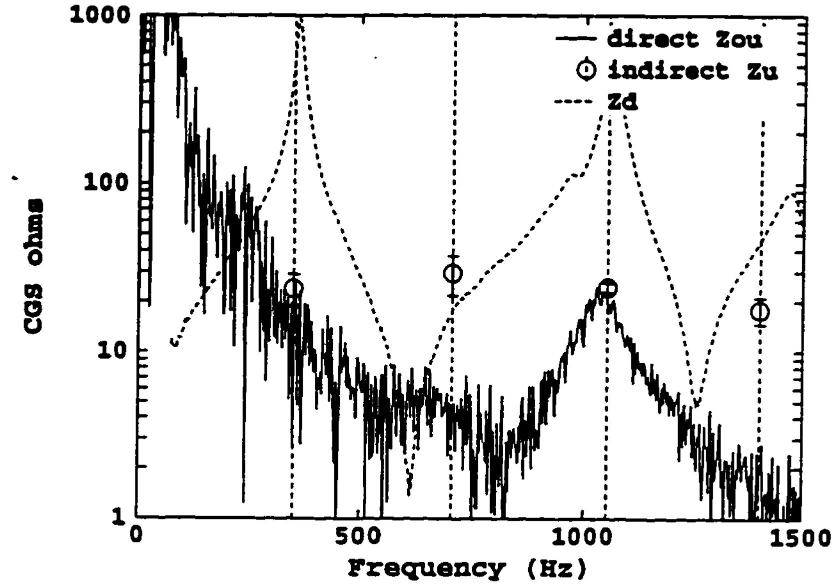


(a) Magnitude.

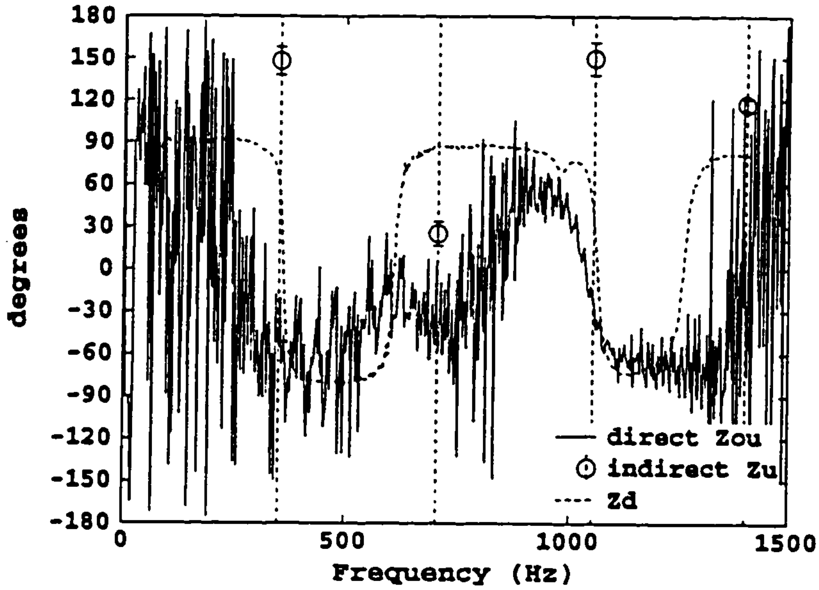


(b) Phase.

Figure 5.4: Direct and indirect measurements of the upstream impedance for $G4$, performer B. The vertical dashed lines are at harmonics of the playing frequency.

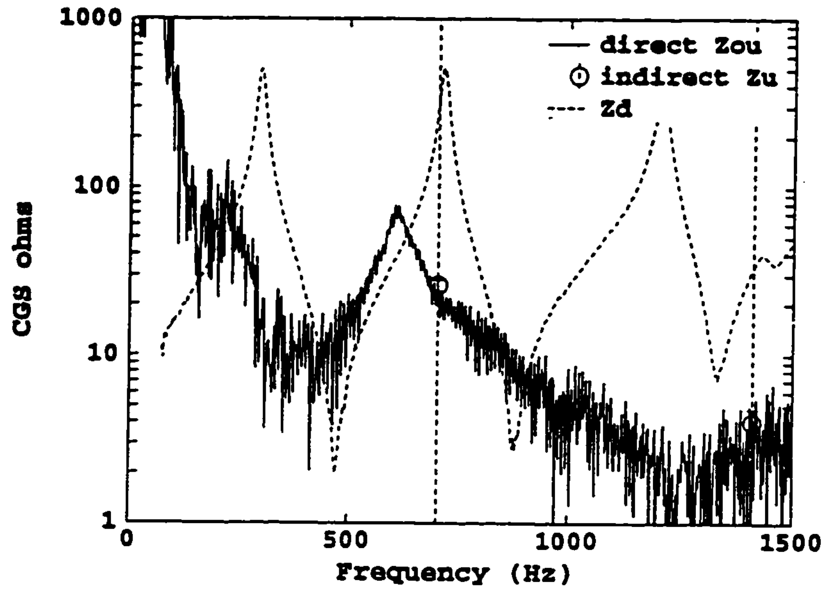


(a) Magnitude.

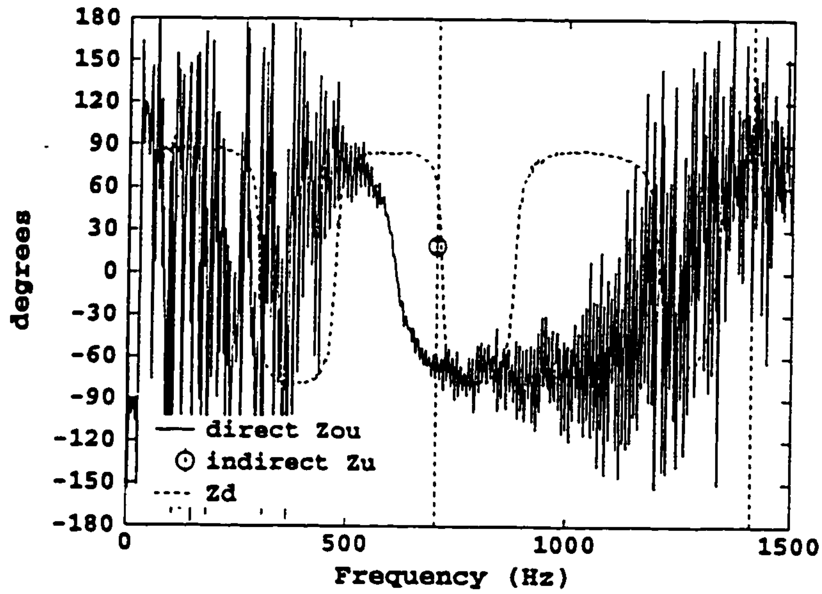


(b) Phase.

Figure 5.5: Direct and indirect measurements of the upstream impedance for $G4$, performer D.

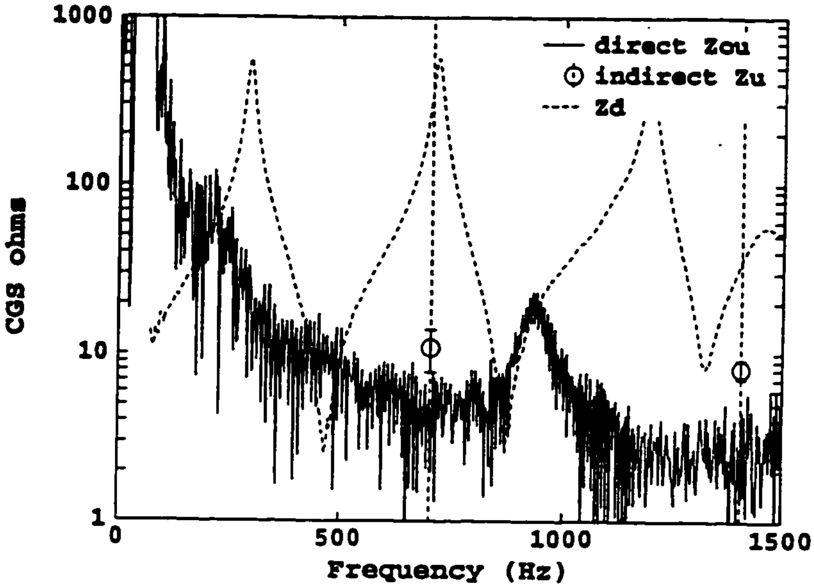


(a) Magnitude.

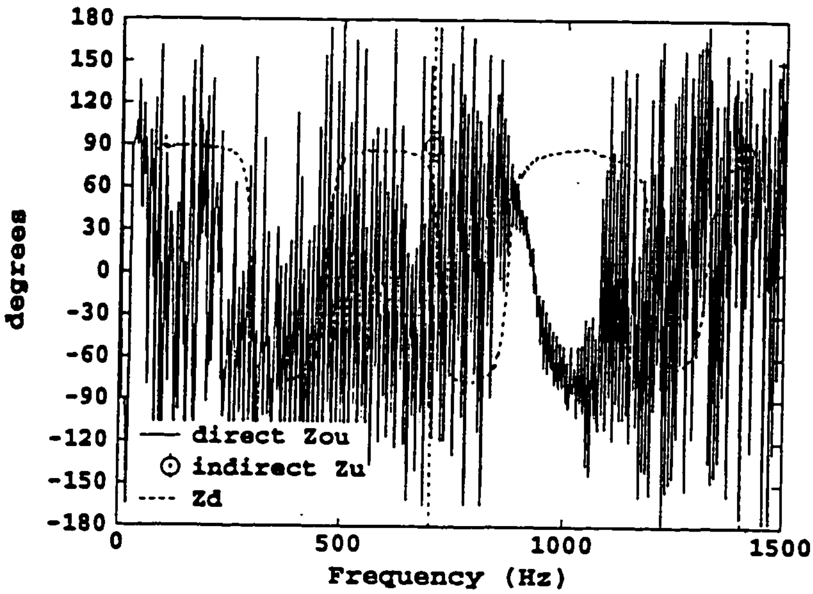


(b) Phase.

Figure 5.6: Direct and indirect measurements of the upstream impedance for $G5$, performer B.

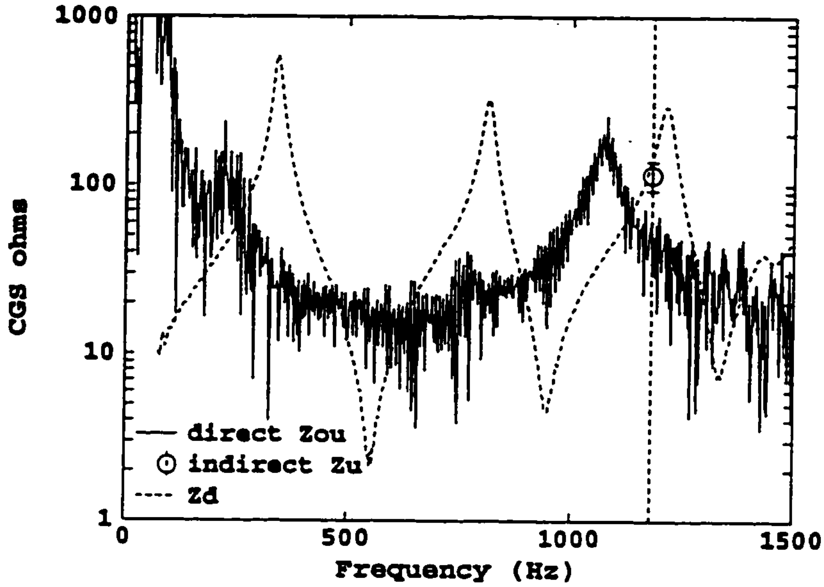


(a) Magnitude.

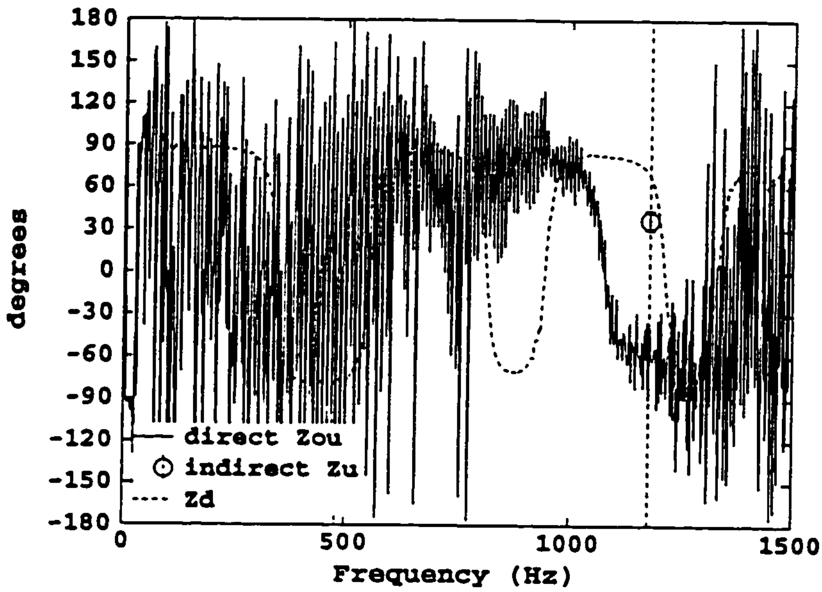


(b) Phase.

Figure 5.7: Direct and indirect measurements of the upstream impedance for $G5$, performer D.

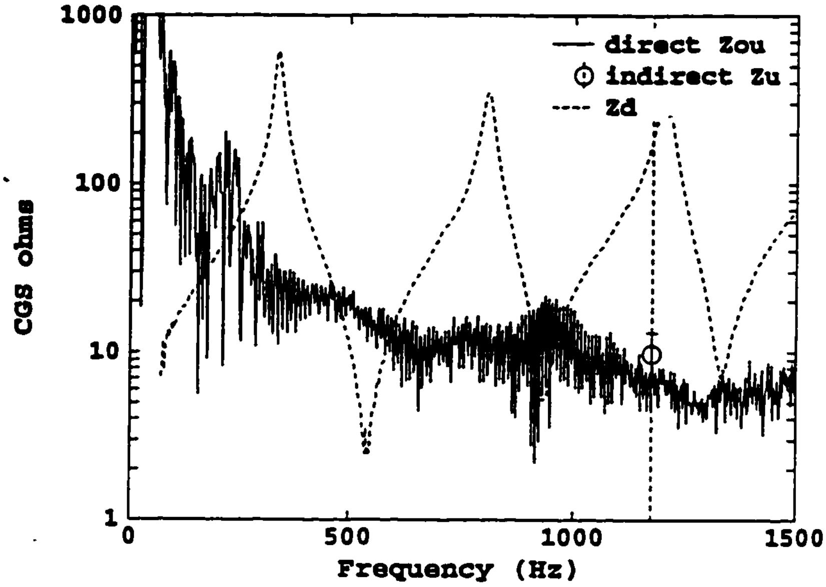


(a) Magnitude.

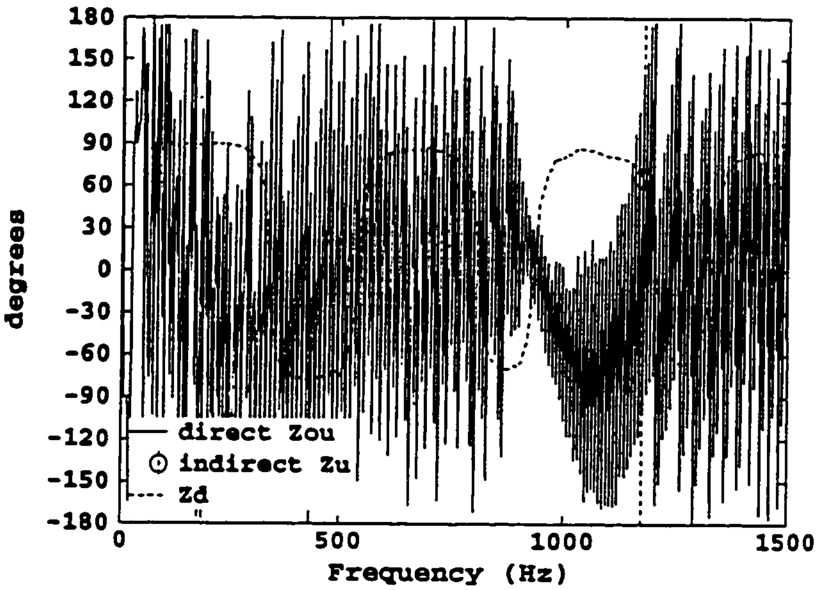


(b) Phase.

Figure 5.8: Direct and indirect measurements of the upstream impedance for $E6$, performer B.



(a) Magnitude.



(b) Phase.

Figure 5.9: Direct and indirect measurements of the upstream impedance for $E6$, performer D.

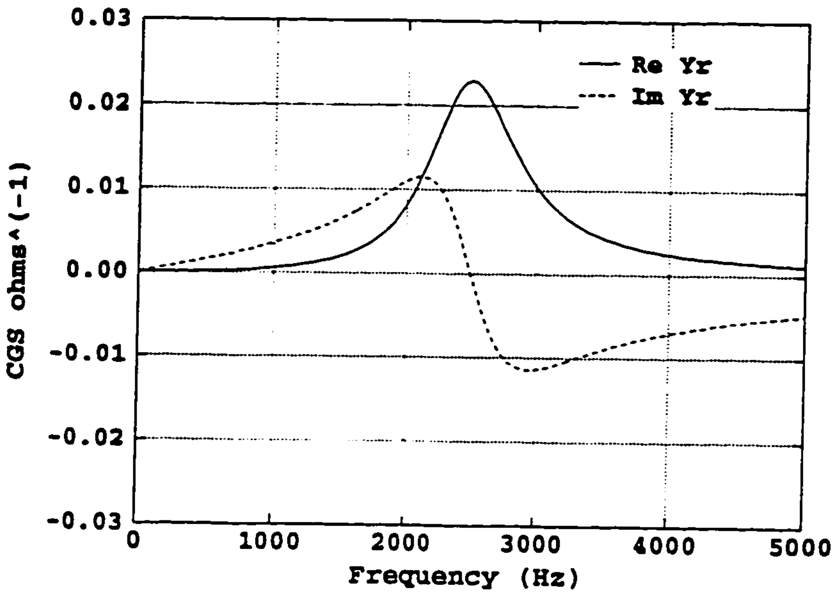
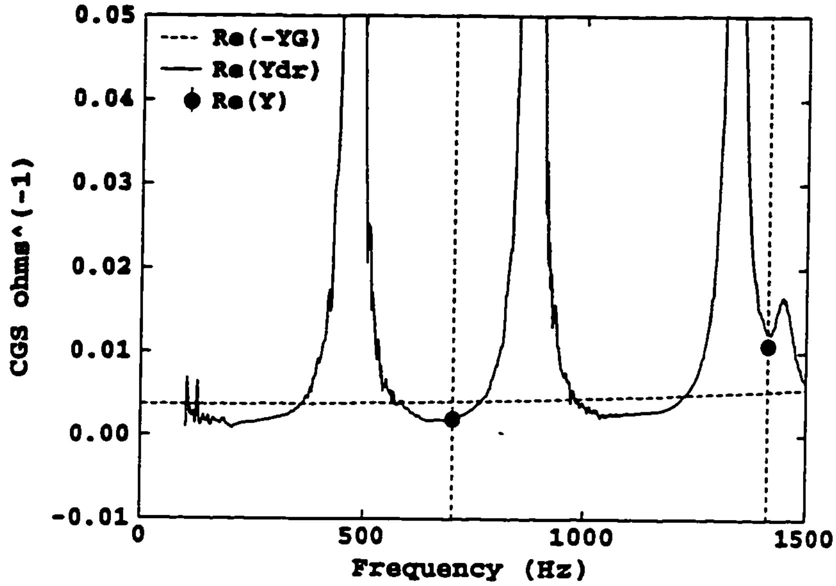
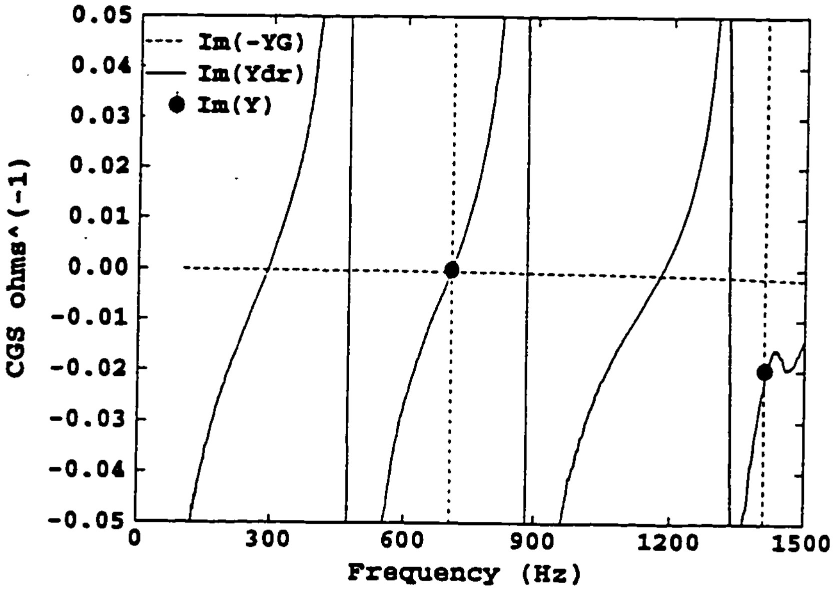


Figure 5.10: The reed admittance Y_r.

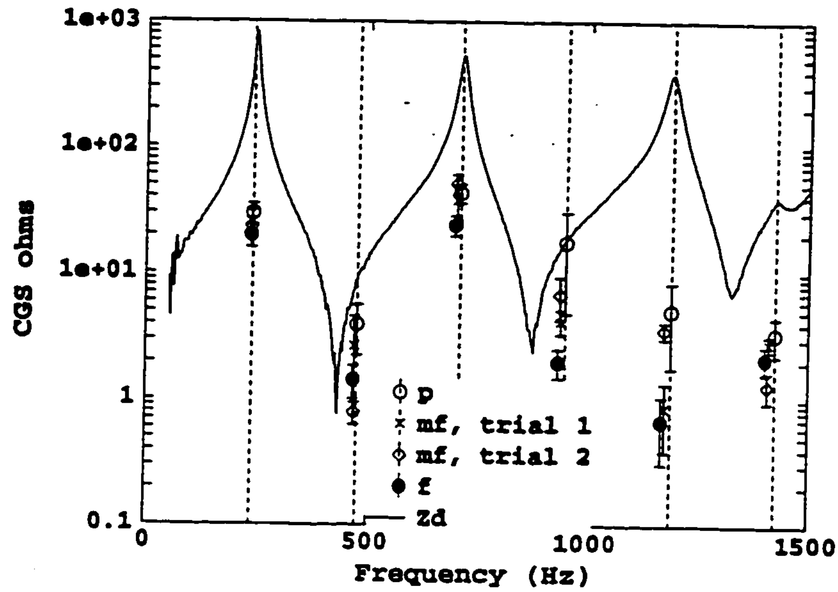


(a) Real.

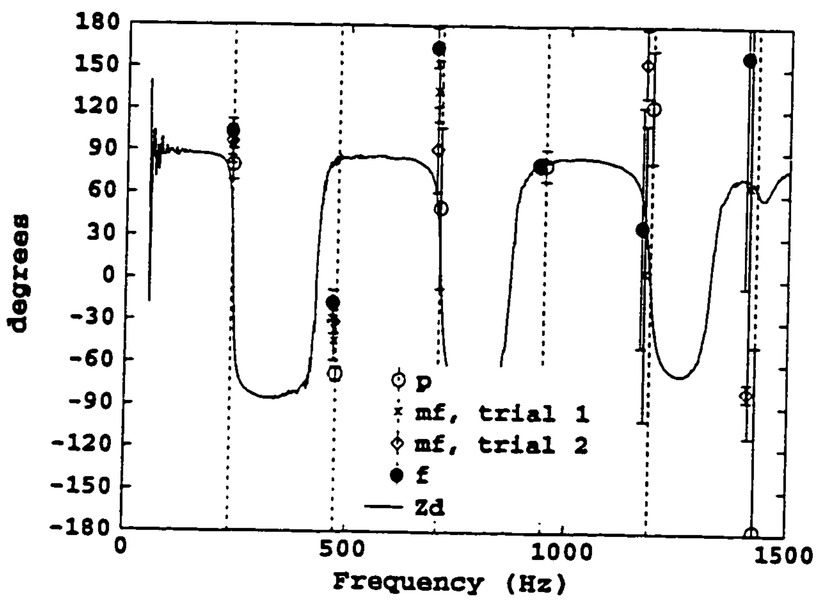


(b) Imaginary.

Figure 5.11: The generator and dissipative admittances for $G5$. The vertical dashed lines mark the harmonics of the playing frequency.

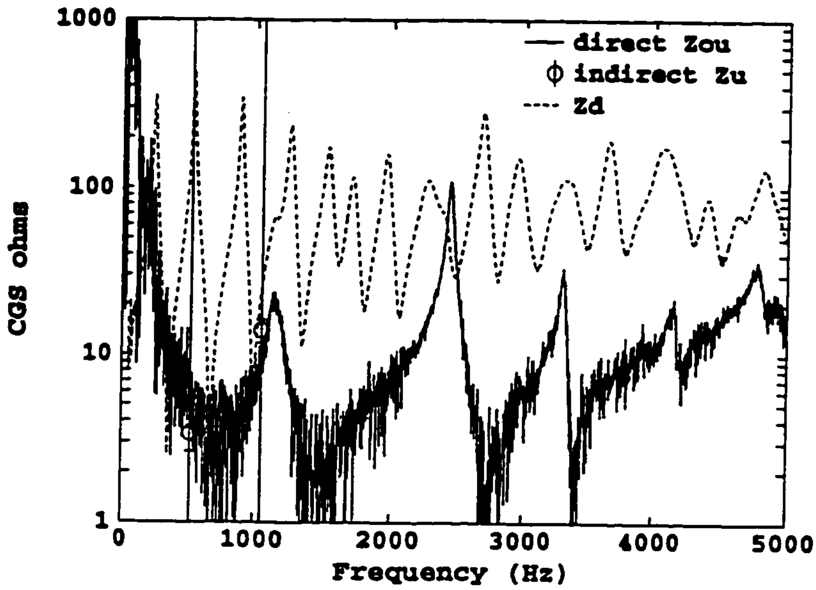


(a) Magnitude.

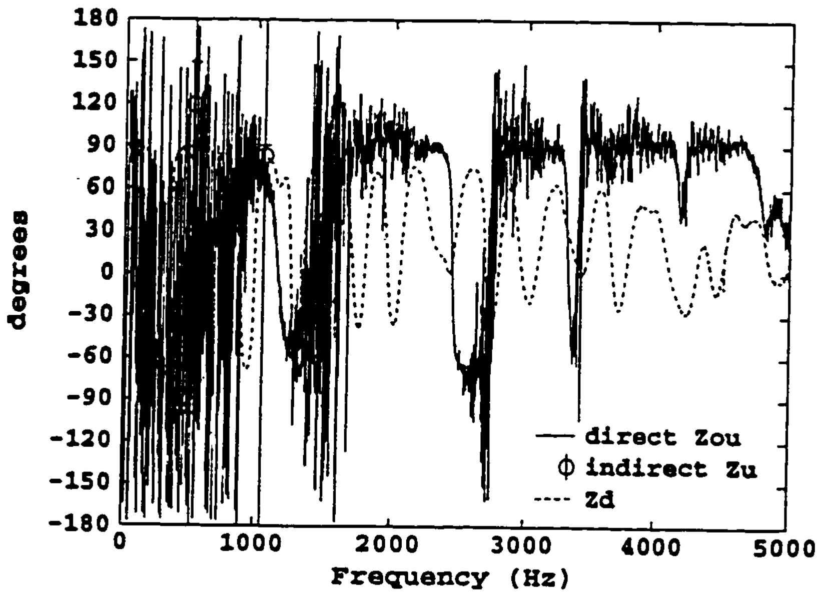


(b) Phase.

Figure 5.12: Z_u for $C4$ played at various dynamic levels.

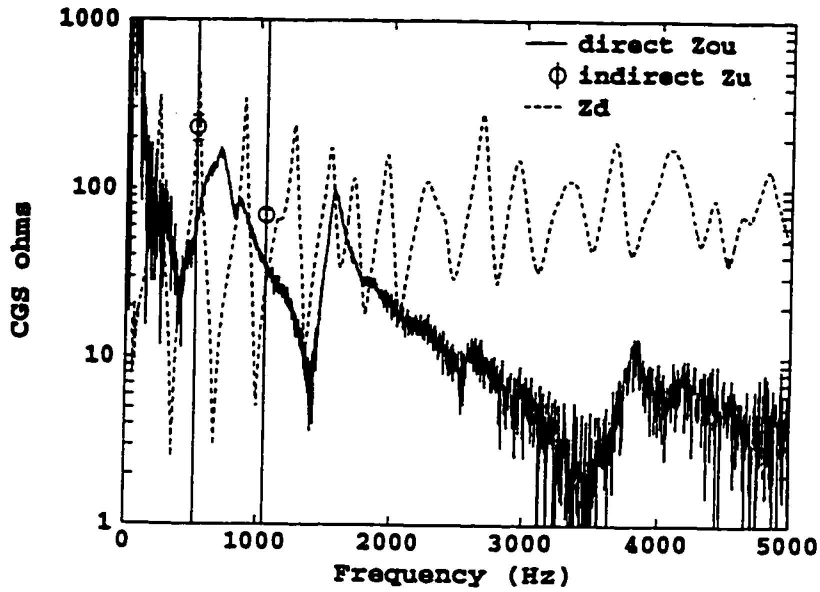


(a) Magnitude.

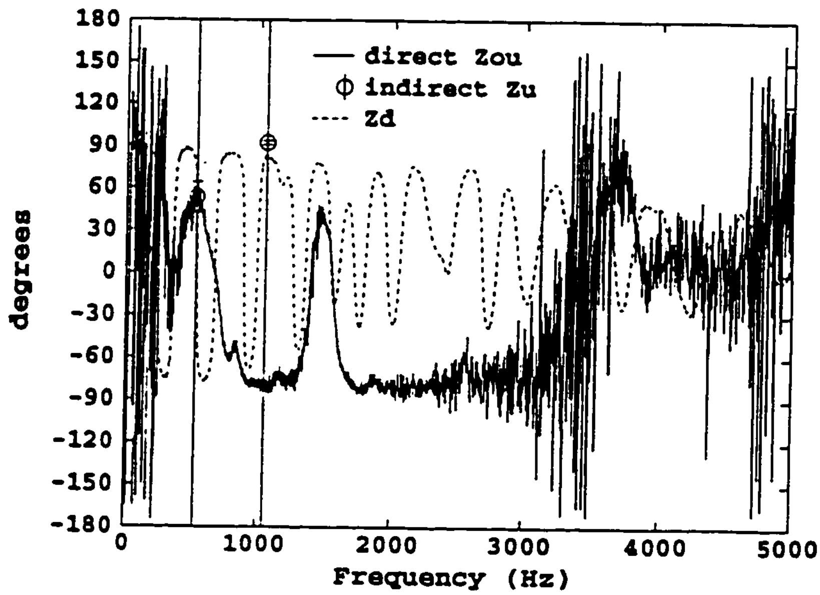


(b) Phase.

Figure 5.13: Direct and indirect measurements of the upstream impedance for the tone $D5$ played with an open throat.

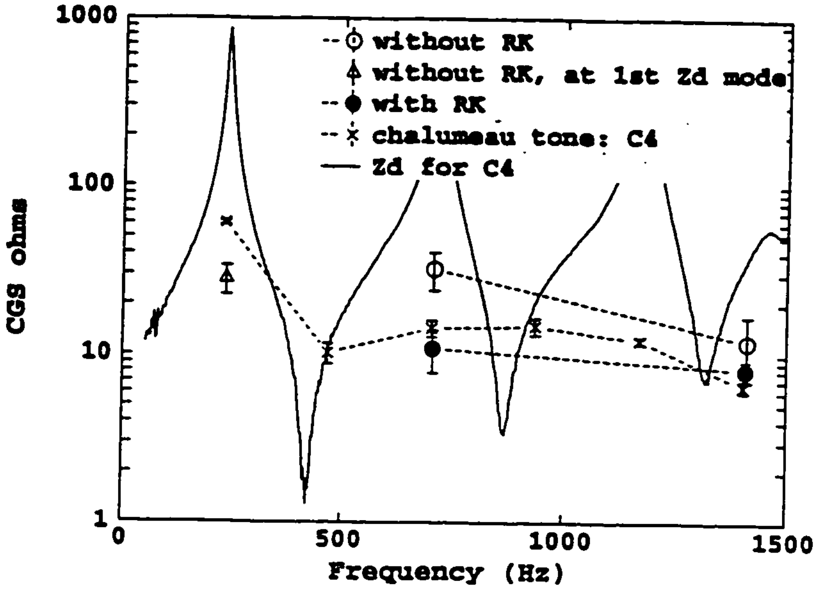


(a) Magnitude.

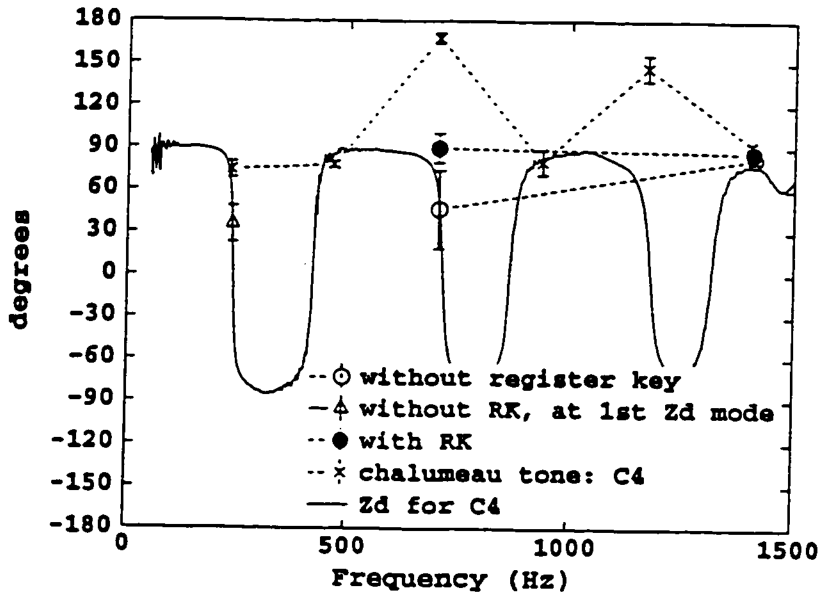


(b) Phase.

Figure 5.14: Direct and indirect measurments of the upstream impedance for the tone $D5$ played with a closed throat.

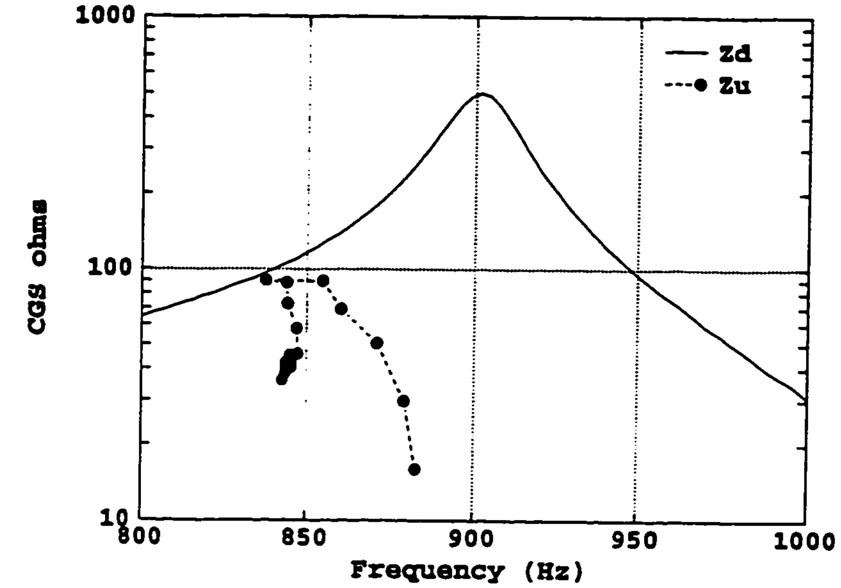


(a) Magnitude.

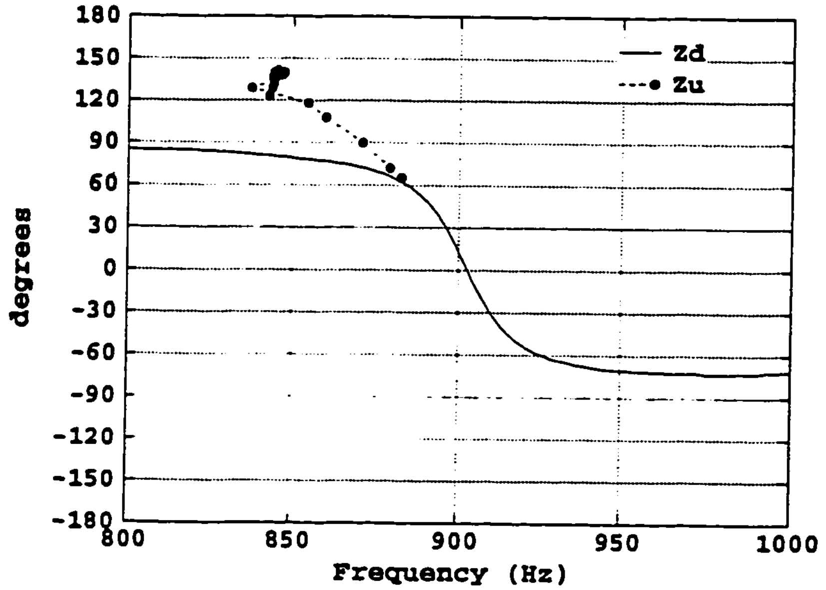


(b) Phase.

Figure 5.15: Z_u for $G5$ played without the register key and with the register key, and for the corresponding chalumeau tone $C4$.

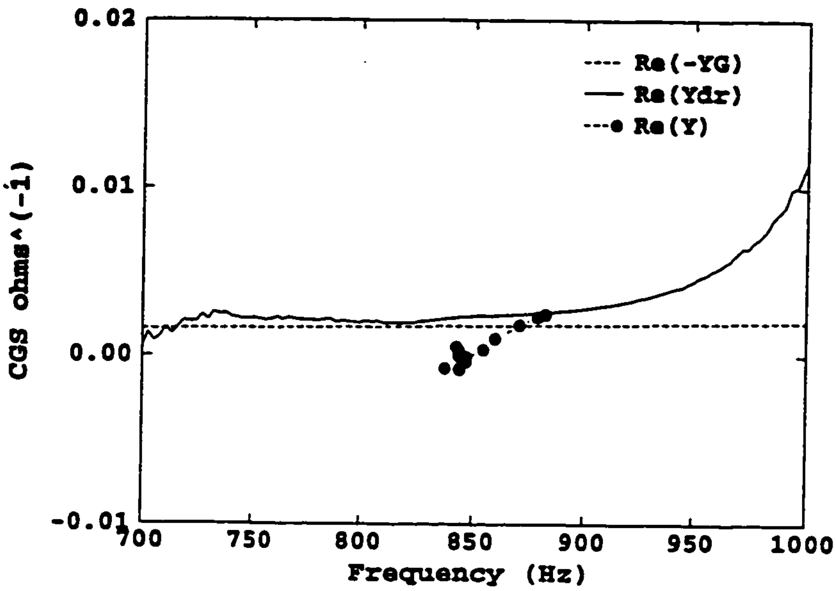


(a) Magnitude.

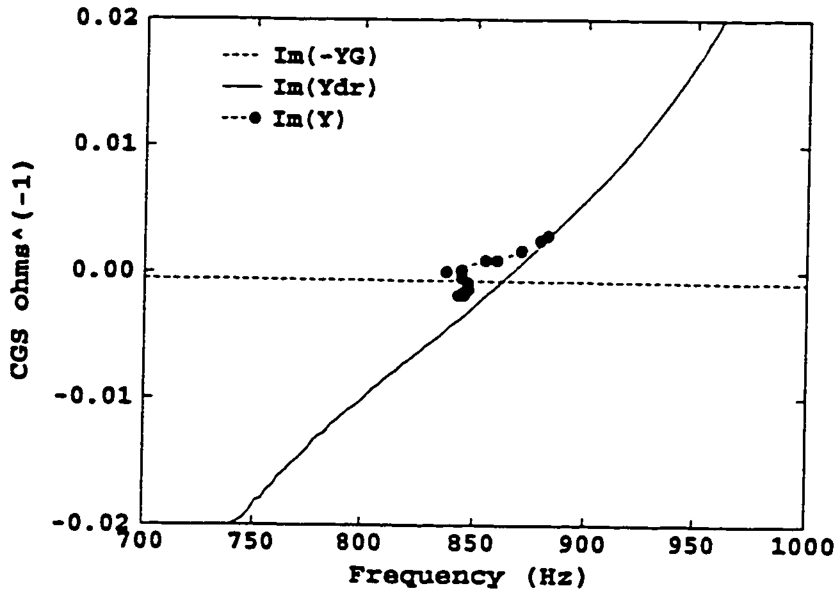


(b) Phase.

Figure 5.16: Upstream and downstream impedances for $B5$ played with pitchbend by performer D.

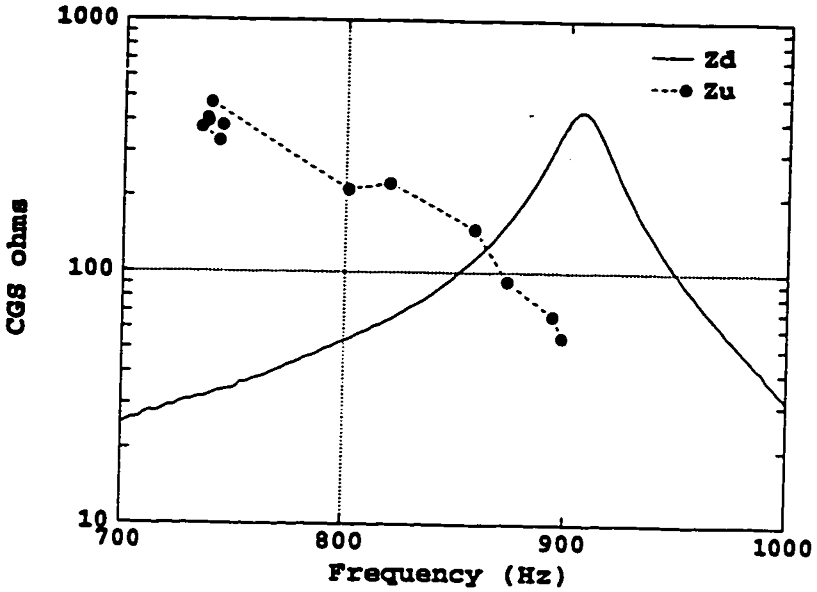


(a) Real.

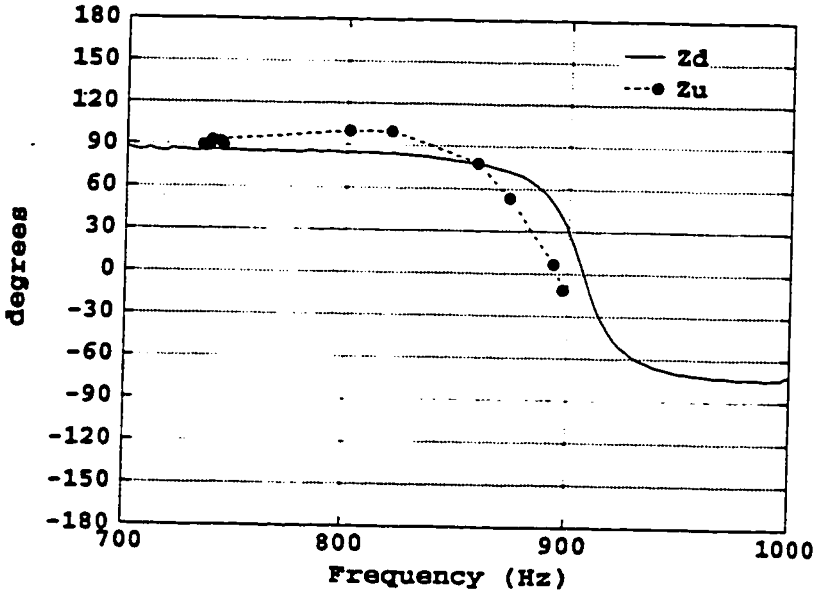


(b) Imaginary.

Figure 5.17: Generator and dissipative admittances for $B5$ played with pitchbend by performer D.

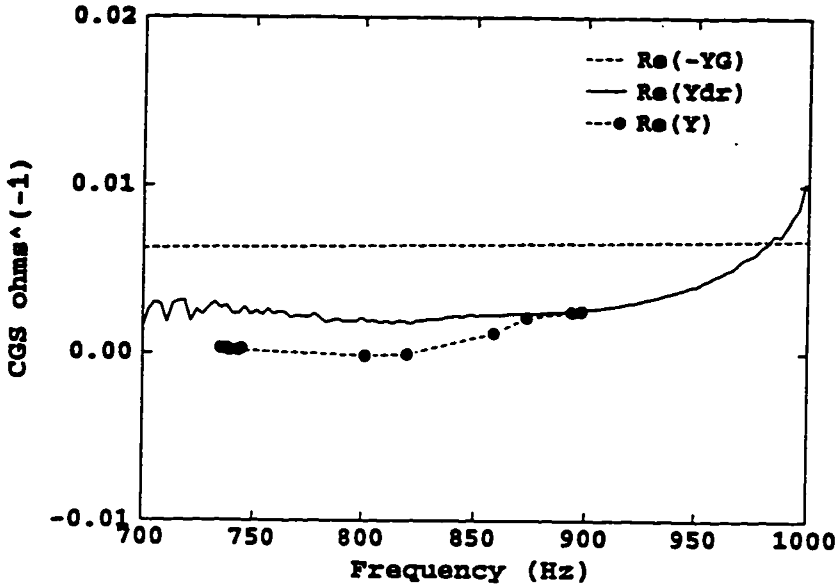


(a) Magnitude.

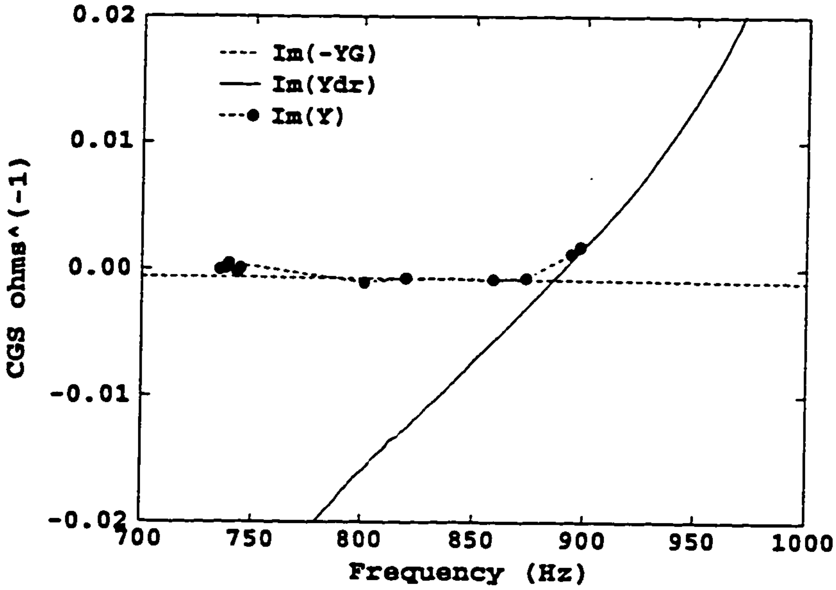


(b) Phase.

Figure 5.18: Upstream and downstream impedances for $B5$ played with pitchbend by performer B.



(a) Real.



(b) Imaginary.

Figure 5.19: Generator and dissipative admittances for $B5$ played with pitchbend by performer B.

Chapter 6

RESULTS: UPSTREAM IMPEDANCE FOR MULTIPHONICS

Multiphonics deserve a chapter of their own because the nonlinear processes are more complex than in the other phenomena studied. The nonlinear interaction between two inharmonic oscillation frequencies is essential to the stability of multiphonics. This also raises the question of whether it is appropriate to measure Z_u from the linear continuity of flow equation for these highly nonlinear phenomena, and this point will be addressed at the end of this chapter.

According to performers, the airways play an important role in multiphonics. Benade [7] offered an explanation as to how the airways could help produce multiphonics. He predicted that the airways could stabilize an oscillation if they have strong resonance peaks that are harmonically aligned with the resonance peaks of the instrument. The indirect measurement of Z_u for multiphonics will test this prediction.

6.1 *The Indirect Measurement of Z_u for Multiphonics*

For normal tones, Z_u was calculated from the continuity of flow equation (Equation 1.31) only at harmonic frequencies since noise in the pressure spectra gives invalid results at nonharmonic frequencies. Since multiphonics are biperiodic, phase-locked oscillations, an appropriate fundamental frequency had to be chosen so that a relatively noise-free Z_u could be calculated at multiples of this fundamental frequency. As noted in Section 1.1.8, Keefe and Laden [51] found that the pressure spectra of multiphonics actually have a single fundamental basis frequency f_o, and the two oscillation frequencies are integer multiples of f_o. Therefore, Z_u was calculated at multiples of this basis frequency f_o. The basis frequency was calculated by a least squares fit to the peaks in the mouthpiece pressure spectrum up to 2000 Hz for each overlapping 32768-sample section. For some sections there was no clear minimum in the least squares error function because there was no basis frequency that produced a good fit with all the pressure peaks. This is possibly due to the unsteadiness of those particular sections.

The upstream impedance Z_u was calculated from Equation 2.4 using cross-spectral averaging (see Section 2.2.3). Cross-spectral averaging was necessary because without it the results were noisy, either due to unsteadiness in the tone, or to the fact that Z_u was calculated at multiples of a small basis frequency (less than 50 Hz), and one or both of the pressure spectra were often in the noise at these frequencies. For each 32768-sample (0.74 second) section of the pressure time series, the spectra of 16 non-overlapping 2048-sample sections was averaged, and Z_u was calculated from the continuity of flow equation at integer multiples of the fundamental frequency of the 32768-sample section.

6.2 Results

The results from three multiphonics will be presented. One was played at a low dynamic level, and its mouthpiece pressure waveform had a small amplitude. It is an example of one of the less "nonlinear" multiphonics, and it should be appropriate to use the linear continuity of flow equation to measure Z_u indirectly. The other two multiphonics were both played with the same fingering. Since the instrument impedance remained constant, the performer must have been making changes, either with the embouchure or the airways, that produced the different pitches.

6.2.1 A Soft and Clear Multiphonic

This multiphonic was played at a low dynamic level and had a clear timbre. The fingering used was that for $A\sharp 5$, using the right-hand side key. The audible pitches were approximately the written pitches $F\sharp 4$ and $A\sharp 5$, and this multiphonic will be designated $F\sharp 4\&A\sharp 5$.

Figure 6.1 shows a portion of the mouthpiece pressure waveform. The peak-to-peak amplitude was less than 1500 Pa. Although the pressure variation, and probably also the reed motion, is more complex than for normal tones, it is assumed that it is appropriate to use the linear continuity of flow equation due to the very low amplitude.

Figure 6.2 shows the mouthpiece and mouth pressure spectra for one 32768-sample section of the pressure time series. In the mouthpiece spectrum (Figure 6.2-a), there were two main peaks at 320.3 Hz and 831.7 Hz with magnitudes of about 140 dB. These correspond to the two audible tones $F\sharp 4$ and $A\sharp 5$, which have fundamental frequencies of 329.6 Hz and 830.6 Hz. There were several other peaks about 100 dB in magnitude corresponding to sum and difference components of the two main peak frequencies. In the mouth pressure spectrum (Figure 6.2-b), the largest peak was the one at 320.3 Hz, but it was 20 dB lower than in the mouthpiece. The next largest peak was at 1152.0 Hz, and it was about 5 dB higher than in the mouthpiece. The noise floor was fairly low in both the mouth and the mouthpiece and was only about 10 dB higher than the noise during a measurement of silence. In the mouthpiece, the noise floor rose slightly around the two largest peaks, and in the mouth the noise floor was flat, except for a rise at low frequencies, which was a characteristic of the transducer.

The peaks in the mouthpiece pressure spectrum (Figure 6.2-a) were fit to multiples of a basis frequency f_o using a least squares optimization. The upstream impedance was then measured indirectly at multiples of the basis frequency. For the data shown, the peak frequencies were well-described as multiples of the basis frequency $f_o = 18.88$ Hz. Figure 6.3 shows the same mouthpiece pressure spectrum, up to 1000 Hz, with vertical dashed lines at multiples of f_o. All of the main peaks are aligned with a harmonic of f_o, and there is a tiny peak at f_o itself. The frequencies of the two main peaks (320.3 Hz and 831.7 Hz) are 16.97 and 44.05 times f_o, respectively, and therefore their ratio is approximately $17 : 44$. The two main frequencies are in a ratio of integers, and the two oscillations are phase-locked.

The upstream impedance Z_u was measured indirectly for the data in Figure 6.2 at multiples of $f_o = 18.88$ Hz. Figure 6.4 shows the magnitude and phase of the upstream and downstream impedances. The solid curve is the downstream (instrument) impedance Z_d for this fingering, and the shaded dots are the upstream impedance Z_u at multiples of f_o. The grayscale density shading of each dot represents the coherence calculated at that frequency, from the cross-spectral averaging calculation. A value of $C = 0$ (pure noise) is shown as white, and a value of $C = 1$ (no noise) is shown as black. Intermediate values are scaled linearly. Only points that are black or near-black are considered noise-free. The solid vertical lines are at the frequencies of the eight largest peaks in the upstream and downstream pressures shown in Figure 6.2. The coherence was high at all eight pressure peak frequencies, as well as in a small frequency range above and below each peak frequency.

The instrument impedance had three peaks in this frequency range at 360 Hz, 850 Hz, and 1380 Hz. The two lowest-frequency peaks supported the fundamental frequencies of the two audible tones and were positioned slightly higher in frequency than the largest peaks in the mouthpiece pressure spectrum. The third Z_d peak at 1380 Hz was slightly higher in frequency than the pressure peak at 1341.8 Hz.

The upstream impedance Z_u had a peak at 340 Hz of 40 CGS ohms, which was aligned with the first Z_d peak. The phase of Z_u at this peak was larger than +90 degrees, which is unphysical. Both the magnitude and coherence of this peak were high, and it is not clear why the phase was in this range. There was a second, broad peak at about 1180 Hz of 70 CGS ohms, and it was larger than $|Z_d|$ at that frequency, which was about 30 CGS ohms. At this peak, Z_u and Z_d were 150 degrees out of phase, which mostly cancelled out this peak. At the third Z_u peak at 1380 Hz, Z_u was equal in magnitude to Z_d, and they were in phase. The two impedances will add constructively at this frequency.

In this and the other multiphonics, all main Z_u peaks had high coherence (C) values, usually below the peak frequency. A high value of the coherence is expected when both the upstream and downstream pressures have a low level of noise, that is, at the peaks in the pressure spectra. The high-C data points tend to be below the Z_u peaks because large pressure peaks (which give the high C values) occur below the peaks of $(Z_u + Z_d)$ due to the presence of the reed (Benade [8]).

The theory predicts that the peaks of the sum $(Z_u + Z_d)$ determine the oscillation, and these peaks should be in harmonic alignment. It is therefore appropriate to examine $(Z_u + Z_d)$ rather than the two impedances separately. Figure 6.5 plots the magnitude and phase of the sum $(Z_u + Z_d)$ and Z_d alone. The grayscale density again corresponds to the coherence of Z_u at that frequency. The total impedance $(Z_u + Z_d)$ had peaks at the three Z_d peaks. The two peaks in $(Z_u + Z_d)$ aligned with the two lowest-frequency Z_d peaks at 360 Hz and 850 Hz. The total impedance was almost unchanged from Z_d since $|Z_u|$ was much less than $|Z_d|$ at these frequencies. The peak in $(Z_u + Z_d)$ at 1380 Hz was actually larger than both the Z_u peak and the Z_d peak. At this frequency there was a peak in both Z_u and Z_d, and they were in phase with each other. The two peaks added constructively to form a peak of 450 CGS ohms, twice as large as the Z_u and Z_d peaks alone. This peak at 1380 Hz was in harmonic alignment with the other two large $(Z_u + Z_d)$ peaks. If the frequencies of the two lowest-frequency peaks are designated f_1^z and f_2^z (the superscript z signifies a peak frequency of impedance rather than pressure), then the third peak is close to the combination $2f_2^z - f_1^z = 1340$ Hz. This strong impedance peak can support the pressure peak at 1341.8 Hz.

This multiphonic had three large peaks in $(Z_u + Z_d)$, of about equal magnitudes, at frequencies f_1^z, f_2^z, and $2f_2^z - f_1^z$. The upstream impedance Z_u had only a small peak at f_1^z, but a large peak at $2f_2^z - f_1^z$. At this frequency Z_u and Z_d were equal in phase and magnitude, and the two peaks added together constructively to form a stronger peak.

6.2.2 Two Multiphonics with the Same Fingering

The upstream impedance was measured indirectly for two different multiphonics played with the same fingering: that of $E3$, the lowest tone on the clarinet. Since the instrument impedance Z_d stays constant, the performer must be changing Z_u or the reed parameters, via embouchure adjustments, to produce different pitches. The measurement of Z_u will show if Z_u is different for these two multiphonics, and if these differences can account for the tones produced.

Each multiphonic had a loud and raucous timbre, and there were two tones audible: $E3$ (fundamental frequency 146.8 Hz) and one other tone. For one, the second tone was $G5$ (fundamental frequency 698.5 Hz), and this multiphonic will be designated $E3\&G5$. For the other, the second tone was $C6$ (fundamental frequency 932.3 Hz), and it will be designated $E3\&C6$.

Both of these multiphonics had complex waveforms. Figure 6.6 shows a portion of the mouthpiece pressure waveform for $E3\&G5$. The peak-to-peak amplitude was about 6000 Pa, much larger than the waveform amplitude for the soft multiphonic, and the dips at negative pressures were jagged.

Figure 6.7 shows the mouthpiece and mouth pressure spectra for $E3\&G5$ for one 32768-sample section. The harmonic structure was richer than for the soft and clear multiphonic, and the noise floor was about 20 dB higher. In the mouthpiece (Figure 6.7-a), the two largest peaks were at 149.4 Hz and 703.9 Hz, corresponding to the fundamental frequencies of $E3$ and $G5$. The largest peaks in the mouth pressure, however, were at 854.6 Hz and 1004 Hz (Figure 6.7-b). If the two main mouthpiece peaks are at $f_1 = 149.4$ Hz and $f_2 = 703.9$ Hz, then these mouth pressure peaks correspond to the intermodulation components $f_1 + f_2 = 853.3$ Hz and $2f_1 + f_2 = 1002.7$ Hz. The noise floor in the mouthpiece was fairly flat, with a slight decrease above 1000 Hz. The noise floor in the mouth had a broad hump centered at 300 Hz and an even broader hump centered at about 900 Hz, where the two largest pressure peaks were located.

The basis frequency calculated from the mouthpiece pressure spectrum was $f_o = 14.98$ Hz. With this basis frequency as a common factor, the two largest mouthpiece peak frequencies were in a ratio of 9.97 : 46.99, or approximately 10 : 47.

Figure 6.8 shows $(Z_u + Z_d)$ and Z_d for the data in Figure 6.7. Z_u was measured indirectly at multiples of the basis frequency. The total impedance (Figure 6.8-a) differed from the instrument impedance over much of the frequency range. This was in contrast to the soft and clear multiphonic, where the upstream impedance modified the total impedance at only a single peak. For $E3\&G5$, there was a large peak at 315 Hz, a smaller peak at 610 Hz, and a cluster of peaks in the range 900–1500 Hz. There were peaks at 900 Hz, 1050 Hz, 1130 Hz, and 1325 Hz. Two of the Z_d peaks that remained unchanged at 190 Hz and 710 Hz supported the fundamental frequencies of $E3$ and $G5$. These impedance peak frequencies will be denoted $f_1^z = 190$ Hz and $f_2^z = 710$ Hz. The peak in $(Z_u + Z_d)$ at 315 Hz was near the combination $f_2^z - 2f_1^z = 330$ Hz. The small $(Z_u + Z_d)$ peak at 610 Hz was slightly above $3f_1^z = 570$ Hz. The broad peak at 900 Hz was aligned with $f_1^z + f_2^z = 900$ Hz. The small peak at 1050 Hz was at $2(f_2^z - f_1^z) = 1040$ Hz. The broad peak at 1130 Hz was just below $2f_1^z + f_2^z = 1090$ Hz. The peak at 1325 Hz was closest to the combination $3f_1^z + f_2^z = 1280$ Hz. All of the peaks in $(Z_u + Z_d)$ that show a large difference from Z_d, due to the effect of the upstream impedance Z_u, were near linear combinations of the two instrument modal frequencies of the audible tones.

The phase of $(Z_u + Z_d)$ (Figure 6.8-b) was often outside of ±90 degrees, even for points that had high coherence and were at peaks in the magnitude. The phase was well-behaved at the peak frequencies 315 Hz, 610 Hz and 900 Hz. At these peaks the phase crossed zero, but with positive slope.

Figure 6.9 shows the mouthpiece and mouth pressures for the other multiphonic played with this fingering, $E3\&C6$. In the mouthpiece (Figure 6.9-a), the three largest pressure peaks were at 148.0 Hz, 442.8 Hz, and 927.3 Hz. These frequencies correspond to the fundamental frequencies of the tones $E3$ (146.8 Hz), $B4$ (440.0 Hz), and $C6$ (932.3 Hz). The loudest peaks in the mouth pressure spectrum (Figure 6.9-b) were at 1075.3 Hz and 1222.0 Hz. If the two largest mouthpiece pressure peaks are $f_1 = 148.0$ Hz and $f_2 = 927.3$ Hz, then the mouth pressure peaks correspond to the intermodulation components $f_1 + f_2 = 1075.3$ Hz and $2f_1 + f_2 = 1223.3$ Hz. The level of the noise floor was about the same as for $E3\&G5$. There was only a slight enhancement of the noise floor in the mouth at 300 Hz, and the broader hump in the mouth pressure was shifted up in frequency so that it was centered at about 1100-1200 Hz.

The basis frequency calculated from the mouthpiece pressure spectrum in Figure 6.9-a was $f_o = 21.07$ Hz. With this basis frequency, the three main mouthpiece pressure peaks are in the ratio 7.02 : 21.02 : 44.01. The second peak is clearly the third harmonic of the first peak, so that the two main components generating the sum and difference frequencies are at 148.0 Hz and 927.3 Hz.

Figure 6.10 shows the total impedance $(Z_u + Z_d)$ and the instrument impedance Z_d for $E3\&C6$. The total impedance magnitude (Figure 6.10-a) for this multiphonic was different from that for $E3\&G5$. The strong peak for $E3\&G5$ at 300 Hz was much lower. The strong, broad peak at 900 Hz was gone, but instead there was another broad peak at 1115 Hz. The peak for $E3\&G5$ at 1325 Hz was split into two peaks for $E3\&C6$ at 1285 Hz and 1380 Hz.

The two impedance peaks supporting the fundamental frequencies of $E3$ and $C6$ were at 190 Hz and 940 Hz and the upstream impedance had very little effect at these frequencies. If these two frequencies are designated $f_{\bar{1}} = 190$ Hz and $f_{\bar{2}} = 940$ Hz, then the peak at 1115 Hz aligned with $f_{\bar{1}} + f_{\bar{2}} = 1130$ Hz. The two narrower peaks at 1285 Hz and 1380 Hz did not clearly align with any combination, but they were closest to $-3f_{\bar{1}} + 2f_{\bar{2}} = 1310$ Hz and $2f_{\bar{1}} + f_{\bar{2}} = 1320$ Hz.

As with $E3\&G5$, the phase of $(Z_u + Z_d)$ (Figure 6.10-b) was often outside of ± 90 degrees for data points with high coherence and large magnitude. The phase was well-behaved at the peak at 1115 Hz, where it crossed zero with positive slope.

6.3 Discussion

The soft and clear multiphonic was produced by an airway resonance at a linear combination of the instrument resonances supporting the two individual tones.

The instrument impedance had peaks at frequencies f_1^z and f_2^z, and the upstream impedance had a peak at the frequency $2f_2^z - f_1^z$, which also happened to be where another Z_d peak was positioned. Since the Z_u and Z_d peaks were in phase at this frequency, they added together constructively to form a strong impedance peak that supported an intermodulation component of the two main frequencies.

The total impedance $(Z_u + Z_d)$ was different for the two multiphonics played with the same fingering. Since Z_d stayed constant, the difference was due to the performer adjusting the airway shape to change Z_u. The multiphonic $E3\&G5$ had large peaks in $(Z_u + Z_d)$ at $f_2^z - 2f_1^z = 330$ Hz and at $f_1^z + f_2^z = 900$ Hz, where f_1^z and f_2^z are the frequencies of the instrument modes supporting $E3$ and $G5$, respectively. There were broad humps in the mouth pressure spectra at each of these frequencies. For the multiphonic $E3\&C6$, the peak in $(Z_u + Z_d)$ at 300 Hz was much lower, and there was a large peak at 1115 Hz, which aligned with $f_1^z + f_2^z$, where f_1^z and f_2^z are the frequencies of the instrument modes supporting $E3$ and $C6$. For $E3\&C6$ there was only a slight enhancement of the mouth pressure noise floor at 300 Hz. There was still a broader hump centered at 1100–1200 Hz, aligned with the peak in $(Z_u + Z_d)$.

In order to produce two different multiphonics with the same fingering, the performer is shifting airway resonances to favor one or the other set of pitches. When playing $E3\&G5$, there is a large Z_u peak at $f_2^z - 2f_1^z = 330$ Hz and another Z_u peak at $f_1^z + f_2^z = 900$ Hz. The function of both peaks is to couple the two oscillation frequencies together so they can exist simultaneously. The peak at 900 Hz has a second function, which is to detune the Z_d peak at 940 Hz. This Z_d peak supports the tone $C6$, which is not involved in the multiphonic $E3\&G5$. By positioning a Z_u peak just below this Z_d peak, the $C6$ oscillation is weakened and the joint oscillation of $E3$ and $G5$ is strengthened.

By shifting the airway resonances, the performer can produce the tone $C6$ instead of $G5$. For the multiphonic $E3\&C6$, there is no longer a strong peak at 300 Hz or at 900 Hz. The disappearance of the peak at 900 Hz allows the nearby Z_d peak at 940 Hz to support $C6$. In addition, there is a large peak at 1115 Hz which, as for $E3\&G5$, is aligned with the combination $f_1^z + f_2^z$. By shifting an upstream resonance from 900 Hz to 1115 Hz, the performer can change the pitch of the tone that sounds. This shift of airway resonances is evident in the mouth pressure spectra. The broad hump shifts from about 900 Hz for $E3\&G5$ to about 1100 Hz for $E3\&C6$. The analysis of Section 4.2 showed that instrument impedance peaks for normal tones are often associated with peaks in the mouthpiece noise floor. The multiphonics analyzed here also appeared to have upstream impedance peaks associated with broad humps in the mouth pressure noise floor.

Benade suggested that performers produce multiphonics by positioning an airway resonance at the frequency of one of the instrument resonances supporting one of the tones, and then the nonlinear reed mechanism produces the sum and difference components in the pressure spectra through heterodyne interactions between the two fundamental frequency components. For the multiphonics studied here, the airway resonances were not aligned with the instrument modes supporting the fundamental frequencies of the tones, but rather the airway resonances were positioned at linear combinations of the instrument modal frequencies. Rather than strengthening one of the tones, the airways were in fact supporting an oscillation at a combination frequency. In other words, the instrument supported the two tones individually, and the performer provided the coupling that allowed both tones to exist simultaneously.

The use of a linear systems model in the continuity of flow equation to measure Z_u indirectly for multiphonics is not necessarily appropriate since they are highly nonlinear phenomena. For the multiphonics studied here, the phase of Z_u was often outside of ± 90 degrees, even for the low-amplitude multiphonic. When the phase did take on these unphysical values, they could not always be explained by low coherence or low magnitude. The phase took on values greater than +90 degrees and less than -90 degrees, in contrast to normal tones, for which the phase was only greater than +90 degrees, when it went outside this range. However, there did not appear to be any obvious problems with the magnitude of Z_u. Therefore, the indirect measurement may still be used to measure $|Z_u|$ for multiphonics, and the mouth pressure spectrum may be used to confirm peaks in $|Z_u|$ since peaks in the mouth pressure noise floor appear to be associated with upstream impedance peaks.

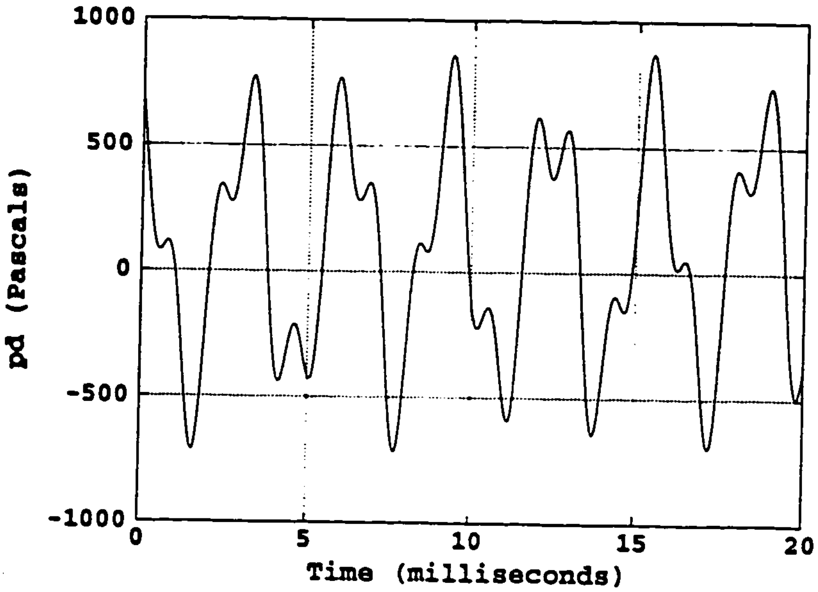
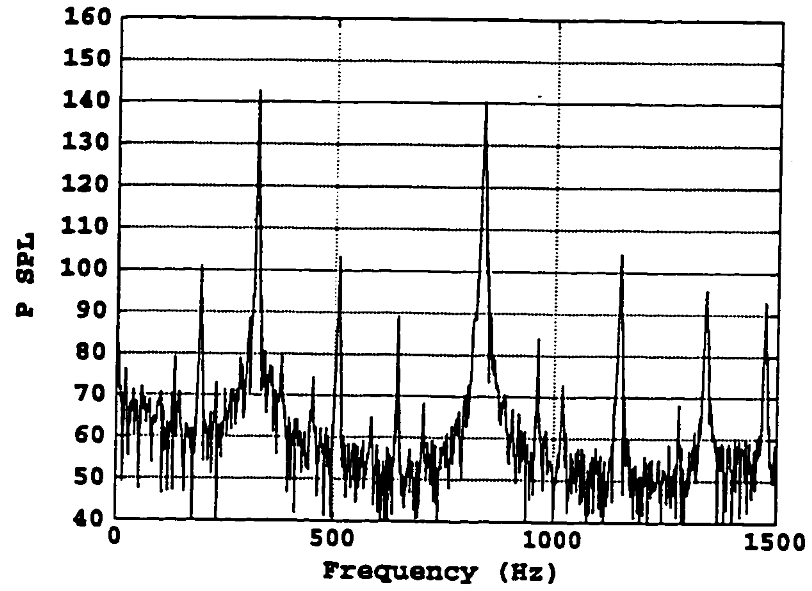
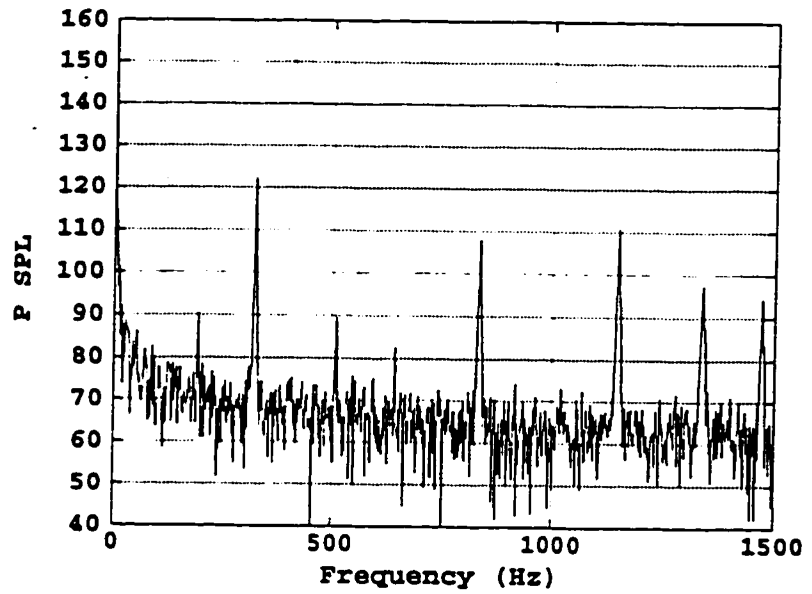


Figure 6.1: p_d waveform for $F\sharp 4 \& A\sharp 5$.



(a) Mouthpiece pressure, p_d.



(b) Mouth pressure, p_u.

Figure 6.2: Mouthpiece and mouth pressures for $F\sharp4\&A\sharp5$.

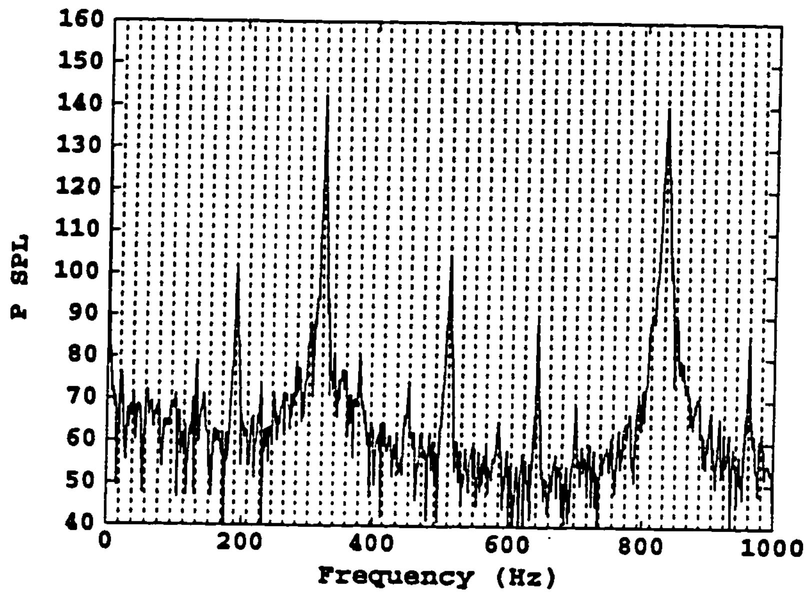
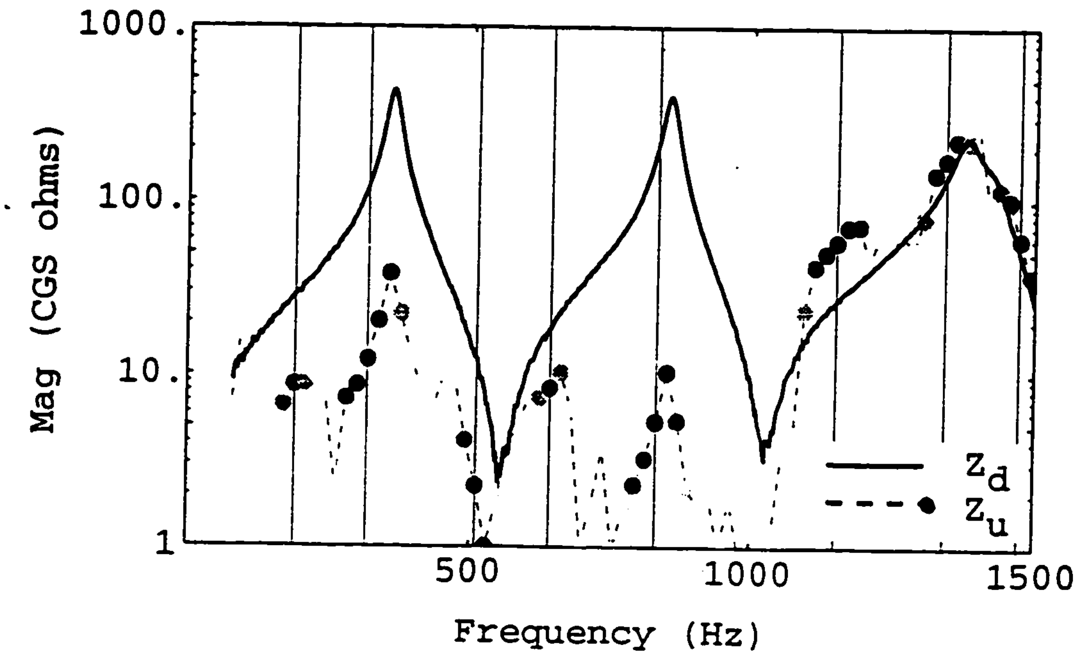
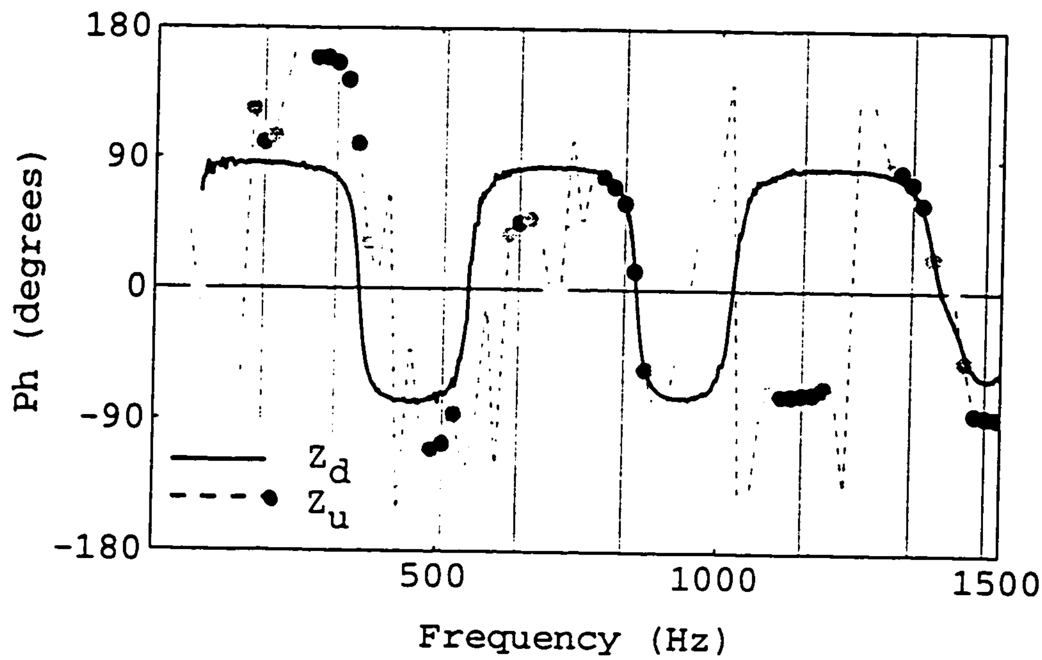


Figure 6.3: Upstream pressure spectrum for one 32768-sample section of $F\sharp4\&A\sharp5$. The dashed vertical lines are at multiples of the basis frequency f_o = 18.88 Hz.

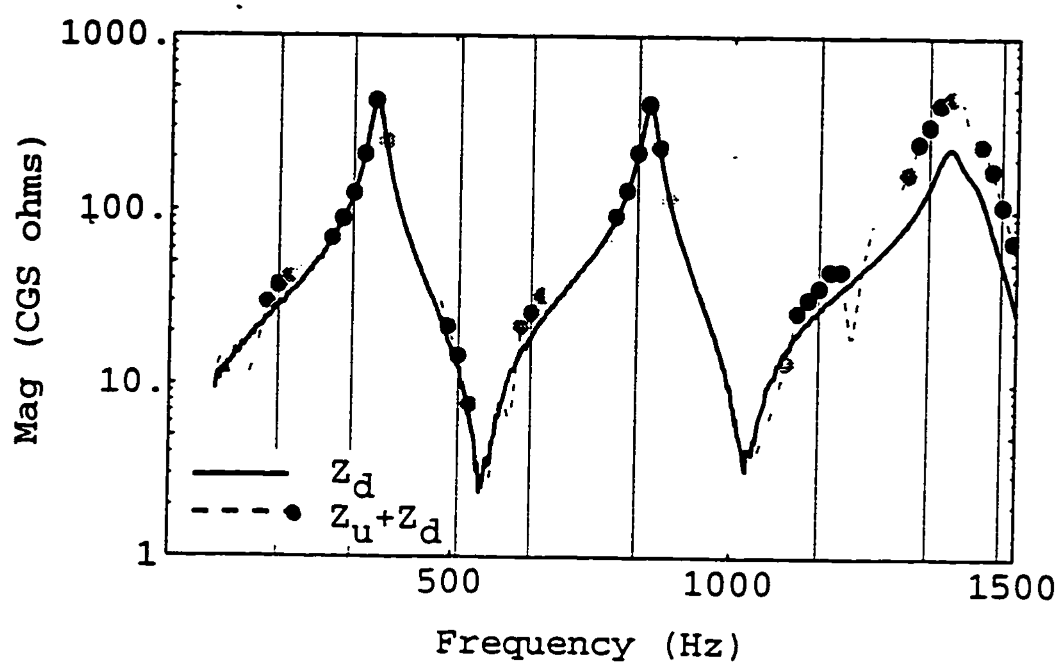


(a) Magnitude.

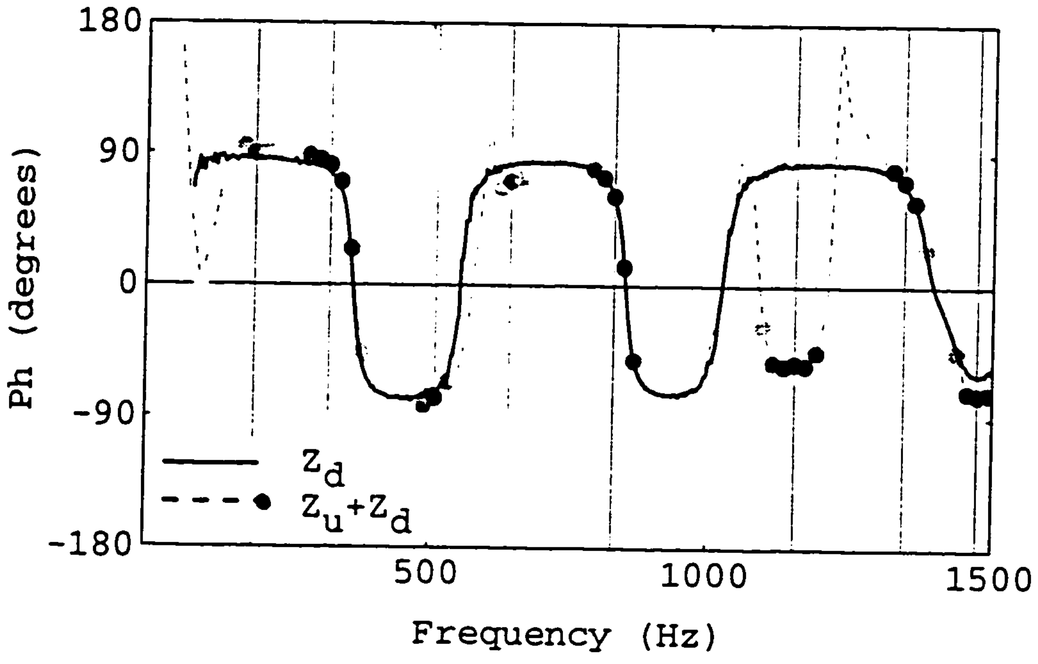


(b) Phase.

Figure 6.4: Z_u and Z_d for $F\sharp4\&A\sharp5$.



(a) Magnitude.



(b) Phase.

Figure 6.5: $(Z_u + Z_d)$ and Z_d for $F\sharp4\&A\sharp5$.

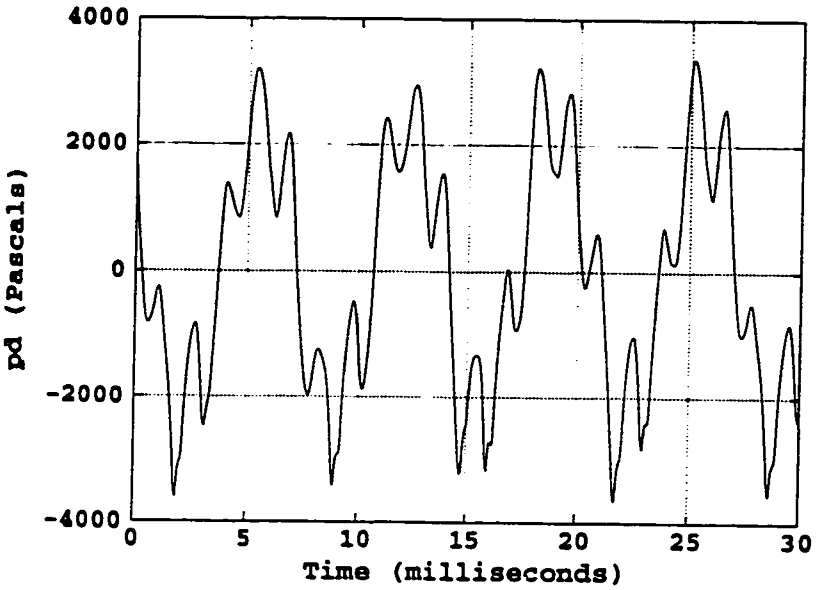
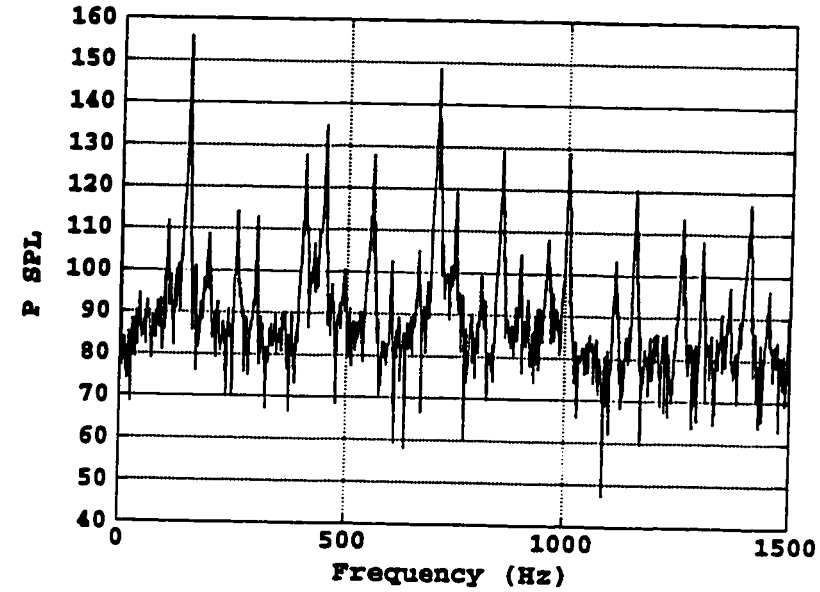
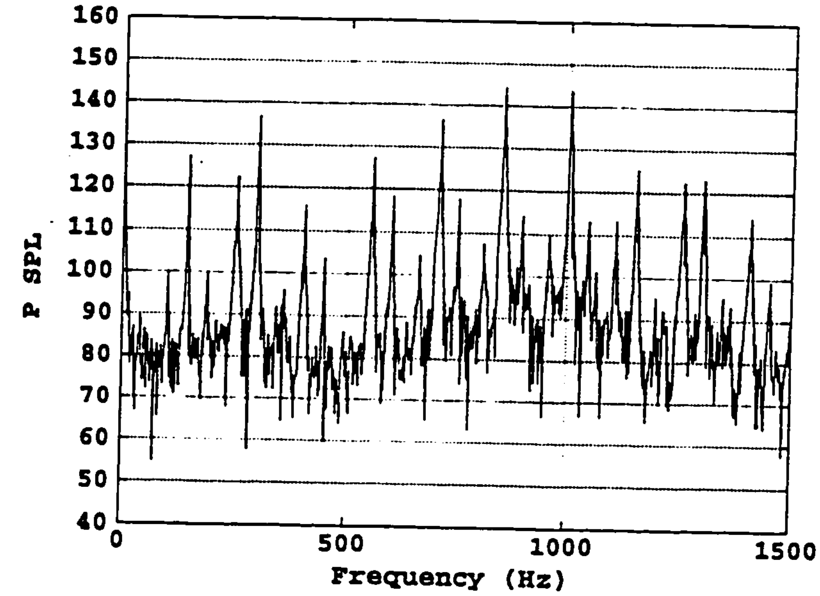


Figure 6.6: p_d waveform for $E3\&G5$.

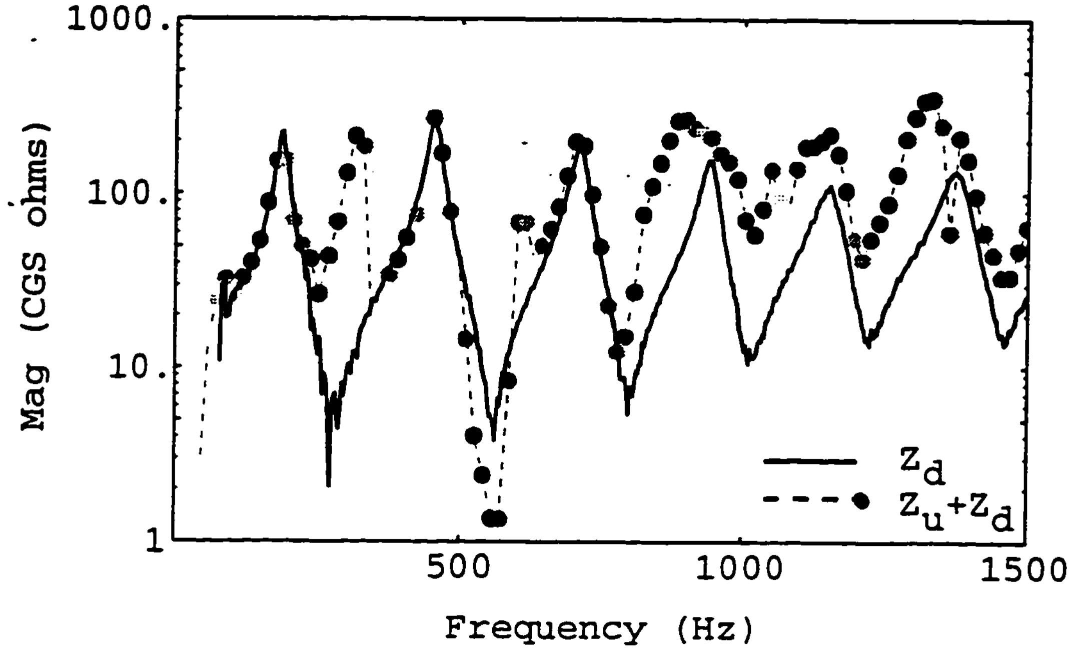


(a) Mouthpiece pressure, p_d.

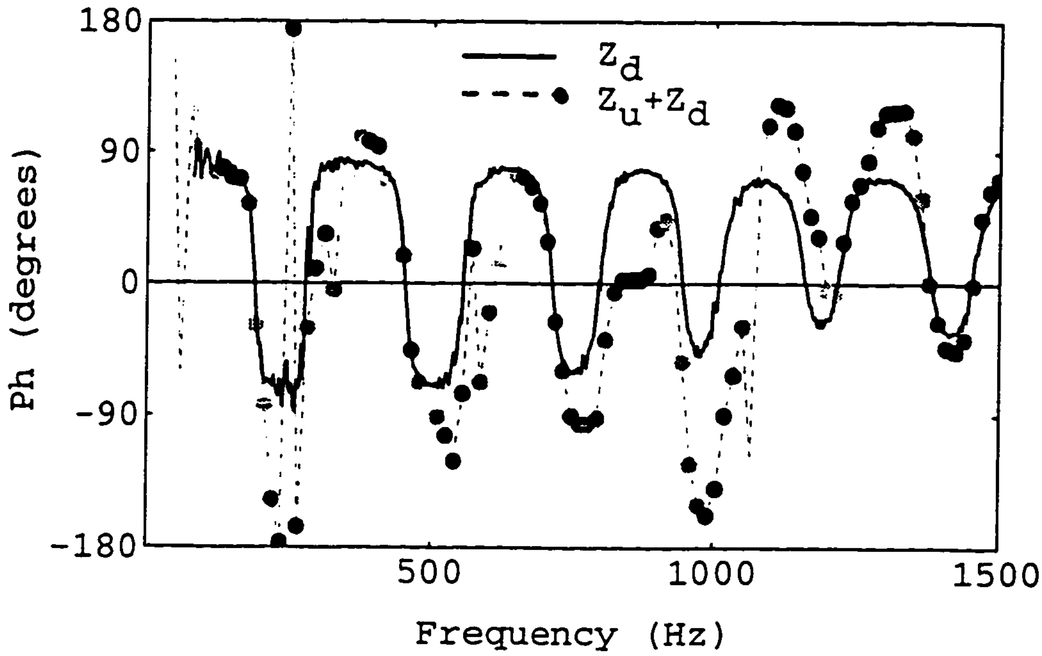


(b) Mouth pressure, p_u.

Figure 6.7: Mouthpiece and mouth pressures for $E3\&G5$.

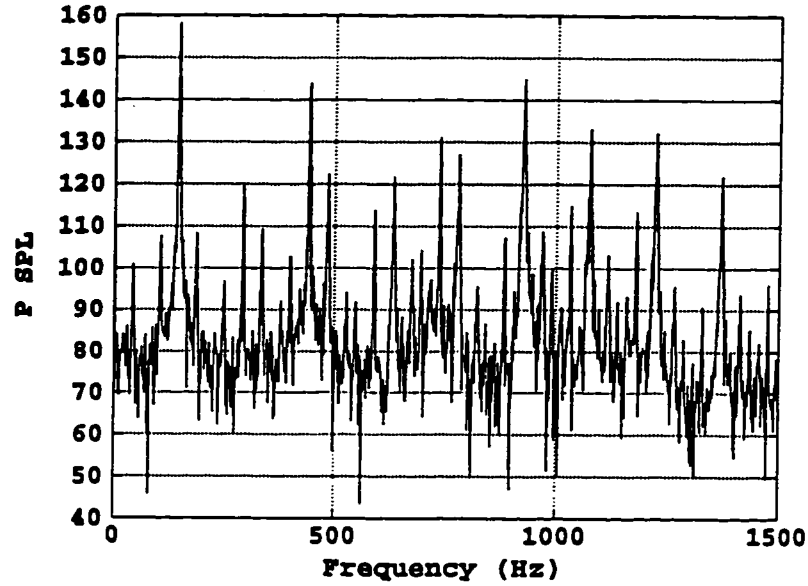


(a) Magnitude.

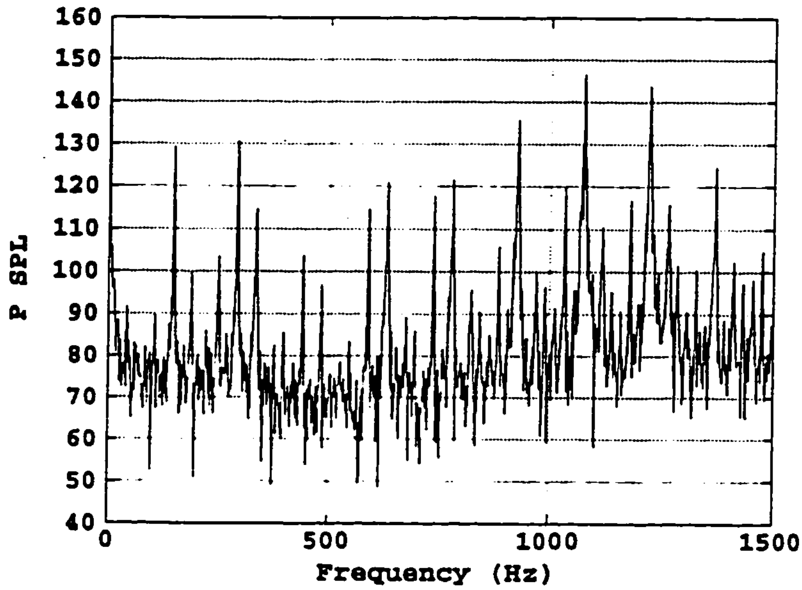


(b) Phase.

Figure 6.8: $(Z_u + Z_d)$ and Z_d for $E3\&G5$.

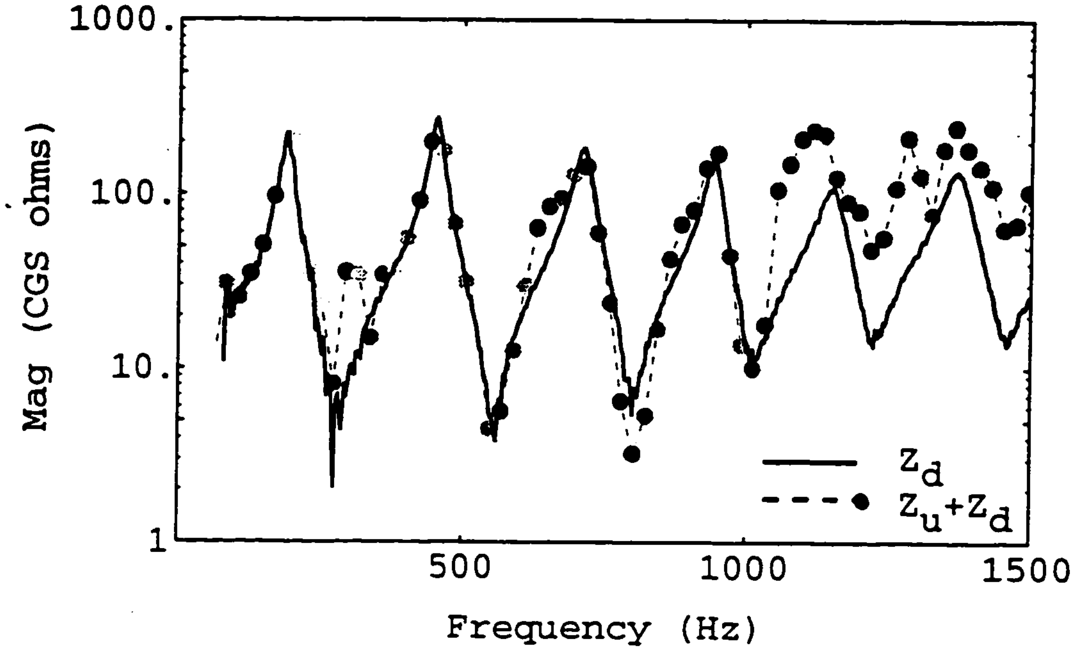


(a) Mouthpiece pressure, p_d.

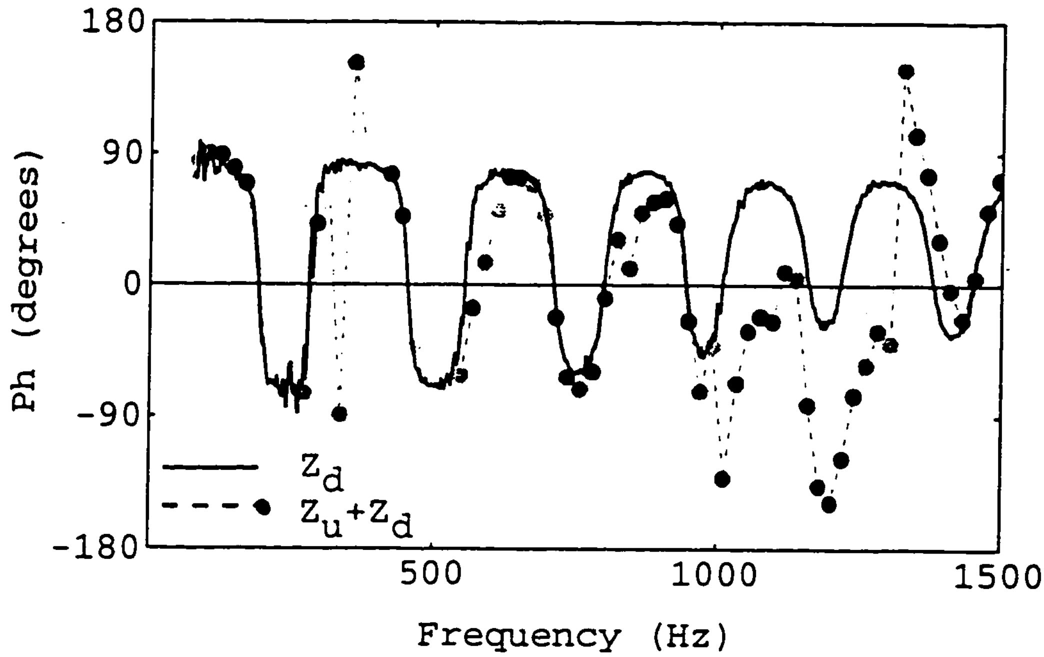


(b) Mouth pressure, p_u.

Figure 6.9: Mouthpiece and mouth pressures for $E3\&C6$.



(a) Magnitude.



(b) Phase.

Figure 6.10: $(Z_u + Z_d)$ and Z_d for $E3\&C6$.

Chapter 7

RESULTS: UPSTREAM IMPEDANCE DURING THE PERFORMANCE OF MUSICAL EXCERPTS

The advantage of using the indirect method of measuring the upstream impedance is that it becomes possible to study the upstream impedance during performance. Z_u can be calculated as a function of time and the upstream resonances can be indirectly tracked in a musical context.

Musical excerpts can be used to study the function of the airways in a musical context. The theory that Z_u resonances should be aligned with harmonic frequencies can be tested in a musical context. and the variation of this alignment with musical context can be studied. Musical excerpts can tell us how the performer uses the airways to create a musical phrase and how or if this differs from the performance of isolated tones. The connection between the airways and musicality can be studied by examining the upstream impedance and how it is related to musical elements such as pitch, tone duration, articulation, and the beginning and end of phrases. The changes that the performer makes to the airways when playing intervals and how these changes are related to the interval characteristics could give information on how the performer changes registers or creates a smooth legato.

Since a musical excerpt consists of tones that are changing, often at a fast rate, the performer may alter the vocal tract from tone to tone in a way that creates conditions that stabilize each tone. According to the theory, a performer should create an upstream resonance that enhances a pressure harmonic of a tone, but since the harmonic frequencies are different for different pitches, the performer should be adjusting the upstream resonances as the pitch changes. The examination of pairs of tones, or intervals, will tell us how the performer is making these adjustments.

The theory does not give any detailed predictions on how well upstream resonances should be aligned for optimal playing conditions. Musical excerpts will give information on how closely the performer must align airway resonances with harmonic frequencies in order to produce an acceptable tone, and how or if this variability is used to create a musical performance.

7.1 The Excerpts

The performer (C), a symphony clarinetist, was asked to choose short excerpts in which the vocal tract plays an important role. The three excerpts chosen are listed in Table 7.1. The scores for these excerpts are shown in Figures 7.1–7.3. Both the mouth and mouthpiece (position 1) pressures were measured simultaneously while the performer played each excerpt. Later, the instrument impedance was measured for each fingering that appeared in the three excerpts. The approximate tempo that the performer used is given at the beginning of each excerpt in Figures 7.1–7.3. Any dynamic or phrasing changes made by the performer in addition to those already in the score are noted in parentheses. Although instructed not to tongue in order to prevent the tongue from touching the mouth pressure transducer, the performer did tongue some tones and these are marked with "T". Some tones in the Beethoven excerpt had an audible undertone in the mouthpiece pressure recording and these are marked with "U". The performer unintentionally squeaked on one tone in the Beethoven, and this is marked. The last tones of the Debussy and Brahms excerpts were cut off by the end of the recording.

The individual tones in the excerpts will be referenced by a label such as $8 - D\flat5$, denoting the eighth tone in an excerpt, which is a written $D\flat5$.

The Debussy excerpt extended from the mid-chalumeau up to the first tone in the altissimo range, but was for the most part in the clarion register. The Brahms excerpt covered a narrow range, from the upper chalumeau to the lower clarion. The Beethoven excerpt covered the upper clarion and altissimo registers.

The performer (C) stated that the reason for choosing all three of these excerpts was that they have difficult intervals that require the use of the vocal tract, although C did not know exactly what the vocal tract was doing. C said that the Beethoven excerpt involves "gymnastics" in playing the intervals. The difficulty in the Debussy was the intervals from the mid-range (clarion) to the high register, and C thought about "floating" when playing this excerpt. C stated that the difficulties of the Brahms excerpt include going over the break (i.e., crossing between the chalumeau and clarion registers) and keeping a smooth legato. The intervals were smaller than in the Debussy, but going over the break made it difficult playing $A4 \rightarrow B4$ and especially $A4 \rightarrow E5$ at the end, and C thinks of changing the air speed.

7.2 Methodology

The upstream impedance Z_u was calculated from Equation 1.31 for consecutive 4096-sample (0.1 second) sections of the pressure time series for the Debussy excerpt and for consecutive 2048-sample (0.05 second) sections for the Brahms and Beethoven. The sections were overlapped by one-half the section length, in order to increase the time resolution. Shorter sections were necessary for the Brahms and Beethoven since the tone durations were shorter. Z_u was calculated for each tone in an excerpt at integer multiples of the fundamental frequency of each 4096- or 2048-sample section of that tone. The sections of the pressure time series containing the initial and final transients of each tone were omitted from the analysis, but an attempt was made to include as much of the tone itself as possible, as long as a fundamental frequency could be calculated for each section.

The 65-tone data set consisting of all tones in the three excerpts was analyzed to determine if $|Z_u|$ was large at harmonic frequencies for single tones and if $|Z_u|$ remained constant or changed level during the duration of the tone. These tones were examined for similarities due to pitch, tone duration, and excerpt of origin. Tones at the beginning and ending of phrases and tongued tones were examined to see if these musical features influenced the airway behavior. Isolated tones played by the same performer were compared to those in the musical excerpts to see if the airways were used differently in a musical context.

The manner in which Z_u changed was compared for tone pairs that occurred more than once in order to determine if the performer changed the airways in a consistent fashion, which may be dependent upon the musical context. Both ascending and descending tone pairs with the same pitches were examined to determine if the Z_u changes were reciprocal, i.e., did the performer play a descending interval by using the airway adjustments of the ascending interval in reverse? Finally, intervals between two different registers were examined for differences according to type of register change and whether the interval was ascending or descending. These intervals are often the most difficult to play, and the changes in the upstream impedance during these intervals could tell why.

7.3 Results

Single tones will be discussed first in order to determine if the performer aligns an upstream resonance with a harmonic frequency, as predicted by the linear regeneration theory. This analysis will also provide an opportunity to study how the performer uses the airways for a single tone in different musical situations. Then, the analysis of pairs of consecutive tones (intervals) will investigate how the upstream impedance changes across intervals, which was the main difficulty of the excerpts, according to the performer. Finally, the relationship between some musical features of the excerpts and the upstream impedance will be discussed.

7.3.1 Single Tones

Large Values of $|Z_u|$ at Harmonic Frequencies

The one theoretical prediction that can be applied directly to musical excerpts is that $|Z_u|$ should be large at one or more of the harmonic frequencies since this should stabilize the oscillation. The upstream impedance measured indirectly for the 65 tones of the excerpts was examined for large values of $|Z_u|$ at harmonic frequencies. The definition of "large" was somewhat arbitrarily set to mean "greater than 50 CGS ohms for most of the duration of the tone". The value of 50 CGS ohms was chosen because $|Z_u|$ does tend to stay under this value for the most part, so if it goes above this value, it appears to be large. The instrument impedance $|Z_d|$ is approximately 50 CGS ohms at the even harmonics and ranged from 400 to 1200 CGS ohms at the low-frequency odd harmonics. The definition of 50 CGS ohms or greater as a "large" value of $|Z_u|$ will mean that $|Z_u|$ is comparable to $|Z_d|$ at even harmonics, but still might be a small fraction of $|Z_d|$ at the odd harmonics. Once $|Z_u|$ becomes a significant fraction of $|Z_d|$, the airways should begin to have a noticeable influence, according to the theory.

Table 7.2 shows the (statistical) frequency distribution for the entire 65-tone data set of the harmonic frequencies at which $|Z_u|$ was large. Z_u stayed below 200 CGS ohms for all tones. $|Z_u|$ was large at the first harmonic for almost half of the tones, and it was large at both the first and second harmonics simultaneously for almost one-fourth of the tones. Twenty-two percent of the tones had $|Z_u|$ less than 50 CGS ohms at all harmonics. For these tones, the theory implies that they are stable enough with the Z_d resonances alone and do not need extra help from the airways, or that there is another stabilizing mechanism.

Table 7.3 shows the (statistical) frequency distribution of the harmonic with the largest $|Z_u|$, since in many cases $|Z_u|$ was large at more than one harmonic. For over half the tones, $|Z_u|$ was largest at the first harmonic. The next largest category was tones with no large values of $|Z_u|$. For the rest, either it was not clear or $|Z_u|$ was largest at the second harmonic.

Figure 7.4 plots the distribution of harmonics with large $|Z_u|$ listed in Table 7.2 as a function of pitch. The divisions between registers are indicated by dashed vertical lines. The position of the tones of written pitch class B are marked below the frequency axis. The four separate graphs plot the number of tones that had a large $|Z_u|$ at the indicated harmonic, as a percentage of the total number of tones of each pitch. The graphs are aligned vertically so that bars directly above and below one another correspond to the same pitch. The cut-off at $G5$ for the categories of the second harmonic and for the first and second harmonics is due to the frequency limitation of the indirect measurement of Z_u. For tones above this pitch, the second harmonic is above 1500 Hz, where the indirect measurement is not valid.

Some conclusions can be drawn from this graph, keeping in mind this frequency limitation. Tones with $|Z_u|$ large only at the first harmonic tended to be in the chalumeau, below the throat tones, and in the upper clarion and the altissimo registers, although these higher tones would have second harmonics above 1500 Hz, and so these harmonics would not be included in this graph. Tones with $|Z_u|$ large only at the second harmonic were in the clarion register, up to the frequency limit. Tones with $|Z_u|$ large at both the first and second harmonics were in the upper chalumeau and lower clarion registers, up to the frequency limit. Tones with no large values of $|Z_u|$ were mostly in the clarion register, with the exception of one chalumeau tone and one altissimo tone. This altissimo tone was the tone $16-E6$ of the Beethoven, during which the performer squeaked. This data point is atypical of normal performance.

These graphs indicate that the harmonics that have aligned Z_u resonances may be a function of pitch. Upper chalumeau tones have a large $|Z_u|$ at both the first and second harmonics. Clarion tones show a large variation, and there were tones that fell into all categories. The tones that had no large values of $|Z_u|$ were almost exclusively in the clarion register. Altissimo tones, with the exception of the squeaked tone, had $|Z_u|$ large at the first harmonic, although the higher harmonics of these tones were above of the valid frequency range of the indirect Z_u measurement.

Presumably this variation of Z_u with pitch is related to the different roles the airways must play in each register due to the different instrument mode configurations. To examine these variations in Z_u with pitch more closely, tones from the chalumeau and altissimo registers were analyzed in detail. One tone from each of these registers will be presented here to illustrate the results. Figure 7.5 plots Z_u averaged over the entire tone duration and Z_d for the tone $11 - F\#4$ from the Brahms, which is in the chalumeau register. Tones in this register tended to have a large value of $|Z_u|$ at the first and second harmonics. $|Z_u|$ (Figure 7.5-a) is one-fourth the value of $|Z_d|$ at the first harmonic, $|Z_u|$ exceeds $|Z_d|$ at the second harmonic and is nearly equal to $|Z_d|$ at the fourth harmonic. The phase of Z_u (Figure 7.5-b) is nearly equal to the phase of Z_d at the first and third harmonics, and so the sum $(Z_u + Z_d)$ will have the maximum possible magnitude. Figure 7.6 shows the results of the regeneration calculations for this tone. The parameters used in the calculations are those listed in Table 5.1, with a closing pressure of 6000 Pa. The effect of the upstream impedance was to lower $Re(Y)$ approximately 30% at the first harmonic and 90% at the fourth harmonic, decreasing energy dissipation at both frequencies. The change in $Im(Y)$ was negligible at the first and third harmonics, but $Im(Y)$ increased at both the second and fourth harmonics. This would improve the stability of the playing frequency in the nonlinear theoretical framework, since regeneration of even harmonics for the clarinet requires the inclusion of the nonlinearity in the theory. The upstream impedance tends to have a larger effect at the even harmonics because $|Z_d|$ is lower at those frequencies, and so $|Z_u|$ can become a relatively larger fraction of $|Z_d|$. Although the value of $|Z_u|$ was largest at the first harmonic, its effect was minimal because $|Z_d|$ was still large.

A similar analysis was done on altissimo tones, which tended to have a large value of $|Z_u|$ at the first harmonic. Figure 7.7 shows Z_u and Z_d for the tone $12 - D6$ of the Beethoven. $|Z_u|$ was about one-fourth the value of $|Z_d|$ at the first harmonic (1060 Hz), and the phases of Z_u and Z_d were equal at this frequency, so Z_u and Z_d added together for the maximum possible magnitude. Figure 7.8 shows the generator and dissipative admittances. The parameters used in the calculations are those listed in Table 5.1, with a closing pressure of 6000 Pa. The effect of Z_u was to lower $Re(Y)$ about 10% at the first harmonic, and there was no change in $Im(Y)$ at this frequency. Since $Re(-Y_G)$ is very close to $Re(Y_{dr})$ at this frequency, a large value of Z_u might be necessary to lower $Re(Y)$ enough so that the regeneration condition is fulfilled. However, there were many estimated parameters that went into the calculation of Y_G and Y, and these curves might not represent the true values of these quantities.

Harmonics with Changing $|Z_u|$

The harmonics at which $|Z_u|$ changes during a tone will give information about the frequency range of upstream resonances that can be shifted by changes in the airway configuration. Table 7.4 shows the (statistical) frequency distribution of the harmonic or harmonics at which $|Z_u|$ changed by more than 10 CGS ohms during a tone. In almost half of the tones, $|Z_u|$ changed at the first harmonic alone. In almost all the other tones, either $|Z_u|$ stayed fairly constant or $|Z_u|$ changed at both the first and second harmonics. Figure 7.9 plots the distribution of the harmonics at which $|Z_u|$ changed, shown in Table 7.4, as a function of pitch. The performer could change the first harmonic across the entire pitch range covered by the excerpts, and both the first and second harmonics up to the frequency limit of the indirect measurement. $|Z_u|$ at the second harmonic rarely changed alone. The tones that had no Z_u harmonics changing tended to be in the clarion register.

Consistency

Different tones of the same notated pitch and duration within an excerpt were examined to see if the performer consistently used the same Z_u. Figure 7.10 shows two instances of a $C6$ (fundamental frequency 932.3 Hz) eighth-note from the Beethoven excerpt that illustrate the typical degree of variation among tones of the same pitch and duration. Figure 7.10-a shows $5 - C6$, and Figure 7.10-b shows $11 - C6$. The graphs give $|Z_u|$ vs. time at the first harmonic for each tone. Higher harmonics were above the frequency limit of the indirect measurement. The time scale refers to the time position of the tones within the excerpt as the performer played them. The level of $|Z_u|$ for these two tones differed by about a factor of two, and it changed with time during both. Complicating the situation was the fact that there was a register change before $5 - C6$ and after $11 - C6$, so the performer could be making airway adjustments as a result. In any case, this example shows that the airways do not have to be in exactly the same configuration for every occurrence of the same tone. The performer has some leeway in the use of the airways, and the variability present might be related to the position of the tone in the musical context. In general, although there was some variation, tones of the same pitch and duration did tend to have general similarities.

Tone Duration

Tones of the same pitch, but different duration, within an excerpt were examined to see if the performer used a different Z_u for tones of different duration. As an example, Figure 7.11 shows $|Z_u|$ vs. time at the first harmonic for the tone $7 - C6$ from the Beethoven excerpt. This tone was one note of a sixteenth-note triplet and can be compared to the tones in Figure 7.10, which were the same pitch but were three times the duration. $|Z_u|$ at the first harmonic of $7 - C6$ was between the levels of $|Z_u|$ at the first harmonics of the tones in Figure 7.10. This example was typical of tones in the three excerpts. There was no significant difference between tones of the same pitch when the variable of tone duration was introduced.

Tones Compared between Excerpts

Tones of the same pitch but in different excerpts were compared to see if the performer's use of the airways depended upon the musical context. Figure 7.12 illustrates some of the largest differences found between tones of the same pitch in different excerpts. Z_u vs. time is shown for two instances of the tone $C6$ in the Debussy excerpt, which can be compared with the $C6$ tones from the Beethoven excerpt shown in Figures 7.10 and 7.11. The two tones from the Debussy excerpt were similar to each other. $|Z_u|$ at the first harmonic was low and steady for both tones. However, these two tones were significantly different from the Beethoven tones in Figures 7.10 and 7.11. The overall level of $|Z_u|$ at the first harmonic was lower for the Debussy tones, and it remained steady throughout the duration of the tone. Thus, while tones in the same excerpt are consistent with each other, tones in another excerpt can have different characteristics. This could be one way that a performer uses the airways to play different musical styles. The Debussy and the Beethoven excerpts represent two different musical styles, and the performer could be using the airways to produce a tone quality appropriate for each style. Although there are noticeable differences in the example shown here, as stated above they represent some of the largest differences, and in most cases tones of the same pitch in different excerpts were quite similar.

Articulation

Table 7.5 lists the tones in all three excerpts that were articulated, or tongued. For all the tones, $|Z_u|$ decreased at the beginning of the tone at one harmonic and at two harmonics for one tone. For example, Figure 7.13 plots $|Z_u|$ vs. time for $25 - F\sharp5$ (fundamental frequency 659.3 Hz) from the Beethoven excerpt. There was a sharp drop in $|Z_u|$ at the first harmonic at the beginning of the tone. The size and rate of the decrease varied among all the tones, and this is one of the more extreme examples. The frequencies of the harmonics at which $|Z_u|$ decreased were all in the frequency range 500–1100 Hz, and so it appears that tongue movement affects upstream resonances in this range. The decrease in $|Z_u|$ could be related to an increase in the airway diameter as the tongue withdraws. An increase in the airway diameter would lower the wave impedance and decrease the overall level of $|Z_u|$.

Tones at the Beginning and End of a Phrase

The beginning of a phrase is defined here as a tone after a breath, and the end of a phrase is defined as a tone before a breath, or at the end of an excerpt. Table 7.6 lists the tones that occurred at the beginning of a phrase. Figure 7.14 plots $|Z_u|$ vs. time for $1 - D5$ (fundamental frequency 523.3 Hz), the first tone of the Brahms excerpt, and shows the behavior typical of tones at the beginning of a phrase, although this was the most extreme case. They were characterized by a drop in $|Z_u|$ at the first harmonic, with little change at the other harmonics. For five of these tones, $|Z_u|$ at the first harmonic dropped immediately after the beginning of the tone or soon after, sometimes quite sharply. In one tone ($1 - B\flat4$ of Debussy), $|Z_u|$ at the first harmonic increased at the beginning of the tone and then dropped. It is not clear why this tone is different from the others, but the general trend is that $|Z_u|$ at the first harmonic decreases at the beginning of a phrase.

Table 7.7 lists the tones at the end of a phrase. The last tone of the Brahms excerpt (16 – $D5$) was excluded because it was cut off by the end of the recording. Figure 7.15 shows $|Z_u|$ vs. time for 26 – $G5$ (fundamental frequency 698.5 Hz) of the Beethoven excerpt. The small drop in $|Z_u|$ at the first harmonic at the end of the tone was typical of tones at the end of a phrase, although in one tone $|Z_u|$ remained constant.

The tones at the beginning of a phrase were similar to the tongued tones since they all had a decrease in $|Z_u|$ at the first harmonic at the beginning and there was no significant difference in the type of decrease between the two groups. One possibility is that these tones at the beginning of the phrase were tongued, but it was not audible from the recording.

Comparison with Isolated Tones

Three single isolated tones played by performer C were compared with tones of the same pitch in the excerpts to see if the airways were used differently in a musical context. The three tones ($C4$, $G5$, and $E6$) were held 6–8 seconds, and the performer was instructed to play steady, mezzo forte tones. The indirectly measured Z_u for the tones $G5$ and $E6$ was similar to Z_u for tones of the same pitch in the excerpts, within the amount of variation present in the excerpt tones.

Z_u for the isolated tone $C4$ was large at the first and third harmonics, while Z_u was large only at the first harmonic of $C4$ in the Debussy excerpt. Performers B and D also played an isolated $C4$ tone. The tone played by D had a large value of Z_u at the first harmonic similar to the $C4$ played in the excerpt, but the tone played by performer B had $|Z_u|$ large at the first and third harmonics, similar to the isolated tone played by C. There appears to be an airway resonance in the neighborhood of the third harmonic of C that the performer sometimes tunes to the harmonic frequency.

Except for $C4$, these isolated tones show that the airways function in a similar way for isolated tones and for tones in a musical context. The range of variation found for tones in a musical context could be related to the musical function of those tones.

7.3.2 Pairs of Consecutive Tones

Much of musicality is contained in the transition from one tone to the next, and smooth transitions, called "playing with legato", can create phrases that are both beautiful and musical. According to performers, the vocal tract facilitates these transitions, and clarinetists often speak of "voicing" each tone correctly, especially between registers. The performer of the excerpts in this study chose these excerpts because of the difficult intervals involved. Physical theory predicts that a performer can use the airways to stabilize a tone by aligning an upstream resonance with a harmonic frequency of that tone. When two tones of different pitches are played consecutively, this theory implies that the performer should shift the upstream resonances during the transition in order to stabilize the second tone. The physiological changes corresponding to these resonance shifts could account for the difficulty of playing smooth intervals across register breaks.

Data presented in this section will help in understanding how the performer uses the airways to make the transition from one tone to the next. The upstream impedance Z_u will be examined at harmonic frequencies for pairs of consecutive tones. Changes in Z_u near the transition between the two tones will tell how the performer is adjusting upstream resonances.

Consistency

Intervals containing the same pitches were compared to see if the performer changed Z_u in a consistent manner across the transition. One interval that showed a greater degree of consistency than the others was $G5 \rightarrow B\flat 5$ (fundamental frequencies 698.5 Hz and 830.6 Hz). Figure 7.16 plots $|Z_u|$ vs. time for two occurrences of this interval from the Debussy excerpt. In both instances, $|Z_u|$ at the first harmonic rose slightly before the transition and made a short drop after the transition. $|Z_u|$ at the second harmonic of $G5$ was constant. The only difference between these two intervals was an increase in $|Z_u|$ at the first harmonic after the short drop for 7.16-b that is not present in 7.16-a. The increase in $|Z_u|$ at the first harmonic in Figure 7.16-b could be related to the register change that follows the second tone.

Figure 7.17 shows the same two intervals plotted as harmonic frequency vs. time, with a grayscale representing $|Z_u|$. The first harmonics of these tones are fairly close to each other, so the changes in $|Z_u|$ should be nearly continuous, and they are, as is seen in Figure 7.16.

The intervals shown here were more consistent than others in the excerpts. As with the single tones, different occurrences of the same interval often shared only general characteristics, and there was a wide range of variation. The extent of variation in the single tones implies a corresponding extent of variation in the intervals, which may be used by the performer as a means of musical expression.

Reciprocity of Z_u Patterns for Ascending and Descending Intervals

Intervals that occurred both ascending and descending were compared to see if the changes in Z_u were reciprocal, that is, if the Z_u pattern of an ascending interval was just the pattern of the descending interval in reverse.

For example, Figure 7.18 shows the descending interval $B\flat 5 \rightarrow G5$, which is the reverse of the ascending interval shown in Figure 7.16. There are minor differences between the two intervals that show that the behavior of Z_u was not reciprocal in this case. The short drop seen after the transition in the ascending interval was not mirrored as a short rise before the transition in the descending interval, but it might have occurred in the missing data section between the two tones where a fundamental frequency, and therefore Z_u, could not be calculated. In addition, $|Z_u|$ at the second harmonic of $G5$ decreased slightly after the transition in the descending interval, while $|Z_u|$ at the second harmonic remained constant in the ascending interval.

This seems to indicate that, as far as airway adjustments are concerned, an ascending interval is not clearly a descending interval played in reverse, and the variation of Z_u among tones of the same pitch could be a factor in the different Z_u patterns. More data is needed in order to understand the systematic differences. The changes that are present could be related to vocal tract adjustments that the clarinetist is making in order to play legato or to produce other musical effects.

Register Changes

Intervals that are between different registers are often more difficult to play than those within a single register. The performer believed that the correct use of the vocal tract was necessary to play the register changes in these excerpts smoothly. The analysis of intervals between different registers will try to determine if vocal tract adjustments make these intervals difficult. The intervals will be grouped according to the type of register change.

Chalumeau→Clarion Melodic intervals corresponding to a transition from the chalumeau to the clarion register are listed in Table 7.8, and their Z_u patterns were all quite similar. Figure 7.19 shows $|Z_u|$ vs. time for a typical example, $A4 \rightarrow B4$ (fundamental frequencies 392.0 Hz and 440.0 Hz) from the Brahms excerpt. For these intervals the changes in $|Z_u|$ at the first harmonic (Figure 7.19-a) were characterized by a rise before the transition (except for $B\flat4 \rightarrow C4$), a sharp drop after the transition, and then a slower rise. The level of $|Z_u|$ at the second harmonic was continuous across the transition. Three of the intervals ($B\flat4 \rightarrow C5$ and the two $A4 \rightarrow B4$ intervals) were only one or two semitones. The changes in the first and second harmonic frequencies for these intervals were therefore nearly continuous (Figure 7.19-b), and the corresponding changes in Z_u at these frequencies also appeared to be continuous.

The remaining interval, $A4 \rightarrow E5$ (fundamental frequencies 392.0 Hz and 587.3 Hz) from the Brahms excerpt, was seven semitones and is shown in Figure 7.20. The first and second harmonic frequencies of these two tones were not continuous (Figure 7.20-b), but the behavior of Z_u at the first harmonic across the interval (Figure 7.20-a) was identical to the other three intervals, which were much narrower. The performer stated explicitly that the interval $A4 \rightarrow E5$ was more difficult than the interval $A4 \rightarrow B5$. However the Z_u pattern across the interval transition was nearly identical for these two intervals. The difficulty probably arises as the performer attempts to adjust airway resonances at two frequencies that are far apart, i.e., at the first harmonics of $A4$ and $E5$. When Z_u^o was measured directly with the one-microphone technique, there was only one upstream resonance in this frequency range. When playing the interval $A4 \rightarrow E5$, the performer must be shifting this resonance by a greater distance than for the interval $A4 \rightarrow B4$, and this may be the source of the difficulty.

These intervals show that the airway adjustments for interval transitions occur very quickly, within 0.2 seconds in this case, with the largest change at the first harmonic taking place within 0.1 seconds. Since this is a physiological adjustment of the airways that is taking place, this transition time is limited by the performer's ability to adjust the airways.

Clarion→Chalumeau Table 7.9 lists the melodic intervals from the clarion to the chalumeau register, and their Z_u patterns were all very similar. Figure 7.21 shows a typical example, $B4 \rightarrow A4$ from the Brahms excerpt. The values of $|Z_u|$ at the first and second harmonics and were close to each other in level before the transition. Afterwards, $|Z_u|$ at the first harmonic was greater than $|Z_u|$ at the second harmonic, except for the interval with tone numbers $6 \rightarrow 7$, and both were greater than their levels before the transition. After the transition, Z_u at the first harmonic made a slight dip and then a small increase. The two intervals $C5 \rightarrow G4$ and $D5 \rightarrow A4$ were both 5 semitones in distance, but transposed by two semitones, and their Z_u patterns were almost identical.

Comparison of Chalumeau→Clarion and Clarion→Chalumeau Both of these interval groups were highly consistent within themselves, which makes this a good opportunity to test if the Z_u patterns of these ascending and descending intervals were reciprocal, i.e., if the performer was making the same airway adjustments but in reverse. Figures 7.19-a and 7.21 can be compared since they are the intervals $A4 \rightarrow B4$ and $B4 \rightarrow A4$. The sharp drop with a dip after the ascending transition (Figure 7.19-a) was not mirrored as a dip and a sharp rise before the descending interval (Figure 7.21). This sharp rise might be included in the missing data section during the transition, but it was absent from all descending intervals, so it is not likely to be merely an omission. Furthermore, the values of $|Z_u|$ at the first and second harmonics are about 40 CGS ohms apart after the descending interval, but they are close together before the ascending interval. These two main differences imply that the airway changes for these ascending and descending register changes are not reciprocal and that the performer must make different adjustments when crossing this register break, depending upon the direction of the interval.

Clarion→Altissimo Table 7.10 lists the melodic intervals from the clarion to the altissimo register, and they can be divided into three groups based on the behavior of $|Z_u|$. The first two groups of intervals came from the Beethoven and the third group came from the Debussy.

1. $A5 \rightarrow D6$, $E5 \rightarrow D6$. The first pitches of these two intervals ($A5$ and $E5$) were the lowest in all the intervals in this category. Both intervals end on $D6$.

Figure 7.22 shows $|Z_u|$ vs. time at the first harmonic for $A5 \rightarrow D6$ (fundamental frequencies 784.0 Hz and 1046.5 Hz) and is similar to $E5 \rightarrow D6$. $|Z_u|$ was at a moderately low level (less than 80 CGS ohms) both before and after the transition. Before the transition there was a rise in $|Z_u|$, and in the example shown a slight fall but the fall was not present in the other interval of this category. After the transition $|Z_u|$ was lower than before, but only slightly, and fairly steady.

2. $C6 \rightarrow D6$, two intervals of $B5 \rightarrow D6$. These intervals involved the two highest pitches in the clarion register ($C6$ and $B5$) and $D6$. Figure 7.23 shows $|Z_u|$ vs. time at the first harmonic for $B5 \rightarrow D6$ (fundamental frequencies 880.0 Hz and 1046.5 Hz). For all three intervals, $|Z_u|$ before the transition was large at the first harmonic, and it was larger than in category (1.) by a factor of two. After the transition there was a sharp drop and then a slower drop, and $|Z_u|$ ended much lower than before the transition.

3. $B\flat5 \rightarrow D\flat6$ (fundamental frequencies 830.6 Hz and 987.8 Hz). This interval, which unlike the intervals in the previous two groups came from the Debussy excerpt, is the same distance as $B5 \rightarrow D6$ in (2.) above but transposed down by one semitone, and its $|Z_u|$ pattern was somewhat different (Figure 7.24). In both intervals the level of $|Z_u|$ at the first harmonic was greater before the transition than after. However, in this interval, $|Z_u|$ increased to this large level just preceding the transition, and afterwards $|Z_u|$ was suddenly lower, with a short drop followed by a sharp rise and a levelling off. Even though this interval differed by only one semitone from $B5 \rightarrow D6$, its Z_u pattern was distinctly different. This could be related to the different musical contexts of the two intervals. In addition, $|Z_u|$ of $D\flat6$ changed during the tone in ways that were not typical of most tones. For example, $|Z_u|$ at the first harmonic dropped from 60 to 20 CGS ohms and then remained low. This could be related again to the musical context and could explain some of the differences between this interval and $B5 \rightarrow D6$.

These three groups of intervals can be classified according to two criteria: the pitches involved and the excerpt of origin. These two factors might be responsible for the differences between the three groups. If an interval involves different pitches, the performer might have to make different vocal tract adjustments. On the other hand, the performer might play an interval differently depending upon the musical context. More data is needed in order to further investigate this.

Altissimo→Clarion There were only three of these intervals from the altissimo to the clarion register, and they are listed in Table 7.11. There were fewer similarities among these intervals than in the other three categories, which is surprising since two of the intervals are identical and the other differs by only a semitone. The interval $D\flat6 \rightarrow C6$ from the Debussy is an unusual situation since halfway through $D\flat6$, $|Z_u|$ at the first harmonic drops and then remains low, which was not typical for altissimo tones and which makes $D\flat6$ much different from $D6$ of the other two intervals in this category. The musical context and the omitted sections of data during the transition could account for the differences among these intervals.

Compare Clarion→Altissimo and Altissimo→Clarion There is a wide variety of Z_u patterns among register changes between the clarion and altissimo registers, and this makes it difficult to make generalizations about these intervals. More data is needed to determine if these patterns are replicable and how they are related to the pitches involved and to the musical context.

7.3.3 Musical Features

Two musical features and their relation to Z_u will be discussed: one tone that the performer squeaked and dynamic level changes.

Squeak

Although a squeak is not usually considered a musical feature, it provides an opportunity to see how the airways were involved in its production. The performer squeaked on the tone $16 - E6$ in the Beethoven excerpt, and the upstream impedance could explain why this happened. The tone sounded at first but then veered off into a squeak. Since there was a tone at the very beginning, it was possible to calculate a fundamental frequency for two overlapping segments. The indirectly measured upstream impedance for these two segments compared to that of an isolated, normal $E6$ played by the same performer could give clues as to why this tone did not survive.

Figure 7.25 shows Z_u vs frequency for the $E6$ squeaked in the excerpt and for an isolated, normal $E6$ played by the same performer. The instrument impedance for $E6$ is also plotted. The value of $|Z_u|$ at the first harmonic (1190 Hz) for the squeaked tone as shown in Figure 7.25-a was 30 CGS ohms, whereas it was 65 CGS ohms for the normal tone. The squeaked $E6$ was the only altissimo tone with $|Z_u|$ less than 50 CGS ohms. At the end of the previous tone in the excerpt, the altissimo tone $15 - D\sharp 6$, $|Z_u|$ decreased to 40 CGS ohms, and this might have been the beginning of the problem. Although $|Z_d|$ at the first harmonic of $E6$ was 215 CGS ohms, a slight change in $|Z_u|$ could make a critical difference. When regeneration calculations were performed on an altissimo tone, it appeared that Z_u at the first harmonic lowered the dissipation at the first harmonic so that the real part of the regeneration condition could be fulfilled.

The phase of Z_u was not equal to the phase of Z_d for either the squeaked or the normal tone. The phase of Z_u for both was about +5 degrees, and the phase of Z_d was about +40 degrees. Since Z_u and Z_d are not in phase, $|Z_u|$ must be relatively larger in order for $|Z_u + Z_d|$ to be large.

A low level of $|Z_u|$ may be the reason that this altissimo tone did not survive. Airway resonances in the frequency range of the first harmonic of altissimo tones may be more difficult to control since these tones so often squeak. The role of the airway in supporting these tones could be more important than in other pitch ranges, and this needs to be investigated further.

Crescendo and Decrescendo

The main musical feature of these excerpts was dynamical changes. However, there were no obvious correlations with changes in $|Z_u|$. Other features, such as articulation and register changes appear to be correlated with specific changes in $|Z_u|$, but there were no obvious changes in $|Z_u|$ that could be attributed to the longer-time processes of crescendos and decrescendos. If there is a relation between dynamical changes and airway adjustments then it must be more subtle.

This observation agrees with the results of the isolated tones played at different dynamic levels. Section 5.3 showed that there was only a slight change in $|Z_u|$ observed with dynamic level in single tones. These slight changes might also be present in the tones in the excerpts but could be more difficult to detect since the changes in dynamic level often continue over several tones, and these effects could be confounded with other effects such as those of register changes.

7.4 Discussion

The analysis of single tones in these three excerpts showed that over half of the tones had a large value of $|Z_u|$ at the first harmonic frequency. In addition, there were also many tones that had a large value of Z_u at the second harmonic or at both the first and second harmonics. These tones confirm the prediction that the performer aligns an upstream resonance with a harmonic frequency, which the linear regeneration theory predicts should stabilize the oscillation.

However, about one-fifth of the tones did not have a large value of $|Z_u|$ at any harmonic frequency. These tones were mostly in the clarion register. It is possible that the instrument impedance alone is sufficient for stabilizing the tone, but the tones in the chalumeau register (except for one) all had a large $|Z_u|$ at some harmonic. These chalumeau tones are using two Z_u peaks, as are the clarion tones, and sometimes three, so it is not clear why these tones would need stabilization from the airways, and the tones just above them would not.

For these tones with no aligned airway resonances, there could be some other stabilizing mechanism involved such as the reed resonance, or it could be that the performer was simply unable to adjust the upstream resonances in this frequency range, but many of these tones also appeared at least one other time with a large $|Z_u|$, so the performer obviously had upstream resonances that could appear in this frequency range. The variability of the levels of $|Z_u|$ in the clarion register, as evidenced by the fact that these tones could have one, two, or no prominent Z_u harmonics could be due to the performer adjusting upstream resonances in order to produce musical effects, rather than for oscillation stability.

Altissimo tones usually had a large level of $|Z_u|$ at the first harmonic. Since tones in this pitch range are played using only one instrument impedance peak, the airways could be especially important in stabilizing these tones. This is similar to the role of the reed resonance predicted by Thompson [72], who suggested that for altissimo tones the performer adjusts the reed resonance frequency to align it with a harmonic frequency. The airways may also be involved in supporting these tones. Regeneration calculations showed that the large level of $|Z_u|$ at the first harmonic had the effect of very slightly decreasing the energy dissipation at this frequency. This may be more crucial for altissimo tones since they have the lowest blowing pressure of all tones, which lowers $Re(-Y_G)$ so that $Re(Y)$ must be even lower in order to generate sound. The one altissimo tone that the performer squeaked is further evidence for the importance of the airways. This tone had the lowest $|Z_u|$ of all altissimo tones.

The tones in the upper chalumeau (called "throat tones" by clarinetists) had large levels of Z_u at both the first and second harmonics (Figure 7.4). Worman [75] noted that beginning in this pitch range, tones use only two instrument impedance peaks whereas the tones with lower pitches use more than two, and this is why the tone quality for throat tones is not as resonant as in the lower chalumeau. The performer appears to be compensating by enhancing both the first and second harmonics with the airways. Performers [53] have noted that these tones require a high tongue position as in "ee" to improve the tone quality. This could be the reason for the designation of this pitch range as the "throat tones". Regeneration calculations on chalumeau tones showed that the main effect of Z_u was to stabilize the playing frequency, especially at the second and fourth harmonics, and to decrease energy dissipation at the first harmonic.

The tones $F\sharp 4$, $G4$, and $A4$ in the upper chalumeau register had large values of $|Z_u|$ at both the first and second harmonics. The frequency of the first harmonic for these tones is 330–392 Hz, and the frequency of second harmonic is 659–784 Hz. The directly measured Z_u^o showed one peak at about 200–250 Hz and another peak that ranged over 400–1100 Hz. The peak at 400–1100 Hz had a full-width at half-maximum of less than 100 Hz, so it is unlikely that this peak can enhance both the first and the second harmonics. Either the performer is raising the 200–250 Hz peak in frequency to align it with the first harmonic and aligning the 400–1100 Hz peak with the second harmonic, or the performer is creating two peaks in the second region, which was never observed in the measured Z_u.

The harmonics of the excerpt tones at which $|Z_u|$ was large covered a larger range in frequency and magnitude compared to the peaks in Z_u^o measured directly. Z_u^o had a peak in the range 200-250 Hz and another in the range 400-1100 Hz. The peak in the range 400-1100 Hz had a magnitude of less than 100 CGS ohms, except for an

$E6$ when it had a magnitude of 220 CGS ohms. The harmonics with large values of Z_u in the excerpts ranged from 233 Hz (the first harmonic of $C4$) to 1500 Hz (the frequency limit of the indirect Z_u measurement), and had magnitudes of up to 200 CGS ohms. This frequency range is broader than the range of Z_u^o peaks measured directly and includes the range 250-500 Hz between the two lowest-frequency peaks in the directly measured Z_u^o and the range 1100–1500 Hz where there were no peaks in the Z_u^o. The entire frequency range of the harmonics in the excerpts could conceivably be covered by the three main peaks in Z_u^o, if the performer could adjust them over a larger range. The range of $|Z_u|$ was larger for the excerpts, but many of the tones that had $|Z_u|$ greater than 100 CGS ohms were upper clarion or altissimo tones. In general there is agreement between the indirectly measured Z_u in the excerpts and the directly measured Z_u^o. Discrepancies could be due to musical effects the performer was accomplishing with the airways. On the other hand, Z_u^o was measured directly for this performer for only four tones during a brief period of signal acquisition, and that might not provide a representative sample of Z_u^o for this performer. If Z_u^o for other tones were measured directly with this performer, the results might be significantly different from the other two performers for which Z_u^o was measured directly. Another possibility is that the differences between Z_u^o and Z_u are due to the inability of the performer to reproduce a performance airway configuration, including the correct glottal opening size, under non-performance conditions with no feedback from the instrument. Thus the differences between Z_u from the excerpts and Z_u^o measured directly for isolated tones could be explained by individual performer differences, the differences between isolated tones and tones in a musical context, or by the difficulty of the performer's task in the Z_u^o measurement.

Tones of the same pitch tended to be more similar when they were in the same excerpt, and the pattern of Z_u for intervals between the clarion and altissimo registers seemed to depend on the excerpt of origin. This is evidence that the performer is using the airways in a distinctive way depending upon the musical context. Obviously the performer has some leeway in the use of the airways, and there is not one fixed airway configuration for a certain pitch. The performer could use this flexibility in musically expressive ways.

Table 7.1: The Excerpts

1. Beethoven, Symphony No. 8, Mvt. 3 Trio, mm. 16-20
2. Brahms, Symphony No. 3, Mvt. 2 Andante, mm. 1-4
3. Debussy, Première Rhapsodie pour Orchestre avec Clarinette Principale, mm. 13-18

Table 7.2: Statistical frequency distribution of harmonics (f < 1500 Hz) with large $|Z_u|$.

Harmonics with Large $\|Z_u\|$	% of all tones†
1	48
1 and 2	23
none	22
2	8

†% 's do not add up to 100% due to rounding-off

Table 7.3: Statistical frequency distribution of harmonic with largest $|Z_u|$.

Harmonic with Largest $\|Z_u\|$	% of all tones†
1	57
none	22
not clear	14
2	8

†% 's do not add up to 100% due to rounding-off

Table 7.4: Statistical frequency distribution of harmonics (f < 1500 Hz) with changing $|Z_u|$.

Harmonics with Changing $\|Z_u\|$	% of all tones†
1	54
none	26
1 and 2	17
2	3

†% 's do not add up to 100% due to rounding-off

Table 7.5: Tones that were tongued.

Excerpt	Tone #	Pitch	Harmonic with Decreasing $\|Z_u\|$	Frequency (Hz)
Brahms	12	$F\sharp 4$	2	670
	14	$A4$	2	790
Beethoven	13	$D6$	1	1065
	14	$D6$	1	1065
	17	$E5$	1	600
	23	$B5$	1	890
	25	$F\sharp 5$	1	670
	26	$G5$	1	710
Debussy	8	$D\flat 5$	1	500
	8	$D\flat 5$	2	1000

Table 7.6: Tones at the beginning of a phrase.

Excerpt	Tone #	Pitch
Brahms	1	$D5$
Beethoven	1	$D5$
Debussy	1	$B\flat 4$
	6	$C5$
	14	$G5$
	21	$B\flat 5$

Table 7.7: Tones at the end of a phrase.

Excerpt	Tone #	Pitch
Beethoven	26	$G5$
Debussy	5	$C4$
	13	$C6$
	20	$E\flat 5$

Table 7.8: Intervals with Register Changes: Chalumeau→Clarion.

Excerpt	Tone Numbers	Interval	# Semitones
Brahms	5 → 6	$A4 \rightarrow B4$	2
	7 → 8	$A4 \rightarrow B4$	2
	14 → 15	$A4 \rightarrow E5$	7
Debussy	1 → 2	$B\flat 4 \rightarrow C5$	1

Table 7.9: Intervals with Register Changes: Clarion→Chalumeau.

Excerpt	Tone Numbers	Interval	# Semitones
Brahms	6 → 7	$B4 \rightarrow A4$	2
	8 → 9		
	4 → 5	$D5 \rightarrow A4$	5
Debussy	2 → 3	$C5 \rightarrow G4$	5

Table 7.10: Intervals with Register Changes: Clarion→Altissimo.

Excerpt	Tone Numbers†	Interval	# Semitones
Beethoven	3 → 4(U)	$A5 \rightarrow D6$	5
	11 → 12	$C6 \rightarrow D6$	2
	17 → 18(U)	$E5 \rightarrow D6$	10
	20 → 21	$B5 \rightarrow D6$	3
	23 → 24(U)		
Debussy	15 → 16	$B\flat 5 \rightarrow D\flat 6$	3

†U = undertone

Table 7.11: Intervals with Register Changes: Altissimo→Clarion.

Excerpt	Tone Numbers†	Interval	# Semitones
Beethoven	4 → 5	$D6 \rightarrow C6$	2
	18 → 19		
Debussy	16 → 17(U)	$D\flat 6 \rightarrow C6$	1

†U = undertone

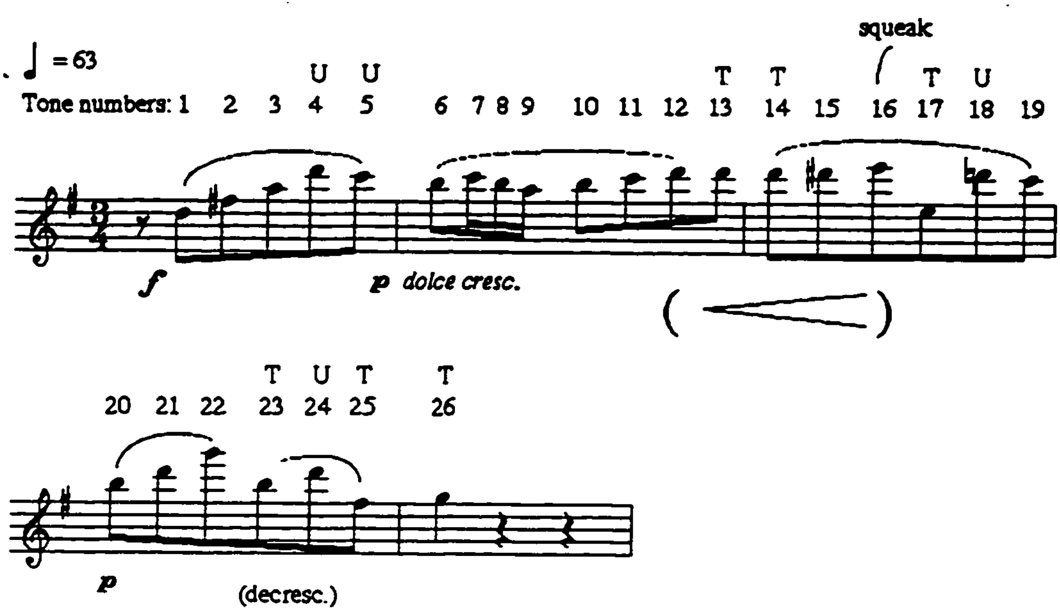


Figure 7.1: Beethoven excerpt: Symphony No. 8, Mvt. 3 Trio, mm. 16-20 .

Figure 7.2: Brahms excerpt: Symphony No. 3, Mvt. 2 Andante, mm. 1-4.

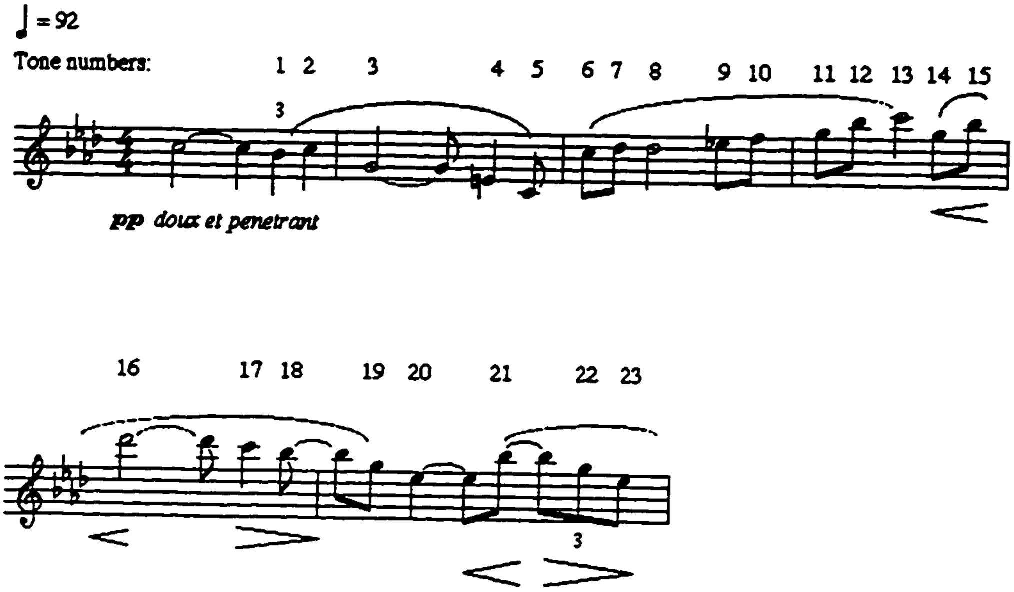


Figure 7.3: Debussy excerpt: Première Rhapsodie pour Orchestre avec Clarinette Principale, mm. 13-18.

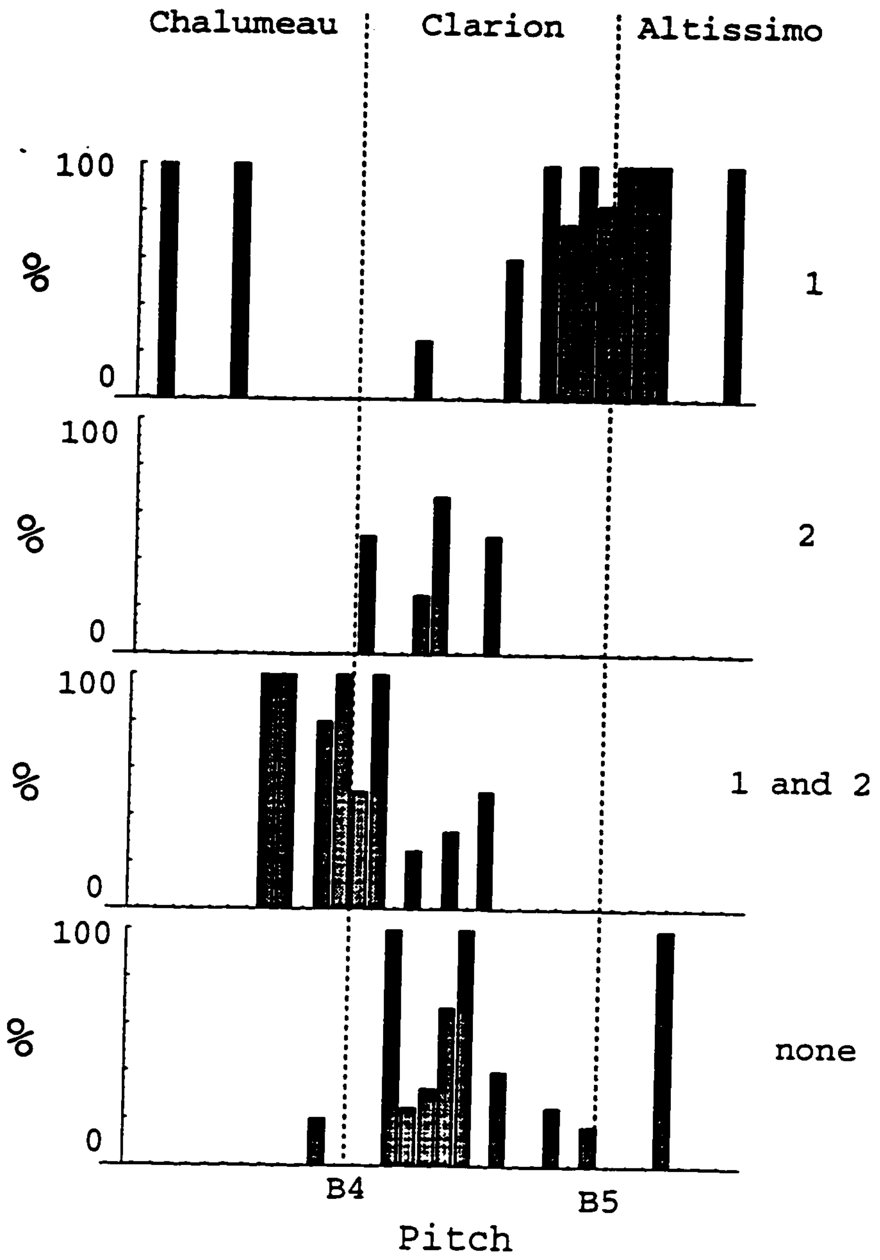
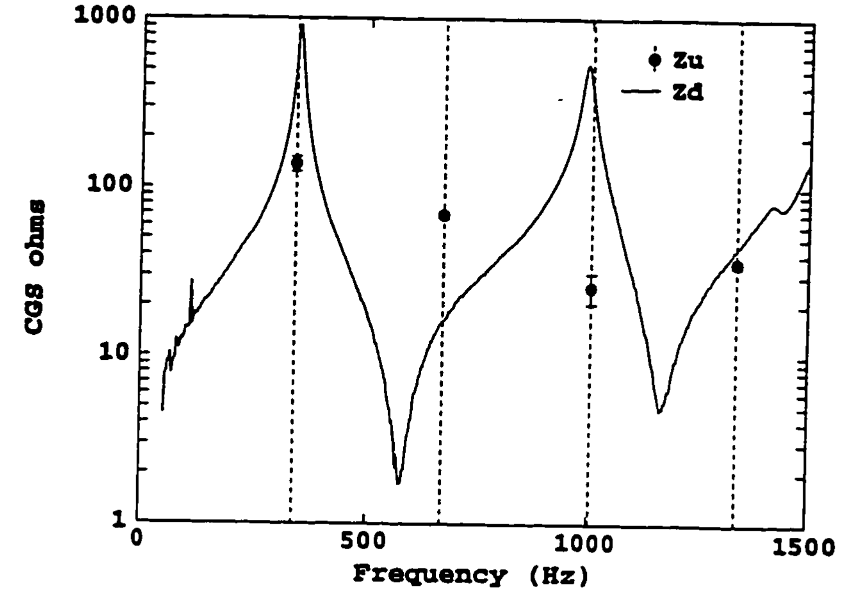
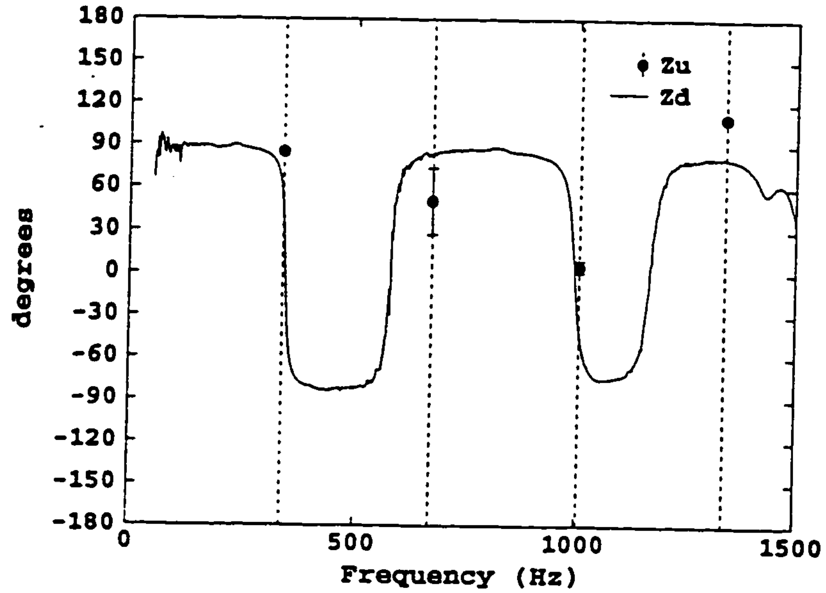


Figure 7.4: Percentage of tones of each pitch that had a large value of $|Z_u|$ at 1st, at 2nd, at both 1st and 2nd, and at no harmonic frequencies, for harmonics less than 1500 Hz.

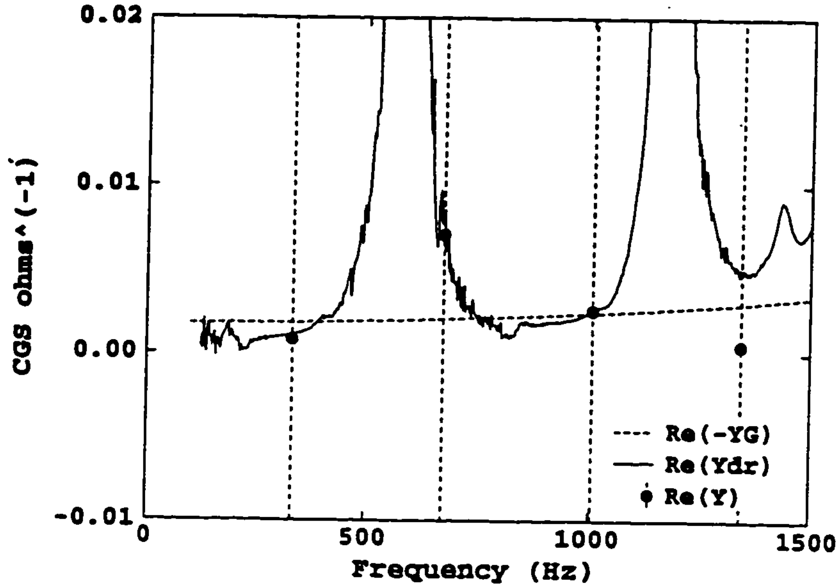


(a) Magnitude.

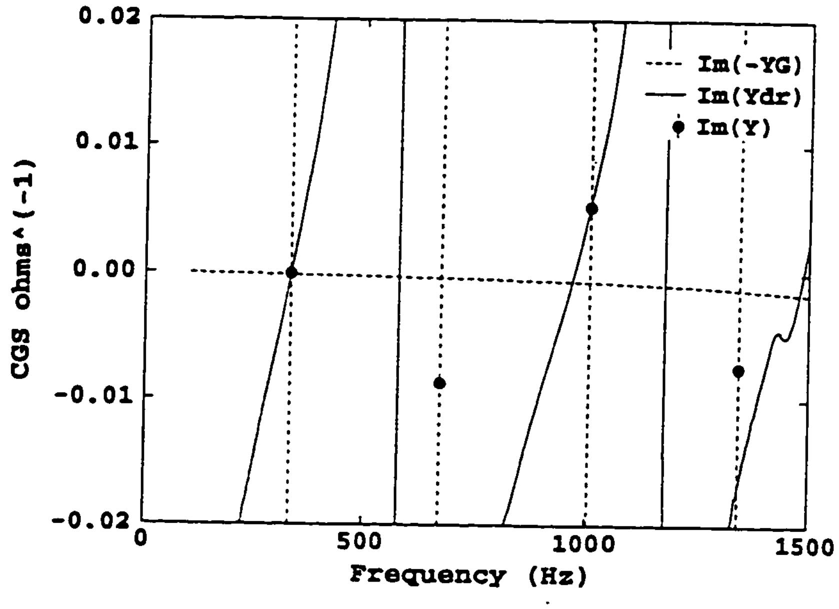


(b) Phase.

Figure 7.5: Z_u and Z_d for 11 – $F\#4$ of Brahms.

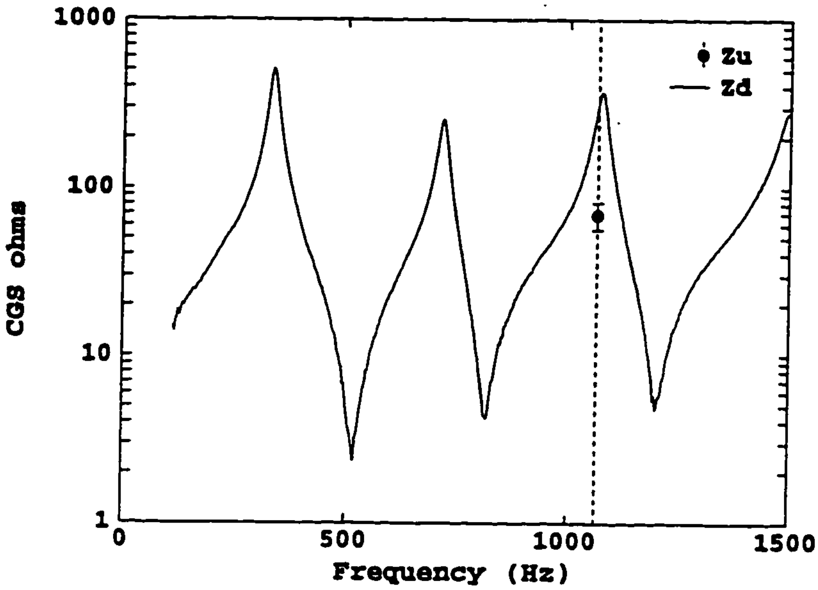


(a) Real part.

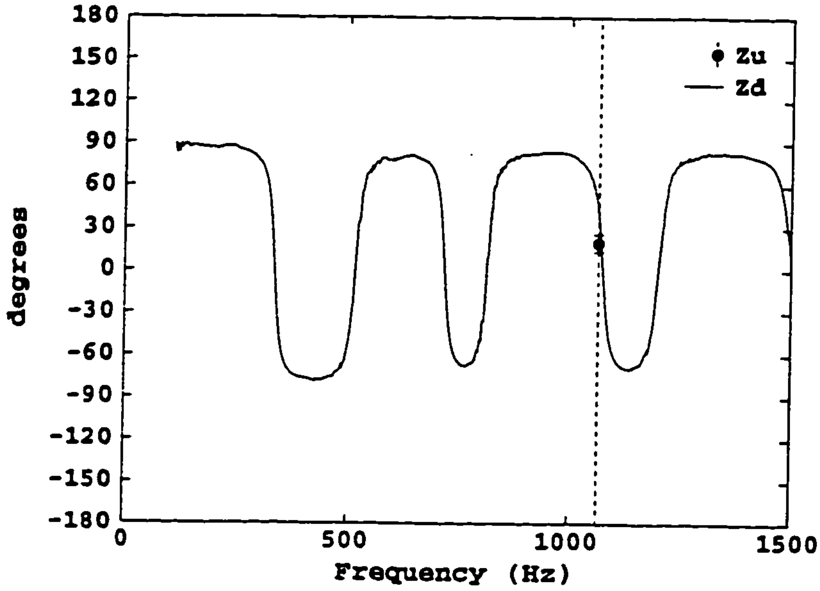


(b) Imaginary part.

Figure 7.6: Generator and dissipative admittances for $11 - F\#4$ of Brahms.

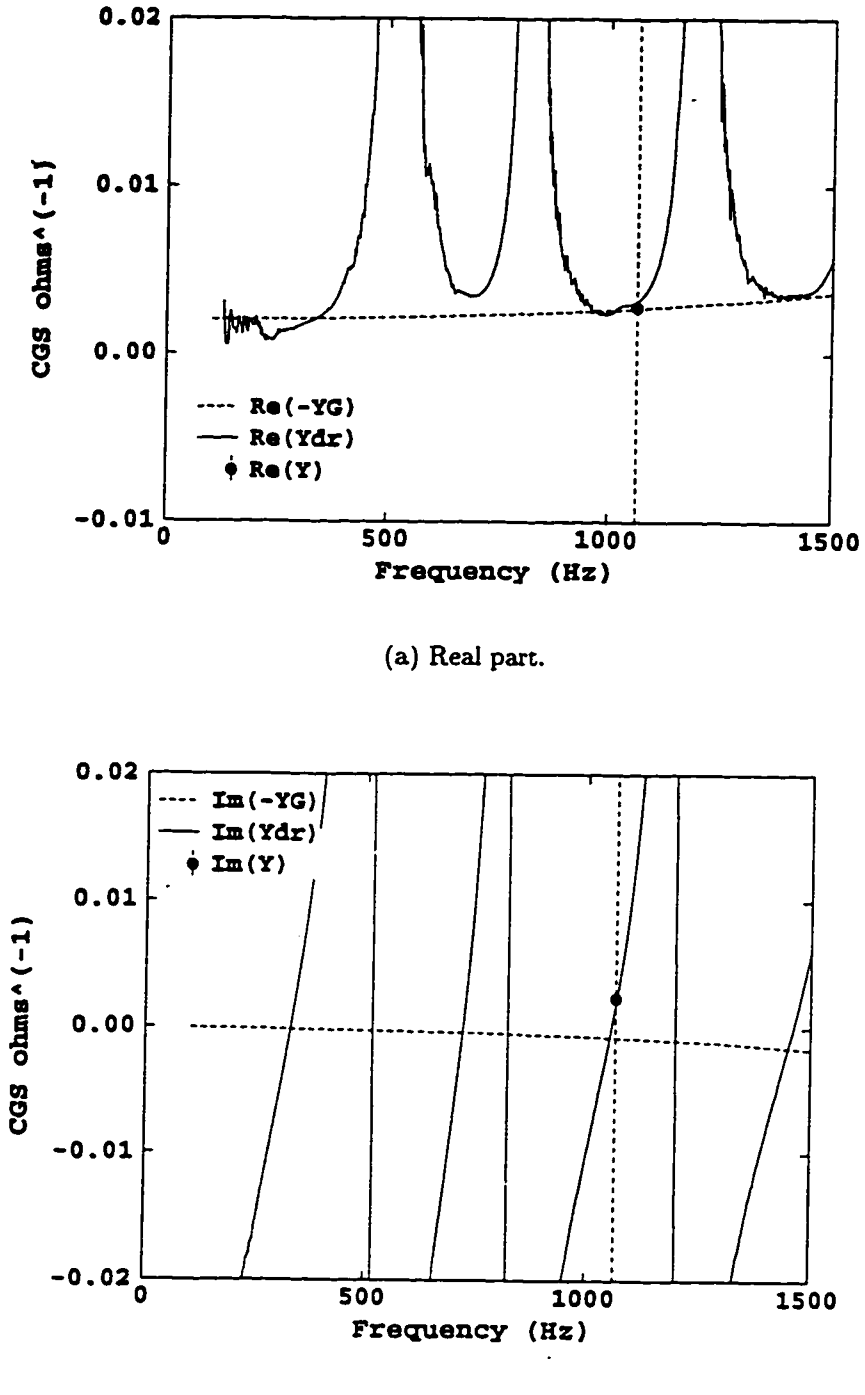


(a) Magnitude.



(b) Phase.

Figure 7.7: Z_u and Z_d for $12 - D6$ of Beethoven.



(a) Real part.

(b) Imaginary part.

Figure 7.8: Generator and dissipative admittances for $12 - D6$ of Beethoven.

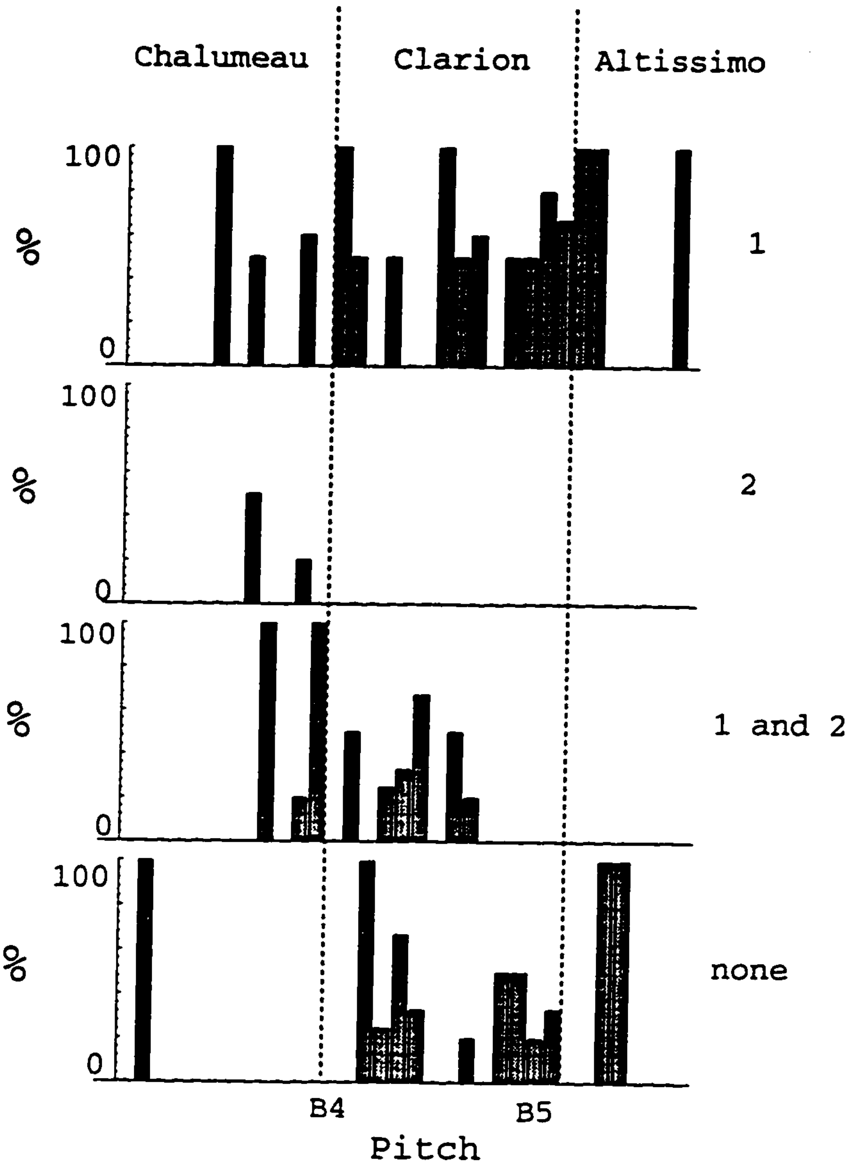
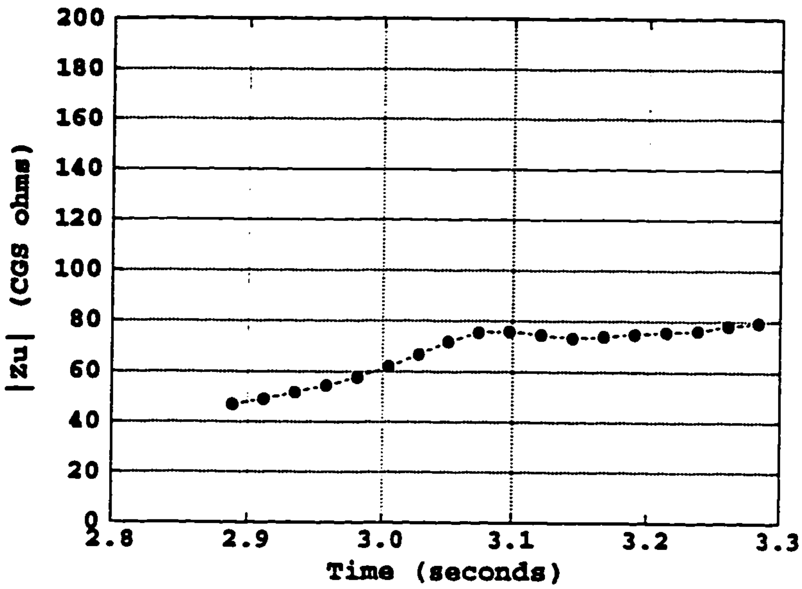
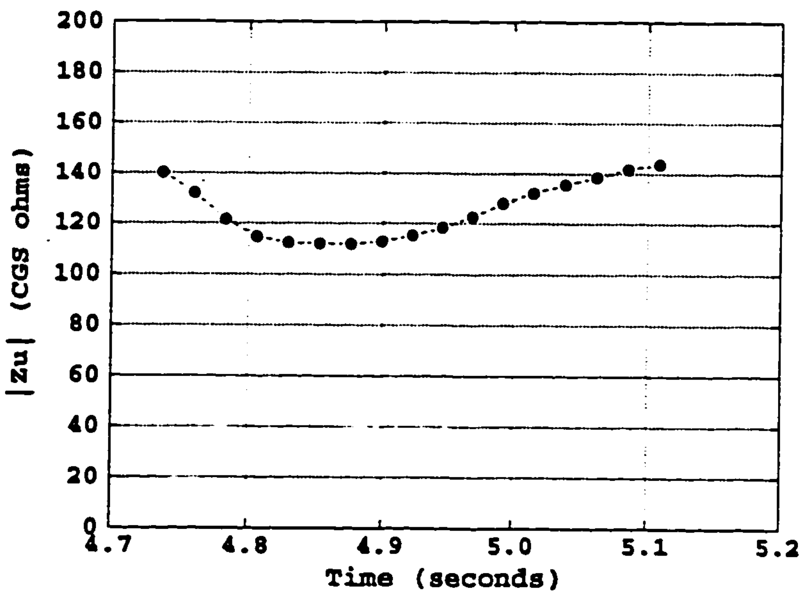


Figure 7.9: Percentage of tones of each pitch that had a changing value of $|Z_u|$ at 1st, at 2nd, at both 1st and 2nd, and at no harmonic frequencies, for harmonics less than 1500 Hz.



(a) Beethoven 5 – $C6$.



(b) Beethoven 11 – $C6$

Figure 7.10: Consistency of $|Z_u|$ for single tones of same pitch and duration: $|Z_u|$ vs. time at first harmonic of $C6$.

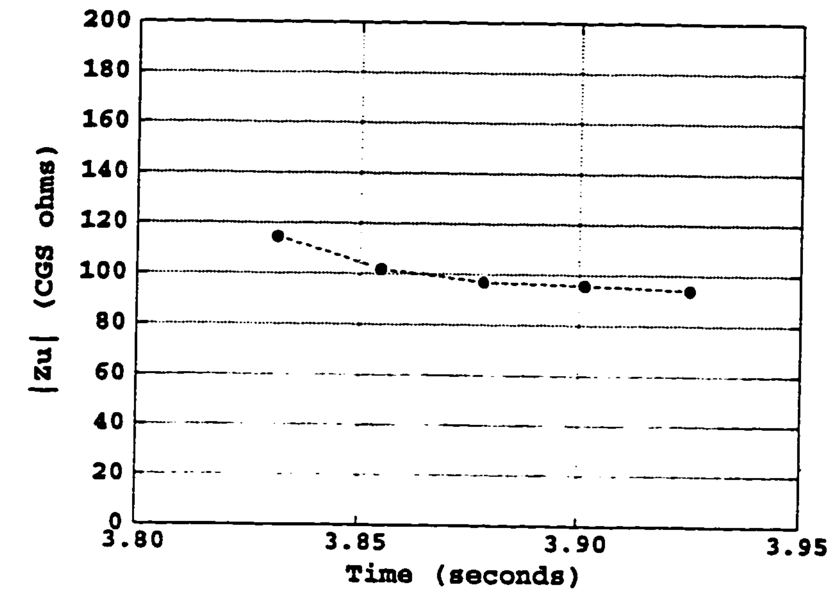
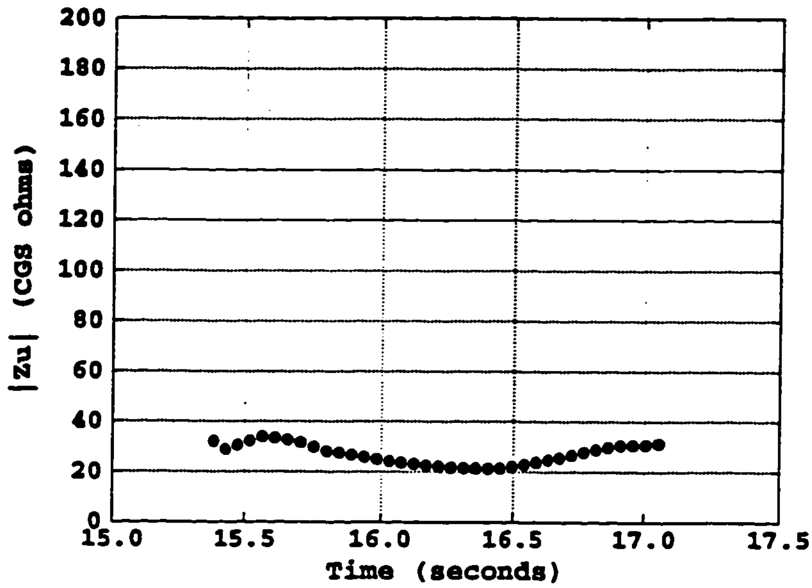
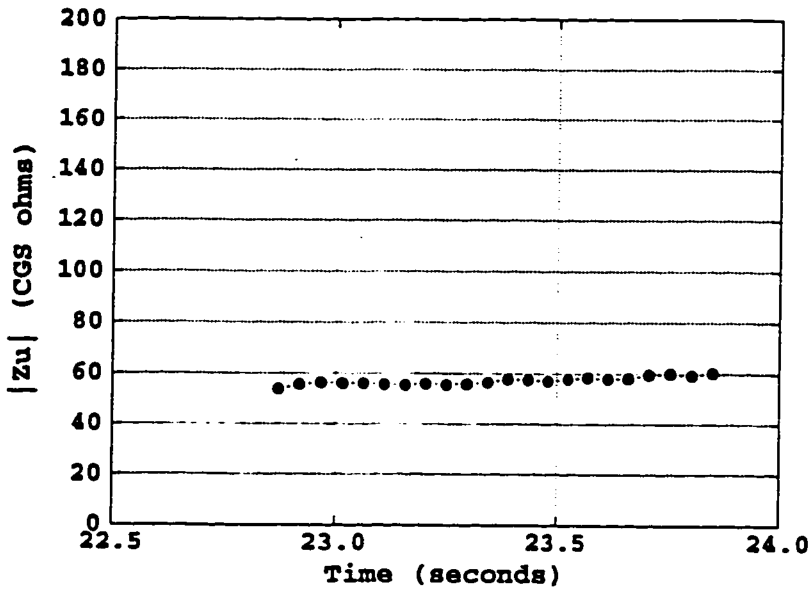


Figure 7.11: Effect of tone duration on $|Z_u|$: $|Z_u|$ vs. time at first harmonic of Beethoven $7 - C6$.



(a) Debussy 13 – $C6$.



(b) Debussy 17 – $C6$.

Figure 7.12: Comparison tones from a different excerpt: $|Z_u|$ vs. time at first harmonic of two $C6$ tones from Debussy.

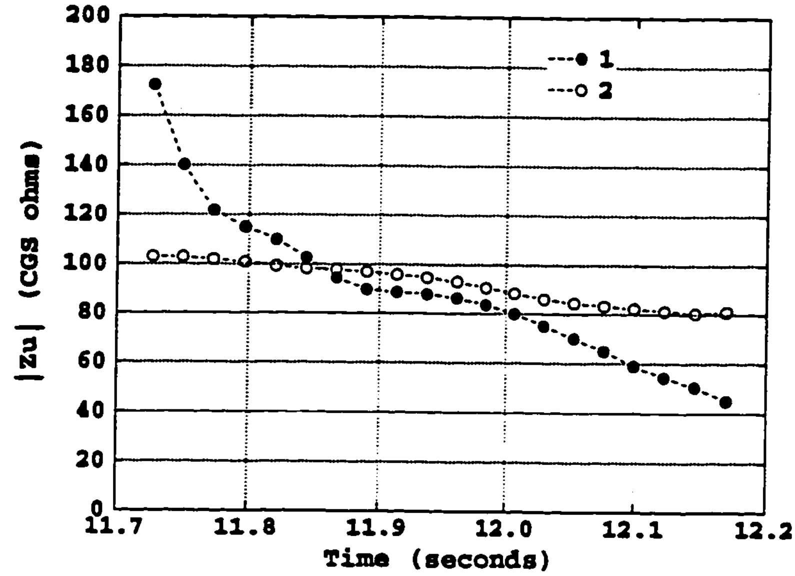


Figure 7.13: Effect of articulation on $|Z_u|$: $|Z_u|$ vs. time at the first two harmonics of Beethoven 25 – $F\sharp 5$.

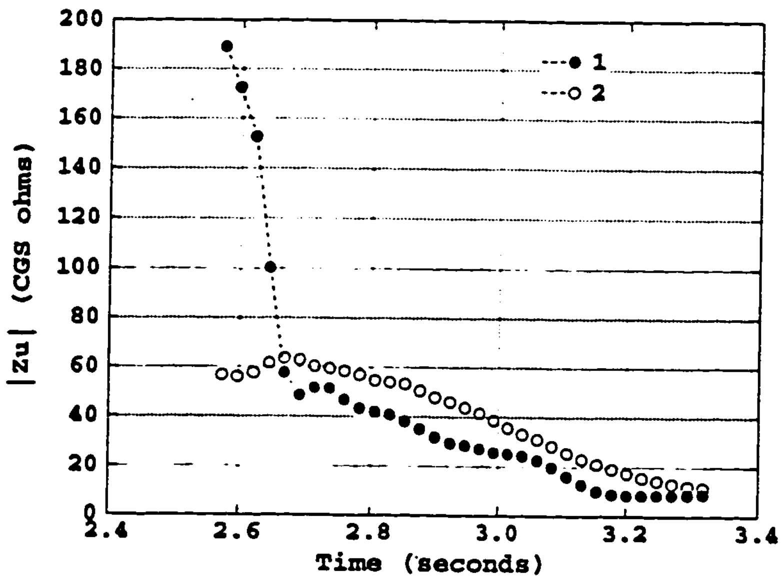


Figure 7.14: $|Z_u|$ for a tone at the beginning of a phrase: $|Z_u|$ vs. time at the first two harmonics of Brahms 1 – $D5$.

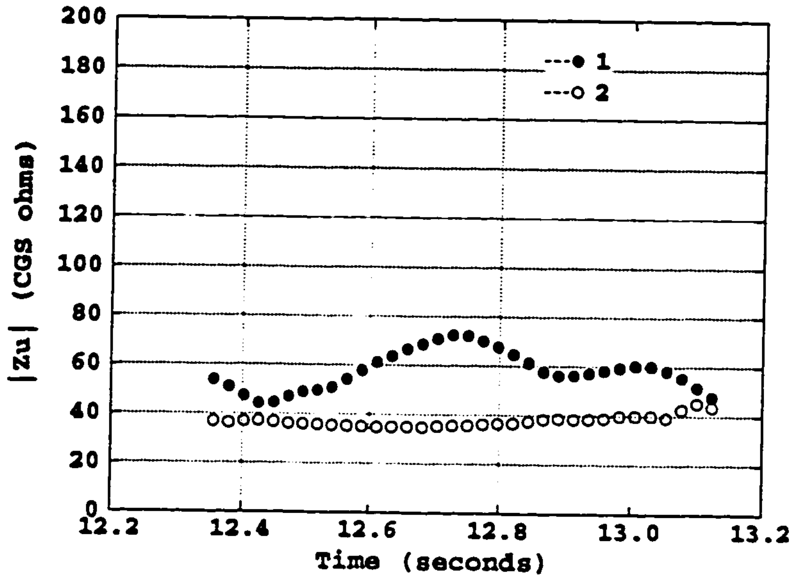
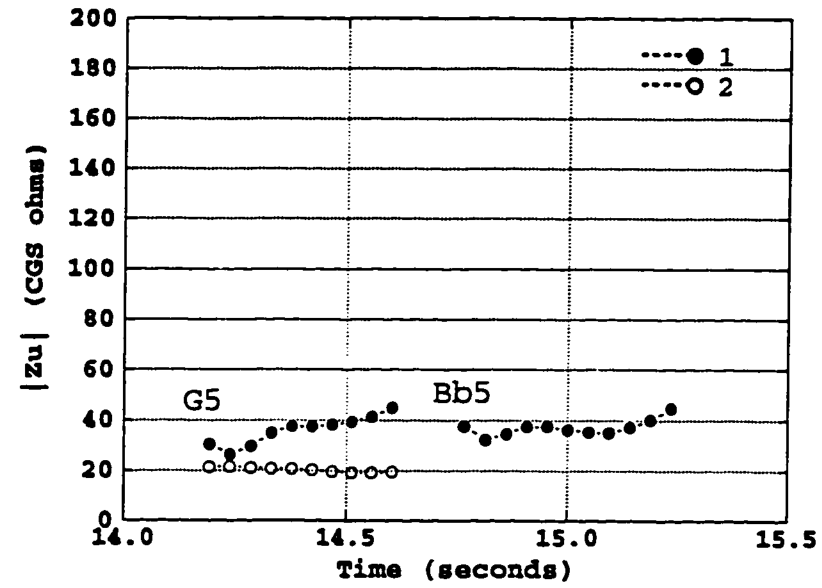
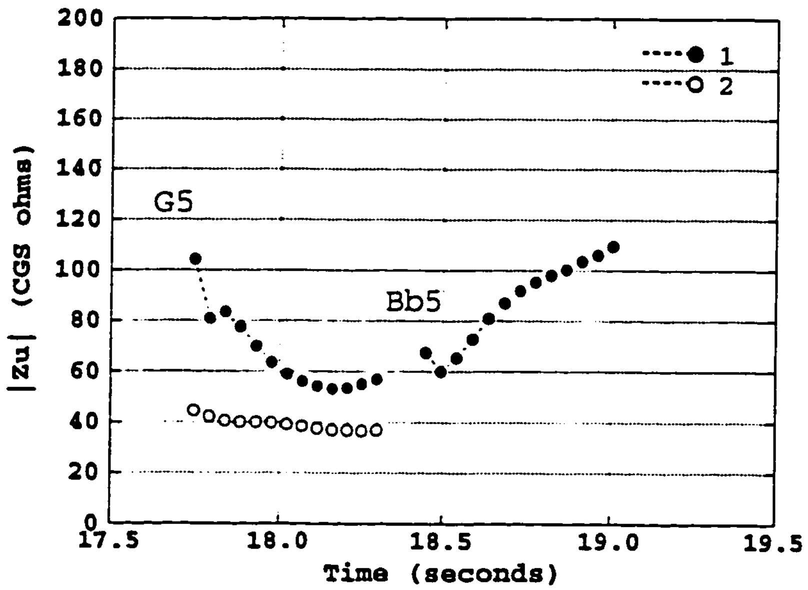


Figure 7.15: $|Z_u|$ for a tone at the end of a phrase: $|Z_u|$ vs. time at the first two harmonics of Beethoven 26 – $G5$.

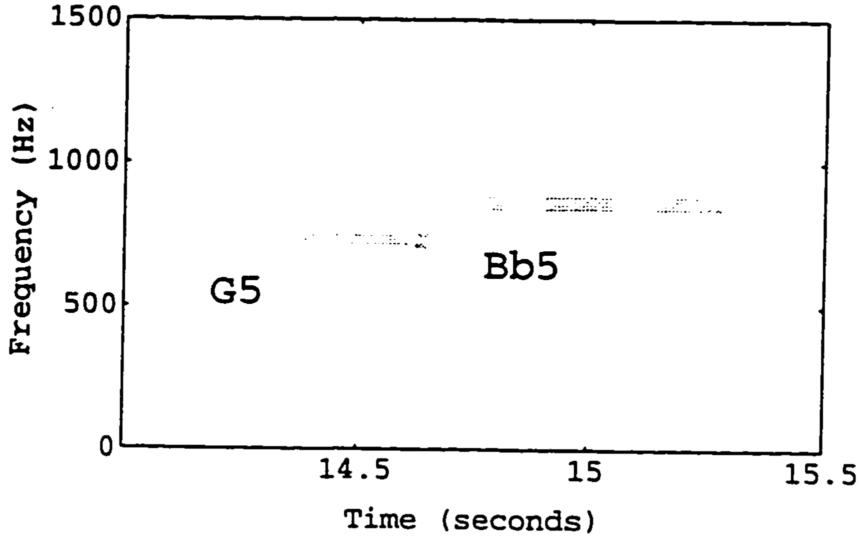


(a) Debussy 11 → 12.

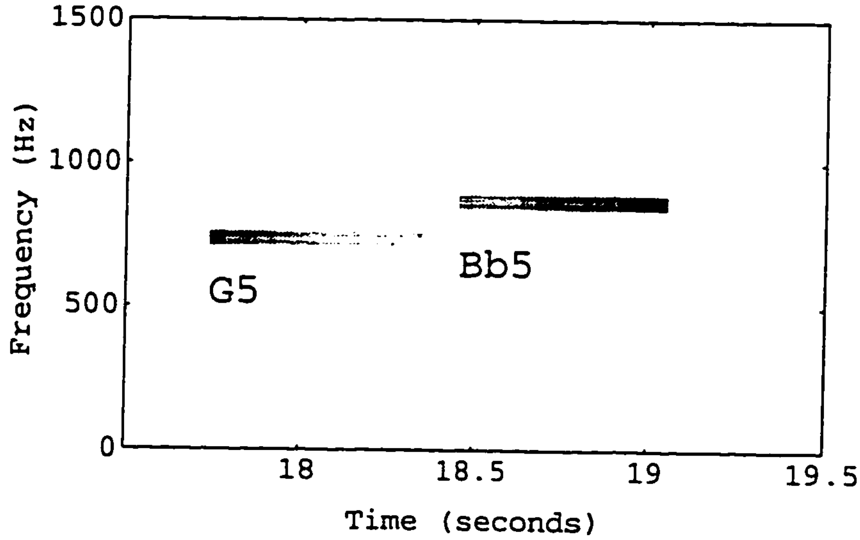


(b) Debussy 14 → 15.

Figure 7.16: Consistency of $|Z_u|$ for tone pairs: $|Z_u|$ vs. time for $G5 \rightarrow B\flat5$.



(a) Debussy 11 → 12.



(b) Debussy 14 → 15.

Figure 7.17: Consistency of $|Z_u|$ for tone pairs: $|Z_u|$ vs. time and frequency for $G5 \to B\flat 5$.

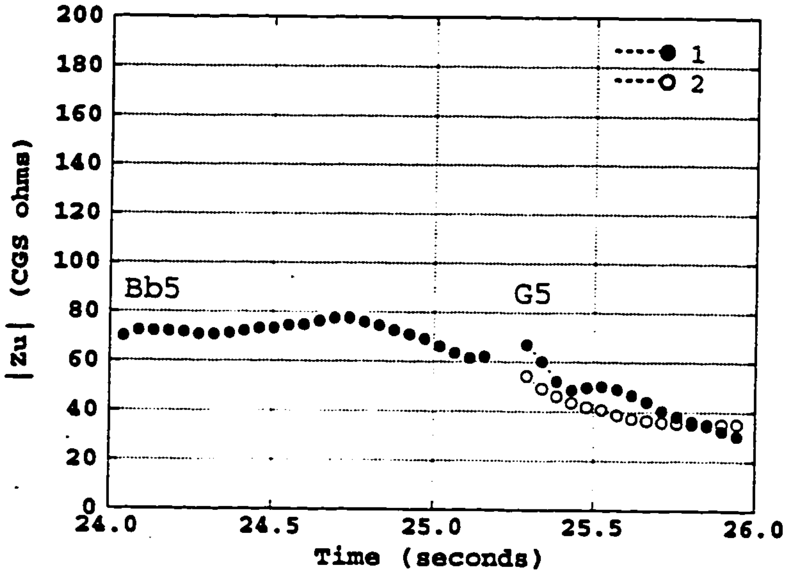
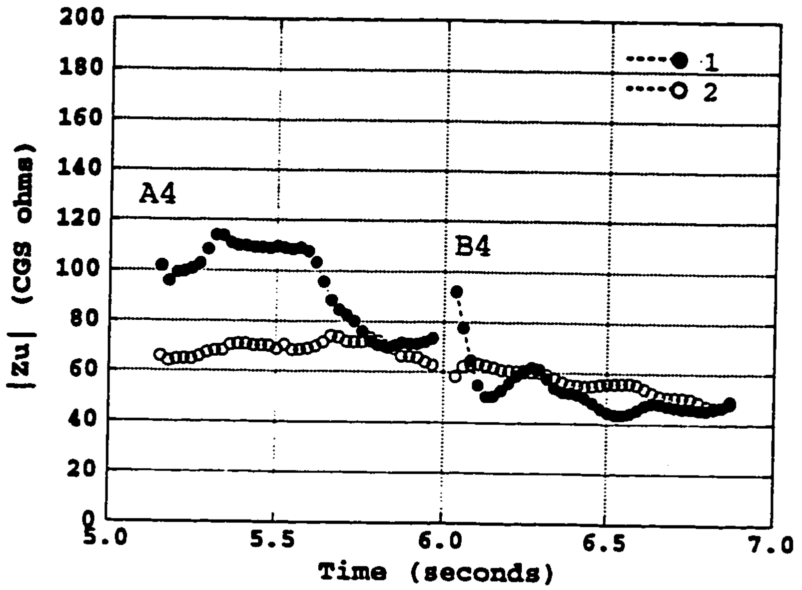
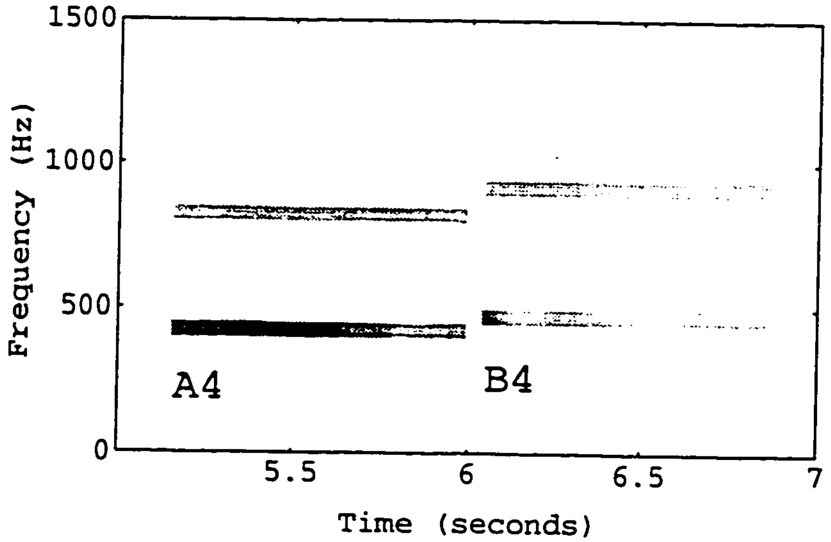


Figure 7.18: Reciprocity of $|Z_u|$ for tone pairs: $|Z_u|$ vs. time for Debussy $18 - B\flat 5 \rightarrow 19 - G5$.

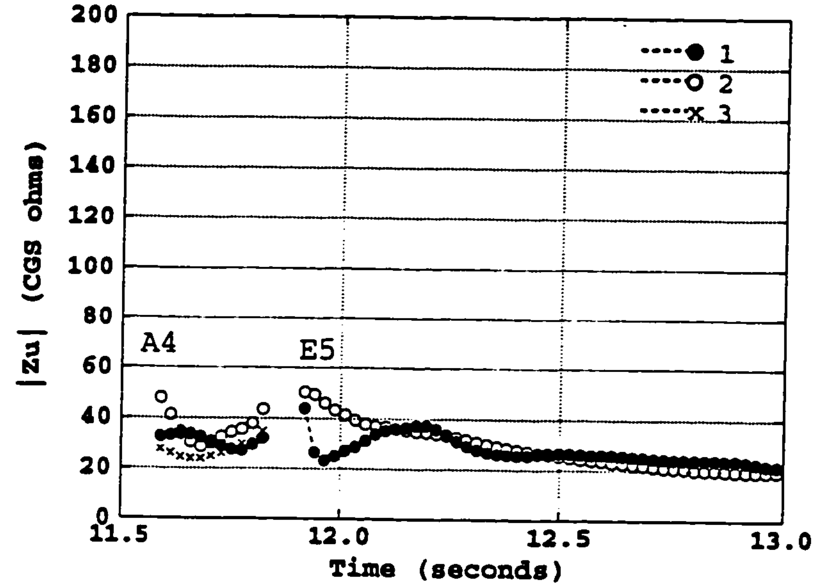


(a) $|Z_u|$ vs. time.

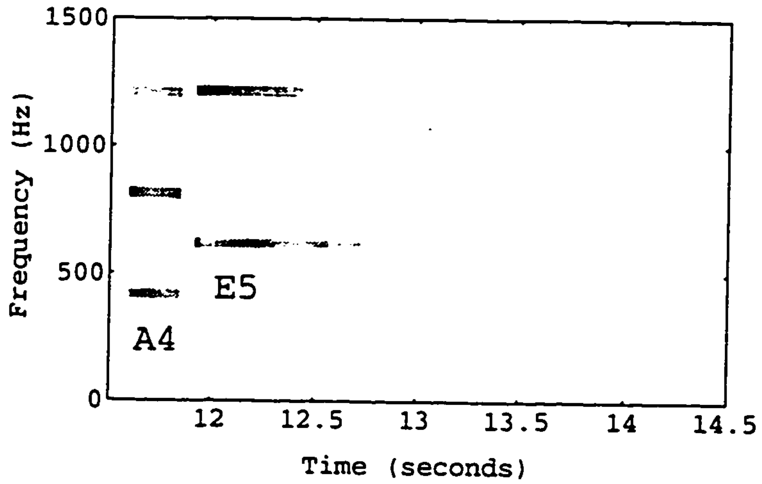


(b) $|Z_u|$ vs. time and frequency.

Figure 7.19: $|Z_u|$ for Chalumeau→Clarion intervals: Brahms $5 - A4 \rightarrow 6 - B4$.



(a) $|Z_u|$ vs. time.



(b) $|Z_u|$ vs. time and frequency.

Figure 7.20: $|Z_u|$ for Chalumeau→Clarion intervals: Brahms $14 - A4 \rightarrow 15 - E5$.

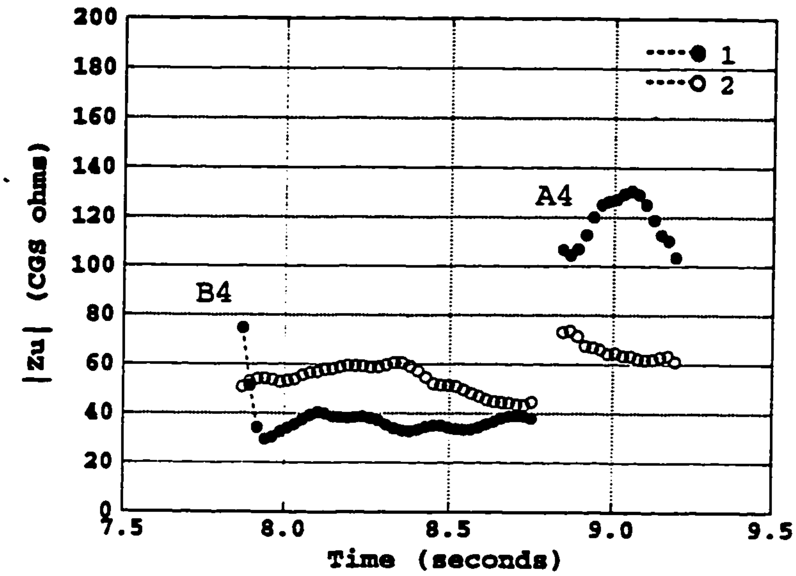


Figure 7.21: $|Z_u|$ for Clarion→Chalumeau intervals. $|Z_u|$ vs. time for the first two harmonics of Brahms 8 – $B4$ → 9 – $A4$.

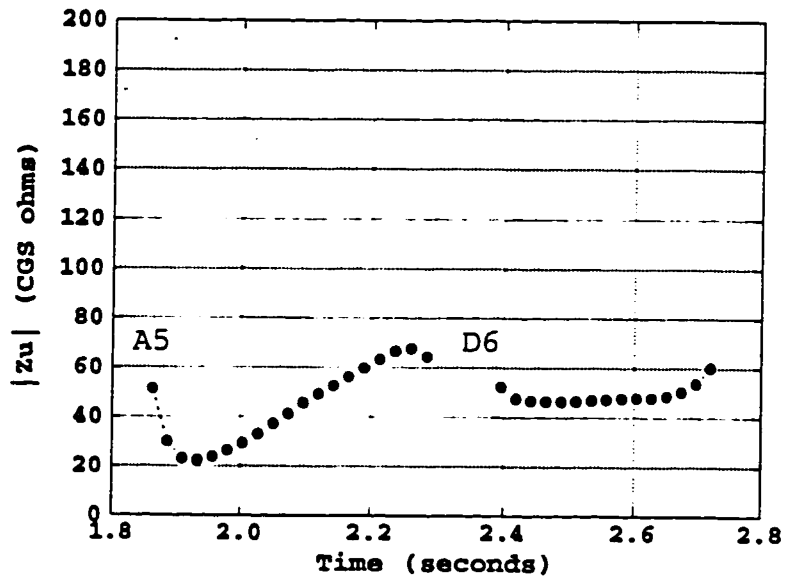


Figure 7.22: $|Z_u|$ for Clarion→Altissimo intervals. $|Z_u|$ vs. time for first harmonic of Beethoven 3 – $A5$ → 4 – $D6$.

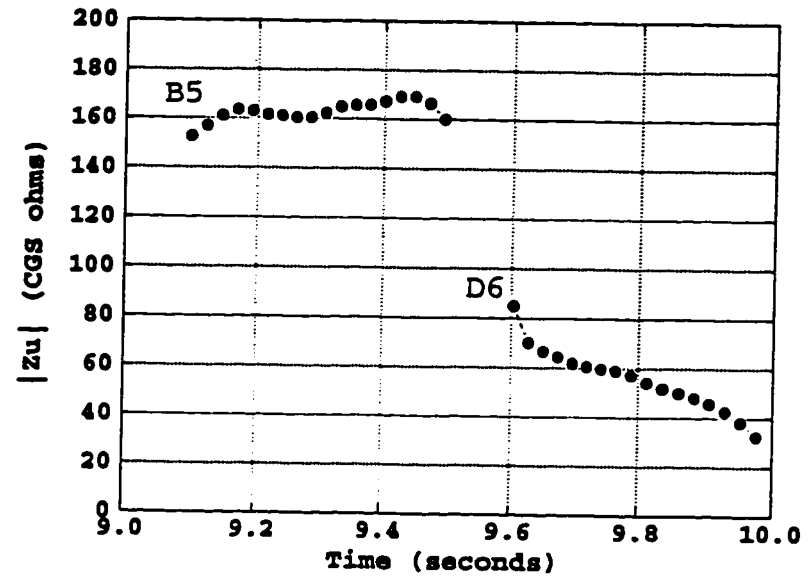


Figure 7.23: $|Z_u|$ for Clarion→Altissimo intervals. $|Z_u|$ vs. time for first harmonic of Beethoven 20 – $B5$ → 21 – $D6$.

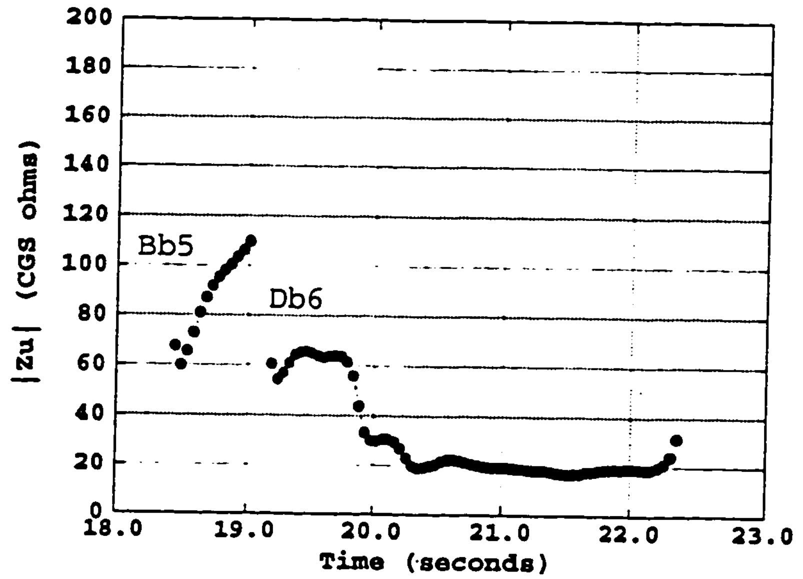
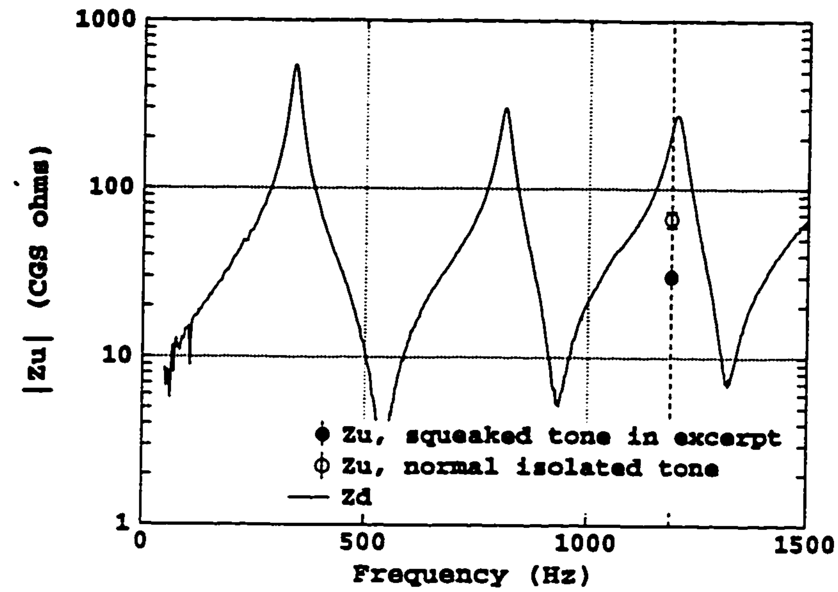
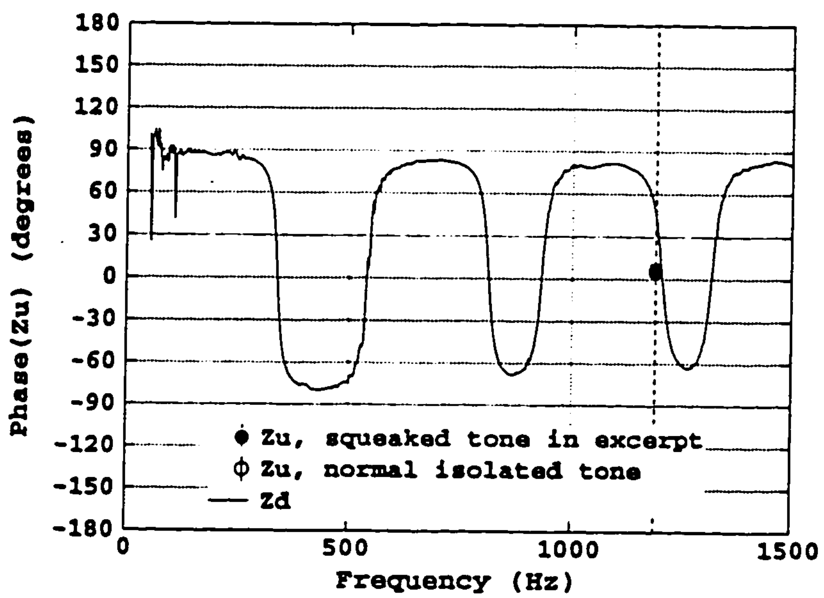


Figure 7.24: $|Z_u|$ for Clarion→Altissimo intervals. $|Z_u|$ vs. time for first harmonic of Debussy 15 – $B\flat5$ → 16 – $D\flat6$.



(a) Magnitude.



(b) Phase.

Figure 7.25: Z_u at the first harmonic and Z_d vs. frequency for Beethoven 16 – $E6$ (squeaked) and for an isolated, normal $E6$ played by the same performer.

Chapter 8

THE ROLE OF THE AIRWAYS IN CLARINET PERFORMANCE: A MUSICIAN'S PERSPECTIVE

Some clarinetists claim that the position of the tongue and the shape of the throat are important for a beautiful tone. Others say that tones must be voiced correctly, especially across intervals with a register change, to produce a good, focussed tone. This "voicing" implies that the performer somehow uses the vocal tract to affect the sound. In nontraditional playing techniques, such as multiphonics or pitchbend, performers say that using the throat can help, but directions are often vague since performers themselves often don't know exactly what they are doing with their throats. The collective anatomical parts of concern here are called the performer's airways, and include the mouth, tongue, throat, and lungs, and they are one variable that performers have at their disposal to influence the sound. Individual differences between performers playing on the same instrument may be due to how each performer uses the airways. The purpose of this study was to determine the role of the airways in clarinet playing. It looked at "normal" tone production, overtones played without the register key, pitchbend, and multiphonics. In this chapter, the results and their relevance to clarinet performance are examined from the point of view of the performer.

The airways are not easily accessible while the performer is playing, and this makes it difficult to study them. It is possible to observe various parts directly with x-ray cinematography or with a laryngoscope inserted through the nasal cavities and into the back of the throat, but this study used a different approach. The *resonances* of the performer's airways were measured to find out how they are related to the instrument resonances and if or how the performer changes them in various musical situations.

Any air column, such as the airways or the clarinet, has a set of resonances that show the frequencies where the air column can support a pressure standing wave. For example, each fingering of the clarinet is associated with a set of resonances. The resonance with the lowest frequency produces the tone normally played with that fingering. Tones can be played at the higher-frequency resonances by overblowing.

The airways also have resonances. They are at frequencies where pressure standing waves can build inside the performer's respiratory tract. In this way, the airways act like a second air column coupled to the air column of the clarinet. Airway resonances can be changed, for example, by altering the tongue position or shape of the throat, or by changing the tension of the airway walls.

Resonances are important for a musical instrument because they can provide stability for the pressure standing wave inside, producing a controllable tone. The audible tone produced by a clarinet is the sound leaking out of the bell and open tone holes from the pressure standing wave inside the air column. This pressure standing wave consists of pressure oscillations at the fundamental frequency of the tone and at harmonics or multiples of this fundamental. If the clarinet has a resonance at the frequency of the fundamental, it is possible to play a tone at that frequency. In addition, if there are resonances at harmonics of the fundamental, the pressure standing wave is more stable because instrument resonances are supporting frequencies present in the tone. What this means musically is that the tone quality will be clearer, and the tone will sound easily and be easier to control. An instrument lacking harmonically aligned resonances will produce a poor tone that will be difficult to control and therefore unreliable. It is not enough that an air column has well-defined resonances, but they must be harmonically aligned for the air column to be a good-quality instrument.

An extension of this theory is that the performer's airways can influence the sound if there is an airway resonance at a harmonic frequency of the tone. The airway resonance can strengthen an instrument resonance already at that frequency or provide a resonance at a frequency where the instrument has none. By tuning an airway resonance to a harmonic frequency, the performer can provide additional tonal stability and make up for instrumental deficiencies. Therefore, the theoretical prediction tested in this study is that the performer has an airway resonance at one or more harmonic frequencies of the tone.

There are two ways to measure the airway resonances: *directly* at the lips or *indirectly* by comparison of the mouth and mouthpiece pressures. Both were used in this study. In the direct method, a small amplitude signal is emitted into the airways at the performer's lips (see Figure 2.8). The performer fingers a note on a clarinet and forms an embouchure around a mouthpiece that has a tiny loudspeaker at the tip to emit the signal and a tiny microphone to measure the pressure response. A plastic plate replaces the reed. The sensation is similar to actual playing, but no air can be blown into the mouthpiece. As the performer pretends to play a note, the microphone measures the pressure response to the signal, which is actually a single tone that is quickly swept through a broad range of frequencies, and the airway resonances can be determined by noting the frequencies where the pressure response is large. The disadvantage of this method is that it cannot be used during performance, and the performer must imagine to play a certain tone, relying on physiological memory to correctly reproduce the airway shape.

The second way to measure the airway resonances is an indirect method that determines the resonances from a comparison of the pressures measured simultaneously in the mouth and mouthpiece during performance. The pressure measurements, combined with a measurement of the instrument resonances, give the airway resonances. For example, if the pressure in the mouth is larger than in the mouthpiece, then the airway resonance is larger than the instrument resonance.

From the direct measurement of the airway resonances, we learned that performers have two airway resonances that are in the pitch range of the clarinet: one at 200–250 Hz, which is in the low chalumeau register, and another in 400–1100 Hz, which covers the low clarion up to and including the altissimo. The performer could tune one of these resonances to the fundamental frequency of the tone played, or to higher harmonics, depending on the pitch. Performers also had resonances in the range 2000–4000 Hz that could be tuned to upper harmonics.

The resonances measured with this direct method were compared with those measured by other researchers for vowels. Although the resonances are similar, the airway configuration for clarinet playing is not exactly that for vowels. This calls into question the practice of some teachers who tell their students to think of different vowels for different registers, for example "ah" for the low register and "ee" for the high register. One explanation is that these vowel airway shapes assist beginning students to at least produce the correct sounding frequency instead of a squeak, but advanced players with a more refined tone use slightly different airway shapes.

The indirect method measured the airway resonances from a comparison of the mouth and mouthpiece pressures during actual performance. This measurement examined the role of the airways in several different musical phenomena, including musical excerpts, tones played with an "open throat" and a "closed throat", clarion tones played without the register key, clarion tones played with pitchbend, and multiphonics. For each of these phenomena the question was: Does the performer have an airway resonance tuned to a harmonic frequency, as predicted by the theory?

The indirect measurement tracked the performer's airway resonances as a function of time during the performance of short excerpts from the following pieces: Beethoven Symphony No. 8, Brahms Symphony No. 3, and Debussy Première Rhapsodie. The analysis of the tones in these musical excerpts showed that for most tones, the performer's airways were tuned to the first harmonic or to the second harmonic, or there was a resonance aligned with both the first and second harmonics. For altissimo tones, this airway resonance might be crucial to their survival. One altissimo tone that ended in a squeak had only a weak airway resonance at the fundamental frequency, while other successful altissimo tones had much stronger airway resonances. Twenty-two percent of the tones appeared to have no airway resonances tuned to a harmonic of the tone. Perhaps these tones were stable enough with the instrument resonances alone and did not need additional help from the performer's airways.

Tones of the same pitch that appeared in more than one of the three musical excerpts often showed consistent differences in their airway resonances depending upon the excerpt of origin. Tones in the same excerpt were similar to one another, while those in different excerpts had significantly different airway resonances. This suggests that the performer uses the airways differently depending on the musical context. One effect of this would be to change the tone quality. By shaping the airways to produce resonances at the desired frequencies and magnitudes, the performer can affect the radiated tone quality, although the actual process is most likely an unconscious one. The performer may be using the airways unconsciously to express a particular conception of how a passage should sound. For example, the performer thought of "floating" while playing the Debussy excerpt, and this imagery may have affected the sound via the performer's use of the mouth and throat to produce a "floating" tone quality. An entirely different tone might be suitable for the music of Brahms or Beethoven, and a slightly different airway configuration could produce this tone. To the extent that the performer can portray the mood or character of a composer's style with a particular tone quality, the airways can potentially be used in a different manner depending on the musical context.

Tones played with an "open throat" and with a "closed throat" showed one of the most striking examples of how the airway resonances can affect the tone quality. The performer who played these tones was not sure what the exact state of the airways was for an "open throat" or a "closed throat", but he believed that the open throat produced the better tone quality, and the pedagogical literature states that the throat should be open to a certain degree for a good tone. According to the performer, the tones were warm and full when played with an open throat, but brittle and shrill with a closed throat. A direct measurement of the airway resonance showed that the open throat had smaller, sharply tuned resonances, and the closed throat had broader, stronger resonances. The resonances of the open throat were at frequencies less than about 1000 Hz, with some resonances at about 2000 Hz, but the closed throat tended to have resonances between 500 and 2000 Hz. The fact that the resonances for the open and closed throats are different, both in magnitude and frequency, means that the tone quality should be different. The broad resonances of the closed throat affect a wide frequency range and are not finely tuned to any harmonic frequency, and this appears to have a detrimental effect on the tone quality. Thus by changing the degree of "openness" of the throat, the performer can affect the tone quality.

The performer consistently altered airway resonances when crossing register breaks in the musical excerpts, and differences appeared to be related to the type of register change, the direction (ascending or descending), the pitches involved, and the excerpt of origin, or the musical context. The patterns of the resonance changes were more consistent crossing the chalumeau-clarion break than crossing the clarion-altissimo break. The adjustments for intervals between the clarion and altissimo registers were more similar if they were from the same excerpt, suggesting that the performer played these intervals differently as a form of musical expression, and this was accomplished by altering the airway resonances. Although the exact function of these resonance changes is not clear, they could help the performer make a smooth transition between registers. For example, if there is an airway resonance tuned to the first harmonic of each tone in an interval, some shifting of the airway resonances, by changing the airway shape, must take place during the transition between the two tones. Exactly how the airways change shape could determine how legato the interval will sound, and the production of smooth register changes could be due to mastery of the necessary changes in the airway shape. These results support the ideas of performers who speak of "voicing" each tone in an interval, especially across register breaks, in order to play the interval smoothly. However, these airway changes may be in disagreement with the laryngoscopic measurements of Compagno [22]. He found that performers who had no laryngeal motion during intervals had audibly smoother intervals, but he did not observe other parts of the airways. The changes in the airway resonances observed here need to be correlated with physiological airway movements in order to understand how motion of the airways affects the smoothness of an interval.

The airways appeared to play a small role when playing a clarion tone without the register key, that is, overblowing the chalumeau fingering. When using the chalumeau fingering, the tone played off the first resonance is the chalumeau tone, and overblowing produces a tone from the second resonance, which is the clarion tone a major twelfth above the chalumeau tone. When playing the clarion tone with the chalumeau fingering, the airway resonance at the fundamental frequency of the clarion tone was a little stronger than when playing the chalumeau tone. This facilitates the sounding of the clarion tone, but it is not certain if the airways alone produce this effect. Performers claim that the overtones of a particular fingering are played by adjusting the embouchure, specifically the position of the lower lip on the reed. It is likely that both the embouchure and the airways are involved in this effect.

The airways were involved in playing a clarion tone with pitchbend. In the study, tones were dropped in pitch as far as the performer could drop them, a technique often called "lipping down". Although the term suggests that the pitch is dropped by loosening the embouchure, the analysis showed that the airway resonance plays a prominent role. As the pitch dropped, the airway resonance at the fundamental frequency grew in strength until it was stronger than the instrument resonance at that frequency. The airways, rather than the instrument, control the playing frequency. The embouchure may also be involved, but this was not possible to determine in this study. Considering the importance of the airways in producing pitchbend, the term "lipping down" may not be entirely appropriate, and when teaching students how to drop the pitch, teachers should focus on what the vocal tract is doing as well as on loosening the embouchure.

The airways also played an important role in the production of multiphonics. For all the multiphonics studied, the airways had a resonance that supported both of the audible pitches simultaneously. To see what this means, consider the multiphonic $F\sharp4\&A\sharp5$. For this multiphonic, the instrument had resonances at the frequencies 360 Hz and 850 Hz that supported the fundamental frequencies of $F\sharp4$ and $A\sharp5$, respectively. The airways had a resonance at 1340 Hz, which happens to be twice 850 Hz minus 360 Hz. The instrument supported the oscillations of the two tones independently, and the airways supported an oscillation that was a combination of the two individual tone oscillations, providing the coupling that allowed both tones to exist simultaneously. From this we can conclude that playing multiphonics requires learning to adjust the mouth, tongue, and throat so that the airways are tuned to the correct frequency.

Performers can also play different multiphonics with the same fingering. For these multiphonics, the instrument resonances are the same, and the performer must make either airway or embouchure adjustments to produce different pitches. Analysis showed that the airway resonances were different for two multiphonics played with the same fingering. By shifting airway resonances, the performer can detune one of the instrument resonances to prevent it from supporting another tone, or the performer can position an airway resonance so that it supports a combination of the two oscillations, as explained above.

The more prominent role of the performer's airways when playing multiphonics or tones with pitchbend is a direct consequence of the historical evolution of the clarinet. The clarinet was originally designed to play the usual tones of the chromatic scale, one at a time. Since the clarinet is designed to do this easily, the performer does not need to exert a great effort to play normal tones. On the other hand, the clarinet was not originally intended to play multiphonics or to provide a continuously variable pitch. For these cases, the performer must provide the extra stability that the instrument lacks. For multiphonics, this means that the performer must create the coupling between the two oscillation frequencies. The instrument does not have this coupling because then it would be difficult to play single tones easily. For pitchbend tones, the oscillation is based on the strong, variable airways resonance created by the performer. The instrument resonances are not variable, which creates a stable pitch, but also means that the performer must work harder to vary the pitch of a single fingering.

In summary, the role of the performer's airways in sound production is important in clarinet playing, and is more prominent for pitchbend and multiphonics than for normal tones. The airways are important because they have resonances that the performer can alter to influence the sound. Although the position of the tongue and the shape of the mouth and throat cavities are probably the main factors affecting the resonances, no attempt was made to correlate the airway resonances with physiological states. The performer can certainly control, for example, the tongue, but to what extent this control is conscious during clarinet performance is debatable. Performers admit that they do not know exactly what they are doing with their vocal tracts, and many are probably unaware that it is their vocal tract that is affecting the sound in certain situations. Clarinetists probably learn such a skill through feedback by hearing the tone and then unconsciously adjusting the airways and embouchure to improve the tone. Further research is needed to understand how clarinetists use the airways to influence the sound.

Chapter 9

CONCLUSIONS

9.1 Summary of Findings

The upstream impedance was used to examine the role of the performer's airways in the sound generation process of the clarinet. Two main predictions were tested: airway resonances are aligned with harmonic frequencies, and the inclusion of the upstream impedance in regeneration calculations satisfies the conditions for sound regeneration.

The upstream impedance for clarinet performance was measured directly and indirectly. For the direct measurement, a small-amplitude chirp signal was emitted directly into the airways at the lips from the tip of a mouthpiece attached to a clarinet. The performer pretended to play a tone on the clarinet, and a microphone measured the pressure response, from which the impedance Z_u^o was calculated. The results of the direct measurement were repeatable, and expert performers shared general characteristics. There were some minor differences between these measurements and those for airway configurations for vowels.

For the indirect measurement, the mouth and mouthpiece pressures were measured simultaneously during performance, and the instrument impedance was measured. The upstream impedance Z_u was calculated from these three quantities using the continuity of flow equation ($p_u/p_d = -Z_u/Z_d$). Since the mouth pressure and the instrument impedance were measured at slightly different locations, a significant phase shift between these two quantities was present for frequencies greater than about 1500 Hz. This indirect measurement was therefore valid only for frequencies less than 1500 Hz. For frequencies above this range or in cases where an indirect measurement of the upstream impedance is unavailable or unreliable due to strong nonlinearities, the presence of upstream resonances can still be inferred using the mouth pressure spectra, since peaks in the noise of the mouth pressure spectrum appear to be associated with upstream impedance peaks.

The upstream impedance was measured directly for single, normal clarinet tones and for tones played with an open and a closed throat. It was measured indirectly in the following musical situations: tones played at different dynamic levels, tones played with an "open throat" and a "closed throat", clarion tones played without the register key, clarion tones played with pitchbend, multiphonics, and musical excerpts.

The validity of the indirect method was tested by comparing the upstream impedances measured directly and indirectly on tones with low-amplitude mouthpiece pressure waveforms, which are assumed to be approximately linear oscillations. The indirect method reliably measured the magnitude for clarion and altissimo tones. The phase was more uncertain due to noise in the direct measurement. For chalumeau tones the magnitude was less reliable, and the phase often took on values greater than 90 degrees, which is unphysical for a dissipative system. There are three possible explanations for this. These unphysical phase values could be due to an incorrect assumption of linearity for these tones. Another explanation is that the airways are no longer a dissipative system due to glottal vibrations under playing conditions for these tones. A third explanation is that the instrument impedance Z_d has a nonlinear component that is not present in the linear measurement of Z_d used in the indirect Z_u measurement. From the data measured here, none of these explanations can be rejected.

The prediction that upstream resonances will be aligned with harmonic frequencies of a tone was verified in most cases. Exceptions were some clarion tones in the musical excerpts. It is possible that the clarion tones in the musical excerpts were stable enough with the instrument impedance alone. For normal tones in the other registers, Z_u had a small effect on the regeneration conditions. For chalumeau and altissimo tones, a large value of $|Z_u|$ at the fundamental frequency decreased the energy dissipation at that frequency, which may be critical for altissimo tones, as demonstrated by one squeaked altissimo tone in the musical excerpts that had a low value of Z_u. Z_u tended to greatly improve the playing frequency stability at the even harmonics. Z_u had a stronger effect at even harmonics because Z_d was low at those frequencies.

The magnitude of Z_u decreased as dynamic level increased, consistent with an increasing glottal diameter. The phase of Z_u for one tone increased greater than 90 degrees, but the other tone showed different phase behavior. More data are needed to explain the changes in phase with dynamic level, which could be due to the invalidity of the linearity assumption or to glottal vibrations.

Tones played with a closed throat had a higher overall value of $|Z_u^o|$ than tones played with an open throat. Closed throat tones generally had two broad peaks in the range 500–2000 Hz, where open throat tones had only one narrow peak.

There were small but consistent differences in Z_u for clarion tones played with and without the register key. $|Z_u|$ increased by no more than 40 CGS ohms at the fundamental for tones without the register key compared to tones with the register key. The change was small compared to $|Z_d|$ at that frequency but did support the production of the clarion tone. The airways may play a role in this phenomenon, but adjustment of the reed resonance frequency via embouchure changes may also play a role, as performers claim.

Tones played with pitchbend had values of $|Z_u|$ at the first harmonic of 130–470 CGS ohms. The fundamental frequency of the tone was controlled by the frequency of the large upstream resonance created by the performer. The reed resonance could also play a role, but this was not possible to determine here.

The upstream impedance for multiphonics had at least one upstream resonance at a frequency that was a simple linear combination of the instrument modal frequencies of the two oscillations. This differs from the hypothesis put forth by Benade, who suggested that the performer aligns an airway resonance with one of the instrument modes. Different multiphonics played with the same fingering had different upstream resonances, suggesting the performer shifts resonances in order to produce the different tones. The upstream resonances were associated with broad humps in the mouth pressure spectra.

Tones in musical excerpts had large values of $|Z_u|$ at either the first harmonic, both the first and second harmonics, or at no harmonics. Altissimo tones may require a large value of $|Z_u|$ at the first harmonic in order to avoid a squeak, and one example was given. Tones of the same pitch generally had consistent patterns of $|Z_u|$, but there was some variation, and tones within the same excerpt were more consistent, possibly indicating that the performer uses the airways differently depending on the musical context. Tones at the beginning of a phrase had a decrease in $|Z_u|$ at the first harmonic at the beginning of the tone, and tones at the end of a phrase had a decrease in $|Z_u|$ at the first harmonic at the end of the tone. Tonguing caused the harmonic in the frequency range 500–1100 Hz to drop. Melodic intervals across register breaks often showed consistent differences that correlated with register, direction of interval, pitches involved, and excerpt of origin.

The effect of the reed was not measured directly, but the reed may be involved in playing clarion tones without the register key since the changes in the upstream impedance were small compared to the downstream impedance, and it may play a role in pitchbend. Since the frequency range of the indirect upstream impedance measurement was restricted to under 1500 Hz due to the experimental set-up, the frequency range of the reed resonance was excluded from the analysis, and direct effects of the reed resonance could not be observed.

9.2 Future Work

This study has examined the upstream impedance in a variety of performance situations and suggests that the performer uses the airways to stabilize the tone, produce effects such as pitchbend and multiphonics, and possibly affect the tone color in different musical contexts. Based upon these results, we can begin to define the role of the airways more clearly, and several areas that can now be addressed are listed below.

The role of the airways in playing clarion tones is not clear. These tones showed more variability than tones in the other registers and could have resonances aligned with one, two, or no harmonic frequencies. It appears that the exact configuration of the airways is not as crucial for tone stability in this pitch range, and the airways may fulfill some other function such as controlling tone color. The influence of the airways is more complex than described by the current theory, and this influence needs to be further clarified.

There are details of pitchbend tones that are not explained by the current theory. Z_u usually reached its maximum before the playing frequency had reached its minimum. The value of Z_u at the first harmonic proceeded to drop even though the playing frequency had stabilized.

Many questions remain concerning the role of the reed. Exactly how does a change in the embouchure affect the reed resonance, reed compliance, and hydrodynamics at the reed tip in order to produce a register change or pitchbend? What is the role of the reed in normal tone playing?

There is no well-defined criterion for determining reed tip closure, given pressure measurements alone. A measurement of the reed displacement will tell the reed motion restriction, but how this appears in the mouth and mouthpiece pressures is not understood. It would be helpful to have a criterion for reed tip closure that can be determined from the pressures alone.

The relation between Z_u and the physiological state of the airways, including the position of the tongue and the shape of the throat, should be studied in order to determine how the directives given by teachers to students ultimately affect the sound. Measurements of the upstream impedance for beginning players will show how performers at different skill levels use the airways.

Most importantly from a musical point of view, the relation between Z_u and tone quality should be studied. If the correct use of the airways is essential in producing a beautiful tone, then understanding this relation is necessary for a complete picture of wind instrument sound production.

In the long run, all the factors that go into producing a musical tone will have to be incorporated and the interrelationships between them worked out. The airways are just one piece of the puzzle. As performer C stated, your total sound depends on your air, the vocal tract, and the embouchure all together; they cannot be separated. In addition, C said that the concept of your sound also depends on the other musicians with whom you are playing. Performing with singers often requires a different sound than when performing with other instrumentalists, and so tone quality is not something that remains constant in all situations. Wind instrument sound production will not be fully understood until all these variables and their interdependence are taken into consideration.

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Appendix A

FREQUENTLY-USED SYMBOLS

Impedance

Z_u	calculated upstream (airway) impedance
Z_u^o	measured upstream (airway) impedance
Z_d	downstream (instrument) impedance
Z_r	reed acoustic impedance
Z	total impedance of airways, instrument, and reed
$\|Z_u\|$	magnitude of Z_u
$\Phi(Z_u)$	phase of Z_u

Admittance

Y_G	generator admittance
Y	admittance of airways, instrument, and reed
Y_{dr}	admittance of instrument and reed

Pressure

p_u	upstream pressure
p_d	downstream pressure
p	$p_d - p_u$
p_0	DC component of p
p_{min}	minimum blowing pressure
p_{th}	threshold blowing pressure
p_c	closing pressure of reed
p_i'	pressure with standing wave effects removed

Flow

u	flow down the instrument
u_0	DC component of u

u_u	upstream flow
u_d	downstream flow
u_r	flow swept out by reed

Frequency

f_i	frequency of a pressure peak
f_{mn}	intermodulation frequency of a multiphonic
f_o	basis frequency of a multiphonic
f_r (ω_r)	reed resonance frequency in Hz (in radians)
f_i^z	frequency of an impedance peak
Δf	full-width at half-maximum of a peak

Miscellaneous

Q	$= f/\Delta f$ quality factor (f = peak frequency)
Q_r	reed quality factor
R	peak height ratio $\|Z_u\|/\|Z_d\|$
λ	wavelength
I	inertance
δl	length correction
N	length of pressure time series used to calculate Z_u
G_{uu}	$=< \|p_u\|^2 >$ autospectrum of p_u
G_{dd}	$=< \|p_d\|^2 >$ autospectrum of p_d
G_{du}	$=< p_d^* p_u >$ cross-spectrum of p_u and p_d
C	$= \|G_{du}\|^2/(G_{dd}G_{uu})$ coherence
h	reed channel height
L	reed channel length
v_i	measured voltage signal from transducers
S	transducer sensitivity
T	$= p_2/p_1$ transfer function between two mouthpiece positions
A, B, C, D	coefficients of ABCD transmission line matrix
ρ	density of air
c	speed of sound
S	an area

A	reed transconductance
g_r	reed damping coefficient
B	scaling factor in nonlinear flow relation
μ, ν	exponents in nonlinear flow relation
x	reed tip displacement
x_0	DC component of x
H	static reed opening
μ_r	dynamic mass per unit area of reed
D_r	static reed compliance
D_n	dynamic reed compliance

number-pitch Ex. 3 – *D*♭5: The third tone in an excerpt, and it is a written *D*♭5. All notes are written pitches for the *B*♭ clarinet, which actually sounds a whole step lower.

Appendix B

IMPEDANCE OF THE CLARINET

The Figures in this Appendix plot the impedance of a Buffet R-13 clarinet for 13 fingerings across the pitch range of the clarinet. Each plot shows the magnitude of the impedance in CGS ohms vs. frequency up to 5000 Hz for each fingering. The fingerings range from the lowest on the instrument, *E*3, up to *G*6 near the high end. The impedance was measured for four of the chalumeau fingerings (*E*3, *A*3, *C*4, *E*4) and their corresponding clarion fingerings (*B*4, *E*6, *G*5, *B*5), obtained by opening the register key. Two throat tones (*G*4, *B*♭4) and three high tones (*C*6, *E*6, *G*6) were also measured.

Except for *E*3 and *B*4 there was an open tone-hole lattice cut-off frequency at about 1500 Hz above which the peaks were no longer regular. The cut-off frequencies for *E*3 and *B*4 differed from those of the other tones and are determined by the radiation out the bell since there is no open tone-hole lattice for these two fingerings.

The highest peak value was for *E*4, with a fundamental peak of almost 1200 CGS ohms. The lowest fundamental peaks were for the low clarion tones *B*4 and *E*5, which had peaks of 400–500 CGS ohms. Fingerings that have more tone holes closed, such as *E*3 and *B*4, would have larger standing wave amplitudes along the air column and therefore larger wall losses, leading to lower impedance peaks. Another explanation for the low impedance peaks for these fingerings could be performer unsteadiness in keeping all the tone holes sealed.

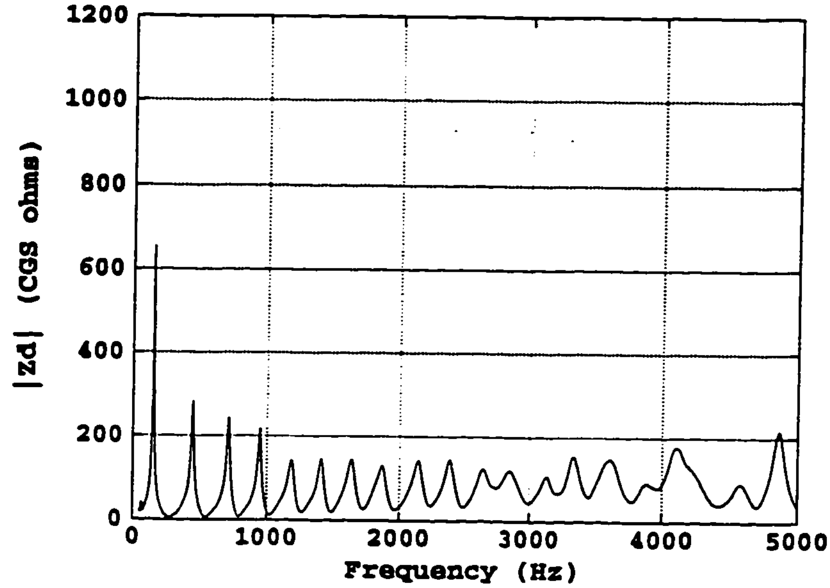


Figure B.1: $|Z_d|$ for $E3$.

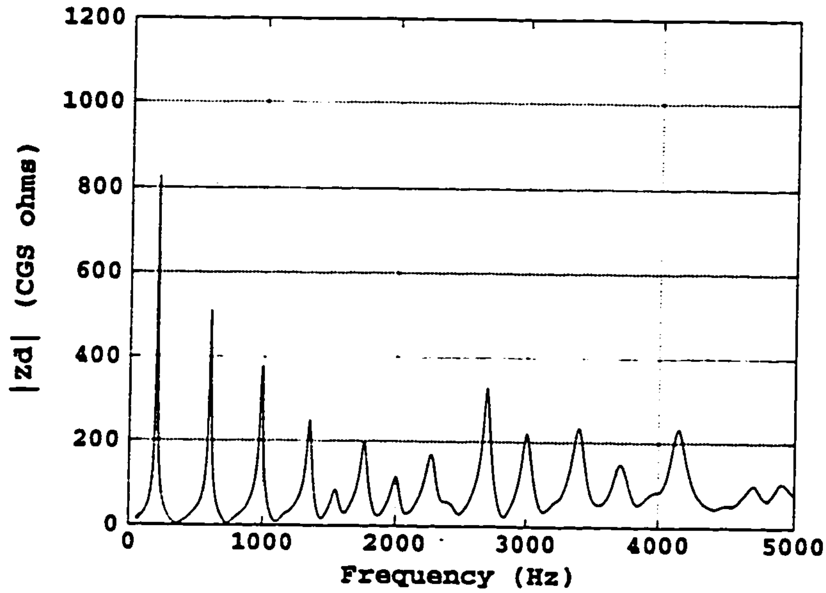


Figure B.2: $|Z_d|$ for $A3$.

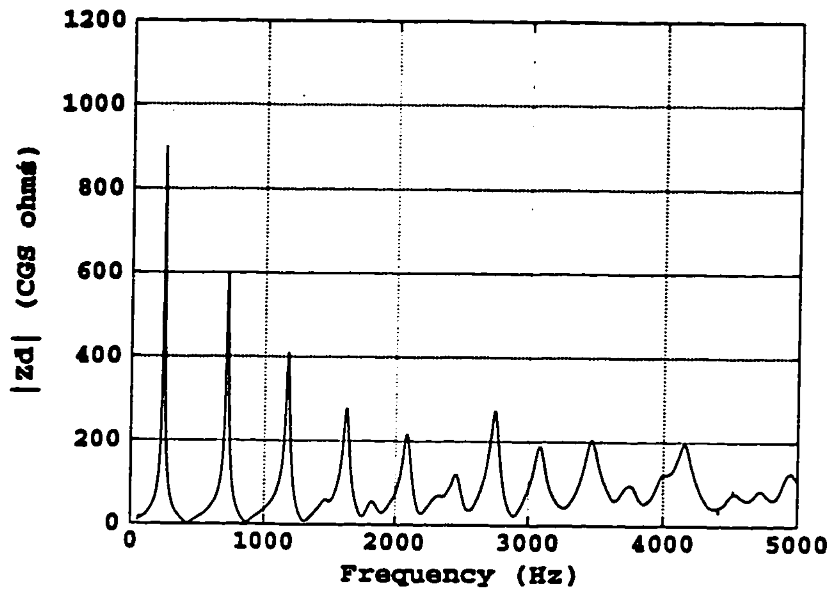


Figure B.3: $|Z_d|$ for $C4$.

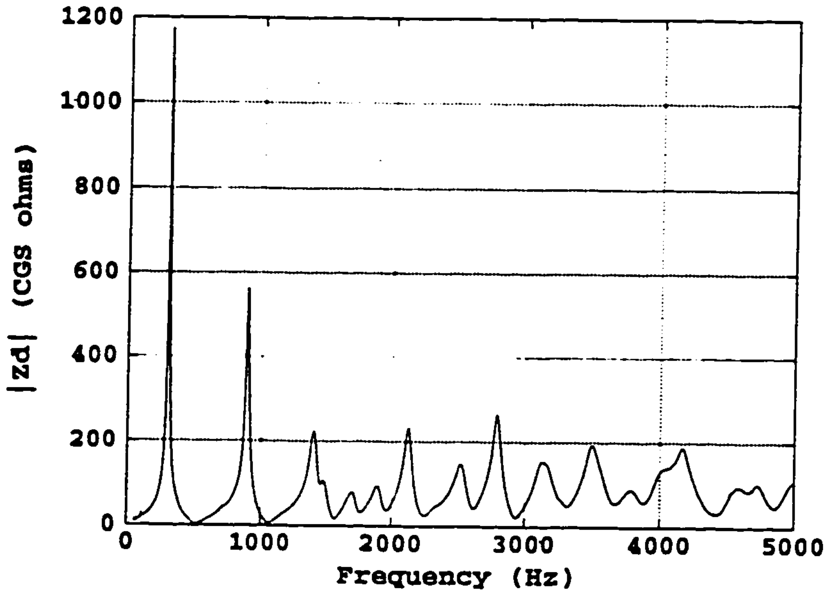


Figure B.4: $|Z_d|$ for $E4$.

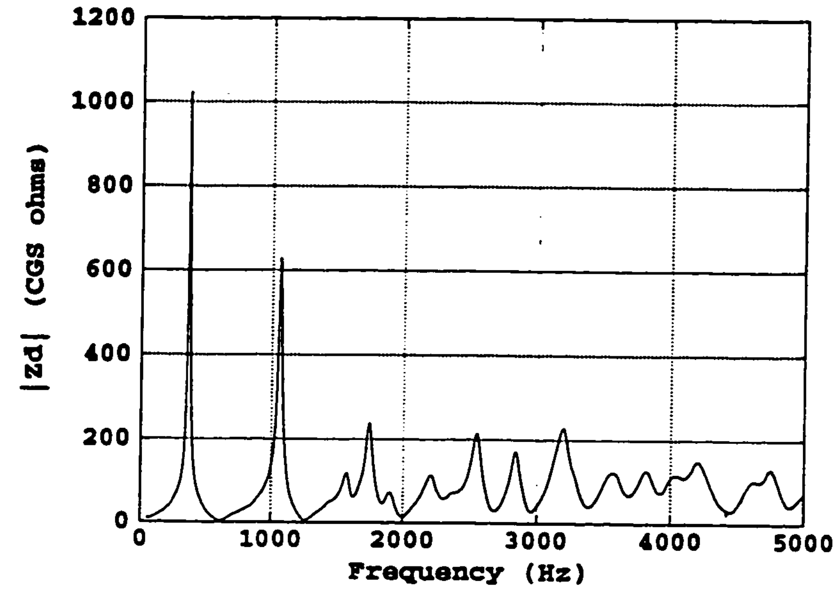


Figure B.5: $|Z_d|$ for $G4$.

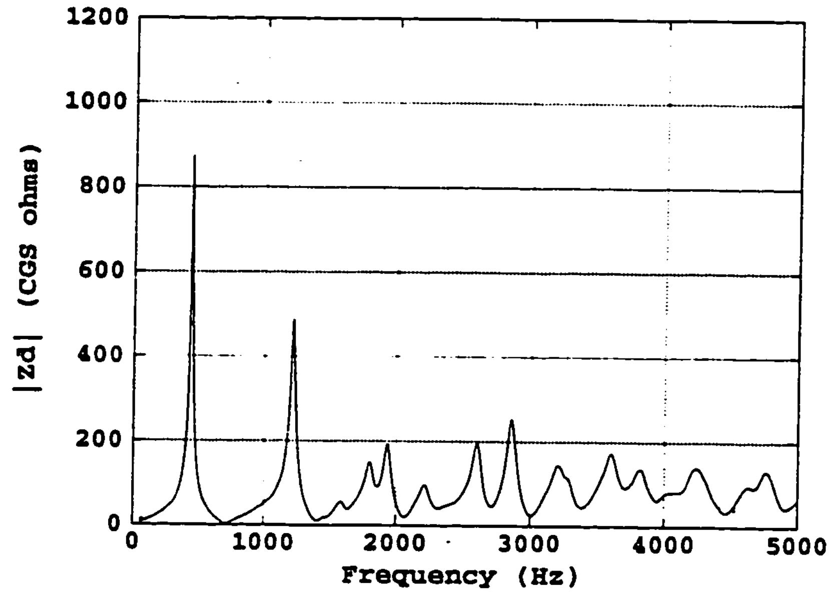


Figure B.6: $|Z_d|$ for $B\flat4$.

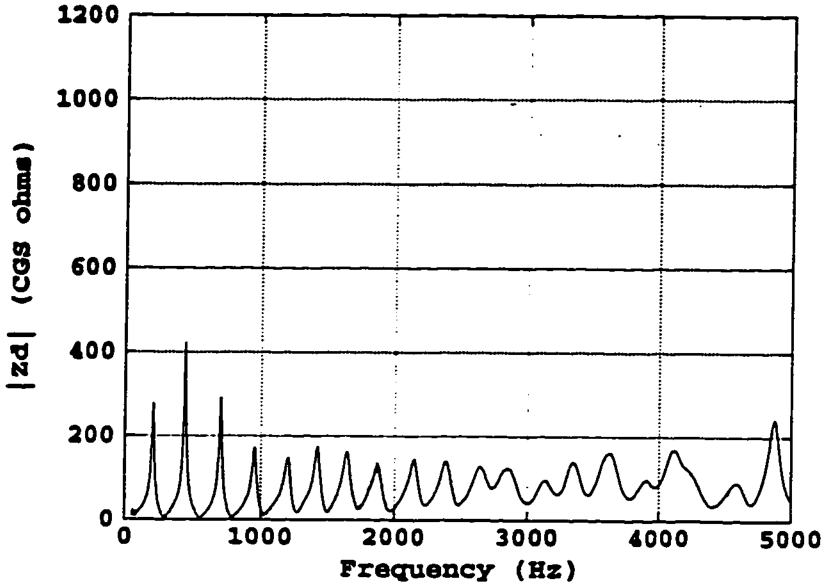


Figure B.7: $|Z_d|$ for $B4$.

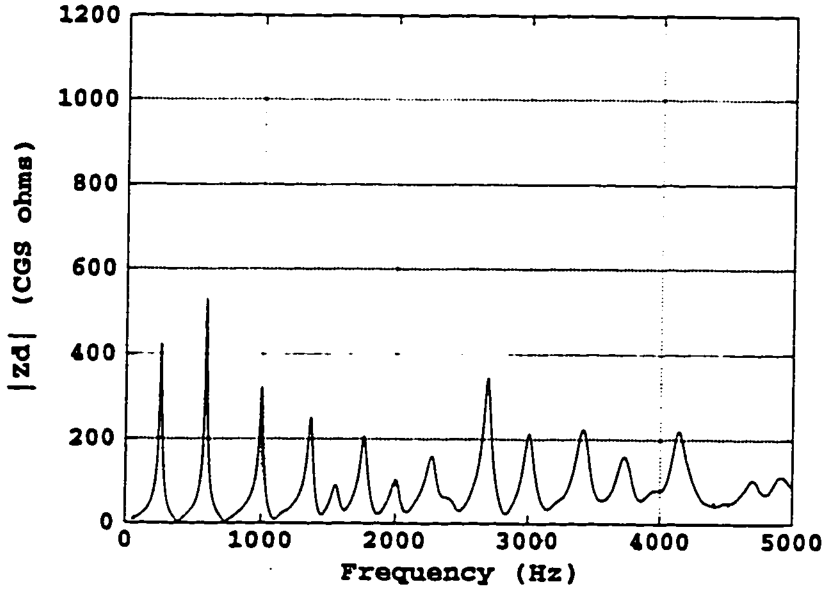


Figure B.8: $|Z_d|$ for $E5$.

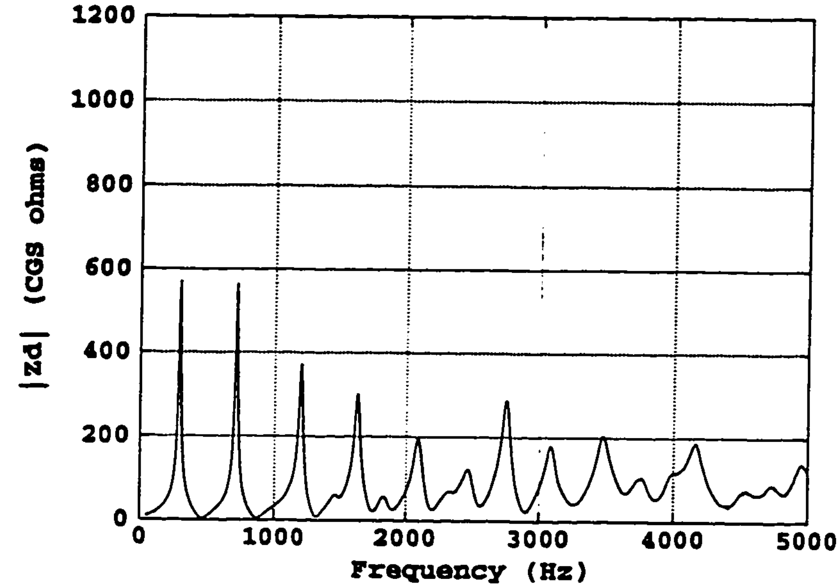


Figure B.9: $|Z_d|$ for $G5$.

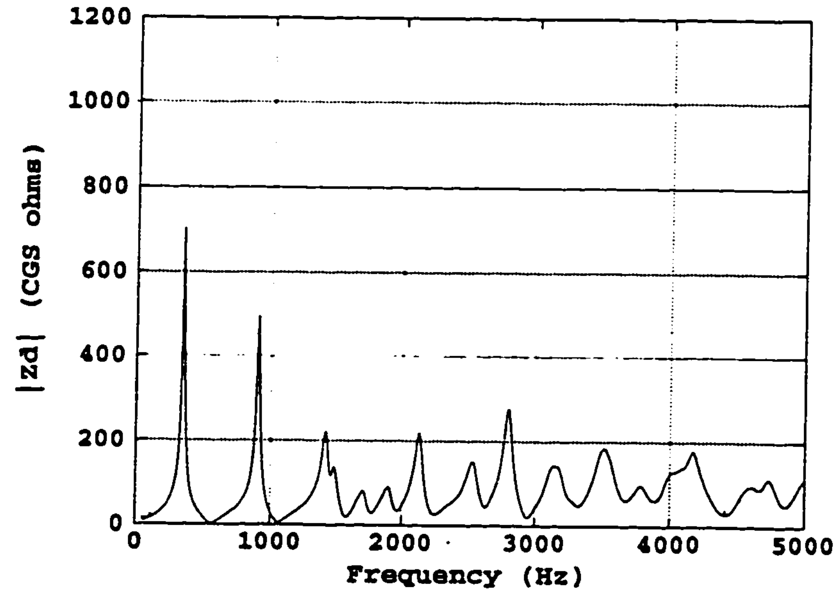


Figure B.10: $|Z_d|$ for $B5$.

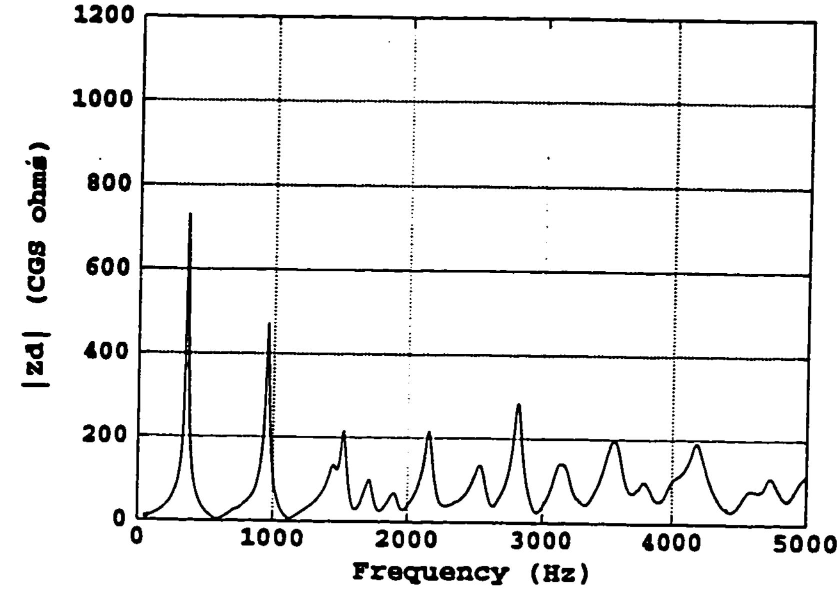


Figure B.11: $|Z_d|$ for $C6$.

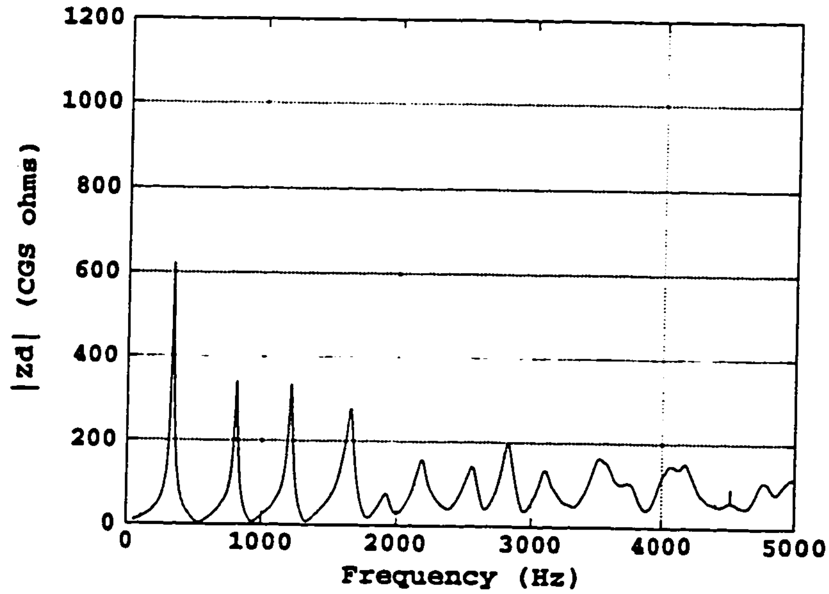


Figure B.12: $|Z_d|$ for $E6$.

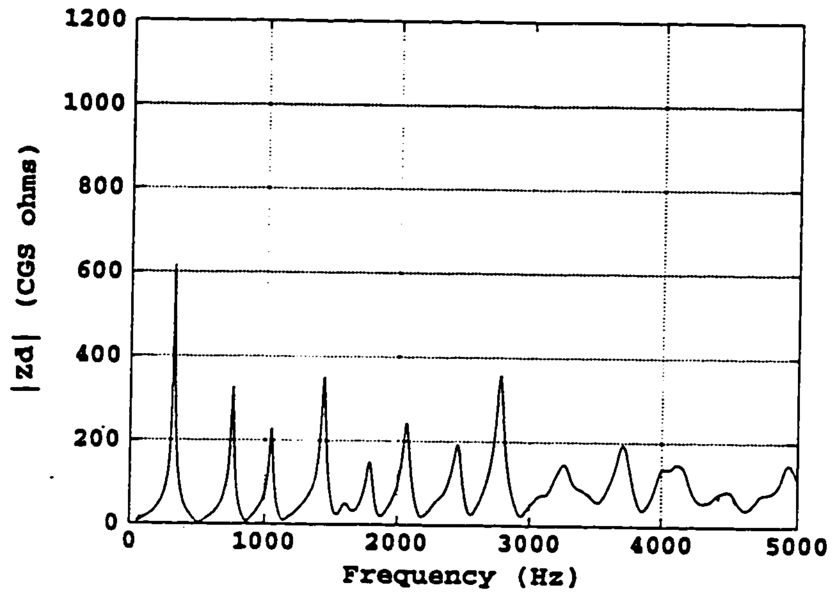


Figure B.13: $|Z_d|$ for $G6$.

Appendix C

MEASUREMENT OF THE REED ACOUSTIC COMPLIANCE

C.1 Introduction

One of the parameters necessary for sound regeneration calculations is the dynamic area of the reed, S_r. There has been no direct measurement of S_r, but it is possible to calculate S_r from a measurement of the reed acoustic compliance C_r using the relation

$$C_r = S_r D_r \qquad \text{(C.1)}$$

D_r is the reed mechanical compliance and can be calculated from

$$D_r = \frac{H}{p_c} \qquad \text{(C.2)}$$

where H is the equilibrium reed tip opening and p_c is the reed closing pressure.

Researchers have used estimates for S_r in their physical models. Nederveen [57] assumed that the maximum moving length of the reed for double reeds is three times the width and for single reeds is even less. Thus he estimated that S_r falls in the range $0.2B^2 < S_r < 2B^2$, where B is the width of the reed tip. For a value of $B =$ 1.3 cm as for the soprano clarinet, S_r would be in the range $0.338 < S_r < 3.38$ cm^2. Worman [75] estimated the area of the reed tip back 1.1 cm to get $S_r = 1.46$ cm^2, which is near the center of Nederveen's range. Schumacher [62] used Worman's value in his calculations. However, Thompson [71, 72] claimed that Worman's value was too large since it is almost the entire moving area of the reed. S_r is the "effective" moving area of the reed, that is, the area that would sweep out the same volume as the reed if it were all moving with the same amplitude as the reed tip, and therefore it should be less than the total moving area of the reed. Thompson took S_r to be about one-half of Worman's value, assuming the reed vibrates as a hinged plate and has some curvature.

This Appendix reports efforts in an attempt to measure C_r in order to find an empirical value for S_r.

C.2 Theory

The reed acoustic compliance C_r is related to the reed admittance Y_r, which at low frequencies can be approximated as a compliance:

$$Y_r = j\omega C_r. \tag{C.3}$$

If Y_r can be measured, then C_r can be calculated from it.

One way to find Y_r is to consider the input admittance Y_{in} measured from the instrument end of the mouthpiece, in the direction of the mouthpiece tip, as shown in Figure C.1. The total admittance Y_{in} can be calculated from a transmission line model in which the air column of the mouthpiece is terminated by the sum of radiation admittance Y_{rad} and the reed admittance Y_r:

$$\begin{pmatrix} p_{in} \\ u_{in} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} p_r \\ p_r(Y_{rad} + Y_r) \end{pmatrix} \tag{C.4}$$

p_r is the pressure radiated out of the mouthpiece tip. The elements of the ABCD matrix represent the air column of the mouthpiece. The radiation admittance Y_{rad} is due to the airways if the mouthpiece is held in a normal, performance embouchure, or is due to radiation to the open air if the reed is closed down with the thumb. The input admittance is then

$$Y_{in} = \frac{u_{in}}{p_{in}} = \frac{C + D(Y_{rad} + Y_r)}{A + B(Y_{rad} + Y_r)} \tag{C.5}$$

A measurement of Y_{in} will give Y_r if Y_{rad} and the ABCD elements are known. The ABCD elements can be found from a measurement of Y_{in} with the reed window sealed off with a brass plate. In this case Y_{rad} and Y_r are both zero and the resulting transmission line equation is:

$$\begin{pmatrix} p_{in} \\ u_{in} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} p_r \\ 0 \end{pmatrix} \tag{C.6}$$

The mouthpiece can be modelled as a series of cones and cylinders. Y_{in} for the model mouthpiece is calculated and the dimensions are varied until a good match is reached between the modelled and measured Y_{in}.

Y_{rad} can be found from a measurement of Y_{in} using a brass reed closed down to the equilibrium opening H during performance. The resulting transmission line equation is:

$$\begin{pmatrix} p_{in} \\ u_{in} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} p_r \\ p_r Y_{rad} \end{pmatrix} \tag{C.7}$$

The brass reed can be closed down with the thumb, in which case Y_{rad} will be the radiation admittance of the slit opening, or the mouthpiece can be held in the mouth as during performance, and Y_{rad} will be the input admittance of the airways.

Finally, Y_r can be calculated from Eqn. C.4 from a measurement of Y_{in} with the cane reed closed down with the thumb or with a performance embouchure, whichever one was used to find Y_{rad}.

C.3 Measurements

The ABCD matrix elements were obtained from a measurement of the mouthpiece sealed off with a brass plate. Y_{rad} was obtained using a brass reed with the profile (but not the thickness) of a cane reed. The sides were sealed with epoxy to prevent leaks, and the reed was closed down with the thumb to a distance $H \approx 0.4$ mm, as measured with a spark plug gauge. Y_r was obtained using a wet cane reed (Vandoren V12 # 4), closed down with the thumb to the same distance.

C.4 Results

C.4.1 Y_{mp}

The mouthpiece was modelled as one cylinder and two cones, as shown in Figure C.2. In the model that was optimized to agree with the measured Y_{in}, the cylinder had a radius of 7.15 mm and a length of 41 mm. These were the actual dimensions of the cylindrical portion of the mouthpiece, minus a 13 mm length section that was taken up by the insertion of the foam tip. At the end of the cylinder was a short cone of length 2 mm, with a radius that decreased from 7.15 mm to 6.3 mm. This short cone was necessary to model the mouthpiece bore discontinuity that occurs at this point when the bore changes from circular cross-section of radius 7.15 mm to rectangular cross section of dimensions 14.3 mm x 8.4 mm. Following the short cone was a longer cone representing the rest of the mouthpiece, of length 31 mm, and a radius that decreased from 6.3 mm to 3 mm. Figure C.3 shows the measured and calculated imaginary part of Y_{in} up to 5000 Hz for the optimized air column dimensions. There is good agreement up to about 3000 Hz.

C.4.2 Y_{rad}

Two measurements of Y_{in} were averaged together in order to calculate Y_{rad} from Eqn. C.7. Figure C.4-a shows the real and imaginary parts of Y_{rad} between 300 and 3000 Hz. Data below 300 Hz were noisy. Y_{rad} can be considered purely imaginary over this frequency range and represents the radiation inertance of the mass of air in the reed channel. Assuming Y_{rad} is a pure inertance,

$$Y_{rad} = \frac{1}{j\omega I_{rad}} \tag{C.8}$$

I_{rad} is plotted in Figure C.4-b, and it is approximately a constant inertance of value I_{rad} =0.002 g/cm^4 in the frequency range 1200–2000 Hz.

Backus found experimentally that I_{rad} (what he called M) was in the range 0.008–0.020 g/cm^4, and it depended on the slit opening H. For $H = 0.4$ mm as used here, Backus measured $I_{rad} \approx 0.014$ g/cm^4 but calculated a value $I_{rad} \approx 0.003 - 0.004$ g/cm^4 from a model that assumed a reed width $w = 1.5$ cm and a reed channel length $l = 0.05$ cm, which are approximately the values for the mouthpiece used in these measurements. The value for I_{rad} measured here with the brass reed is closer to the theoretical values calculated by Backus, although there was uncertainty in the measurements here due to the fact that the reed opening was held at the distance H by the thumb.

C.4.3 Y_r

Four measurements of Y_{in} measured with the cane reed were averaged together, and then Y_r was calculated from Eqn. C.4 using the values for the ABCD matrix elements and Y_{rad} found in the previous two steps. Figure C.5-a shows the real and imaginary parts of Y_r between 300 and 3000 Hz. Y_r can be considered purely imaginary only between about 300 and 1500 Hz. In this range, the reed compliance C_r can be calculated from Eqn. C.3 and is plotted in Figure C.5-b with a log scale for the y-axis. The compliance is not constant with frequency but decreases approximately exponentially. The frequency dependence of C_r implies that the effective reed area varies with frequency and suggests a frequency-dependent modal structure.

The values of C_r from this measurement ranged from 2x10^{-6} to 2x10^{-5} cm^4s^2/g. The dynamic area of the reed calculated from these values, using Eqn.C.1 with H = 0.04 cm and p_c = 60000 dyne/cm^2, ranged from 3 to 30 cm^2. These values are larger than previous estimates, and larger by more than an order of magnitude for frequencies less than 500 Hz. A value of 30 cm^2 for the effective moving area of the reed is unrealistic, and therefore this method for measuring C_r needs further refinement in order to give accurate values.

There are several difficulties associated with this type of measurement. There are practical problems, such as the decrease in visco-thermal damping along the reed when using a brass reed instead of a cane reed. Perhaps a more fundamental problem is the fact that an attempt is being made to measure a single value for C_r when it most likely depends on several variables. The reed has a variable thickness along the length, and so C_r will vary along the length of the reed. During the course of an oscillation, the reed bends along the lay of the mouthpiece, changing the fraction of the length that is free. The reed compliance becomes a function of time. A measurement of C_r should take these factors into account.

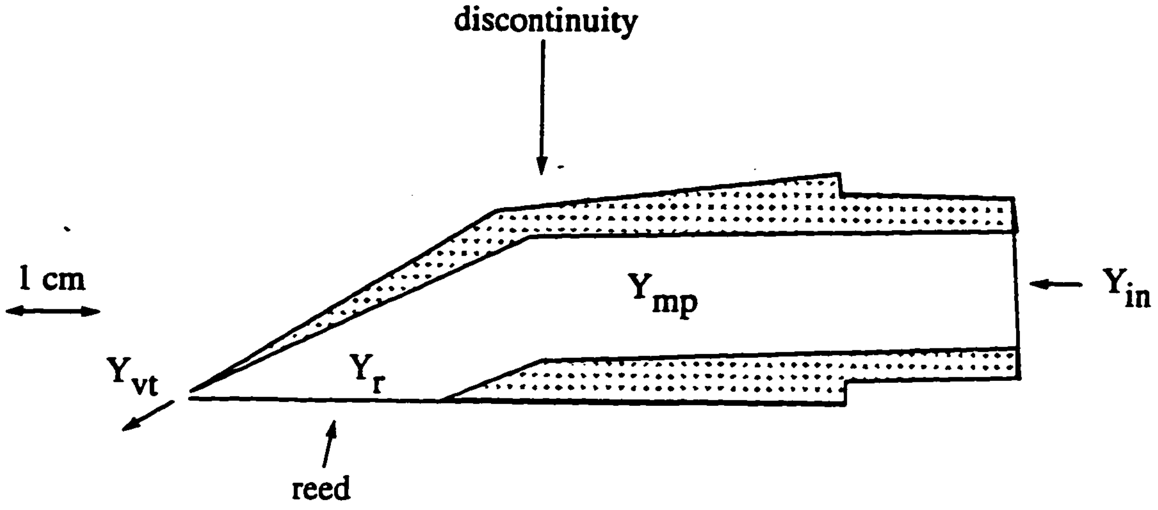


Figure C.1: The admittances used to find Y_r.

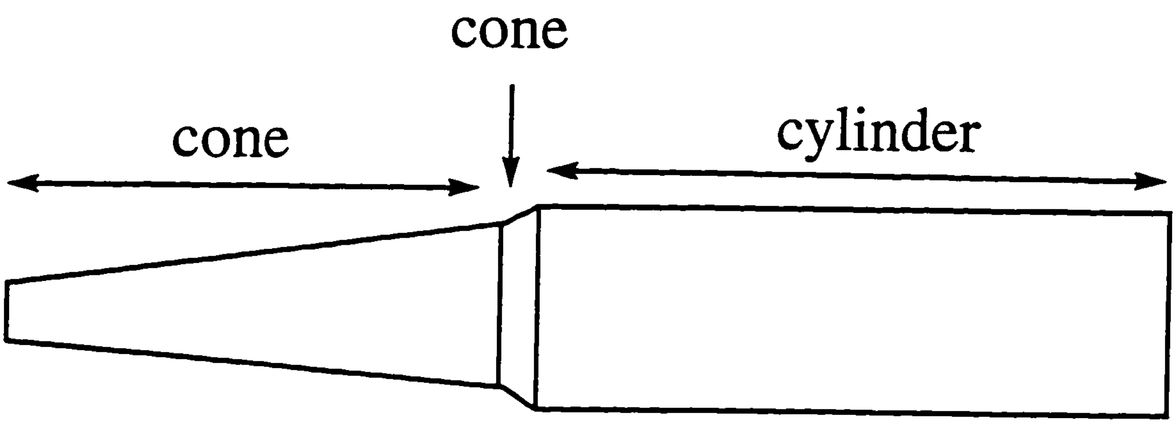


Figure C.2: Model of clarinet mouthpiece.

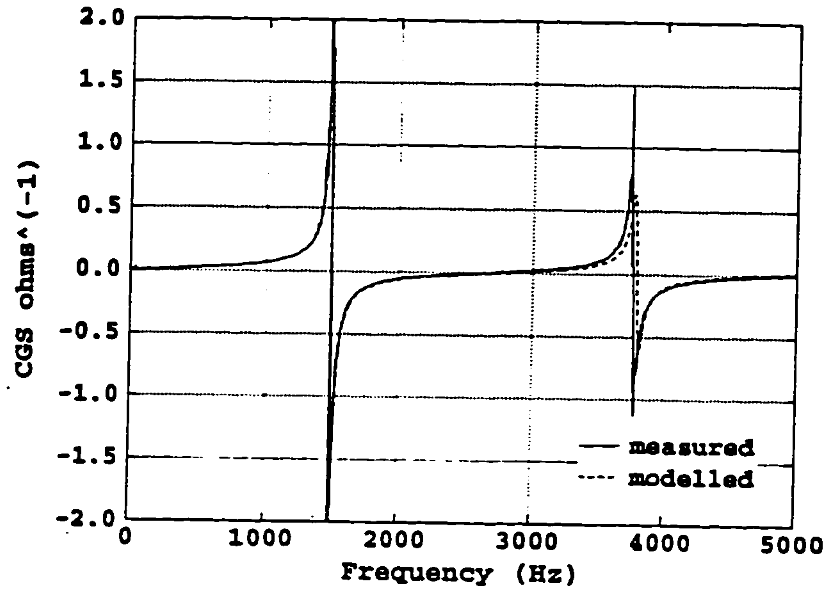
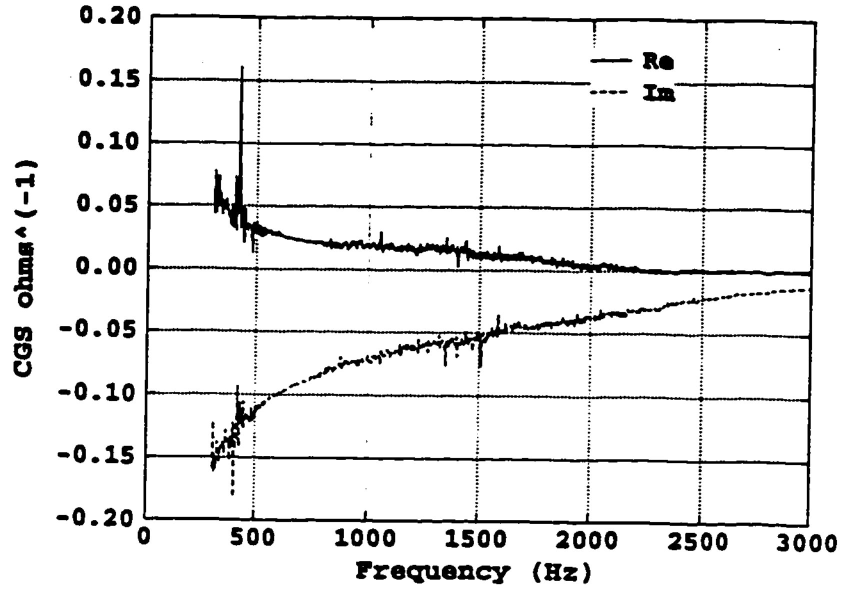
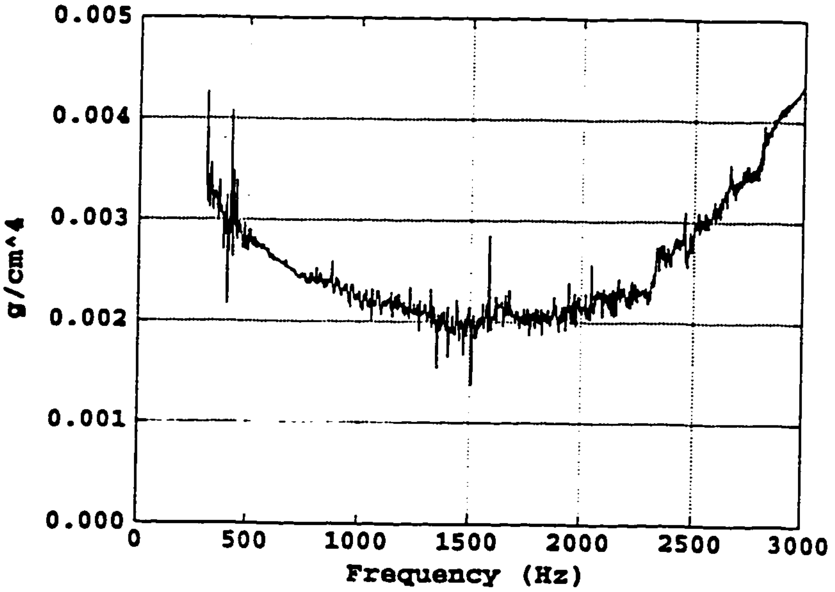


Figure C.3: ImY_{mp} measured for closed condition and calculated from transmission line model.

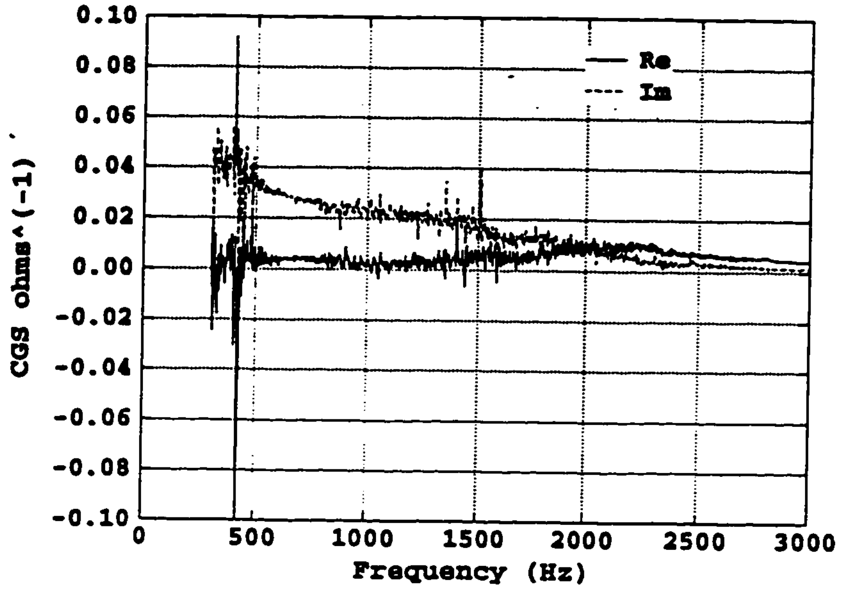


(a) Y_{rad}.

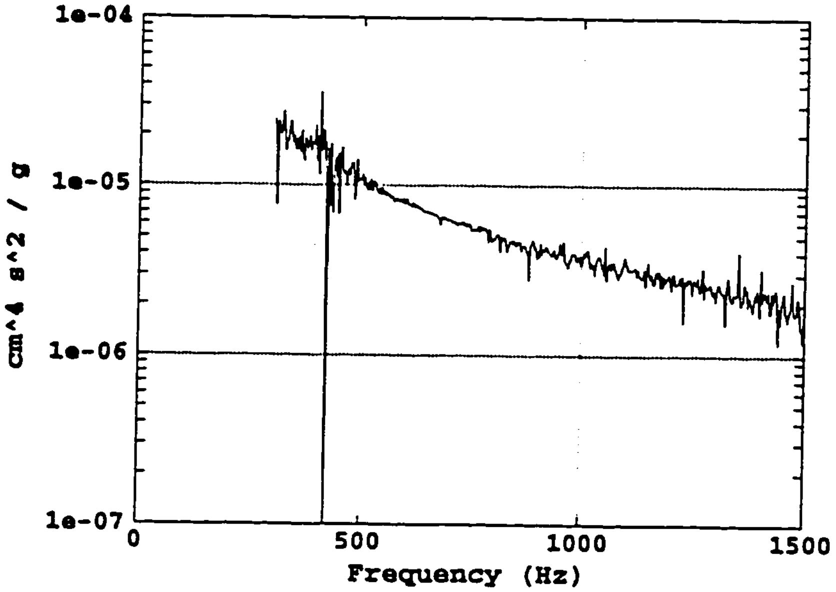


(b) I_{rad}.

Figure C.4: Radiation admittance Y_{vt} with brass reed and inertance I_{vt}.



(a) Y_r.



(b) C_r.

Figure C.5: Reed admittance Y_r with cane reed and compliance C_r.

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