MODELING VOCAL-TRACT INFLUENCE IN REED WIND INSTRUMENTS

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ABSTRACT

This paper explores the influence of upstream vocal tract resonances in reed wind instrument performance and modeling. Vocal tract manipulations are a common, though sometimes subtle, performance practice exploited by experienced musicians to produce a variety of important acoustic effects, including contemporary performance techniques such as multiphonics and extended range playing. Several previous acoustic studies have been conducted and most agree that the upstream system can have significant influence under certain circumstances. There is less agreement regarding the importance of this mechanism in "traditional" playing ranges and conditions. Several digital waveguide structures are proposed to implement this element of the performer-instrument system. The simplest approach involves modeling the oral cavity with a single resonance peak which can be easily controlled to test coupling and reed entrainment, as well as upstream-downstream interactions. The model verifies upstream influence and demonstrates real-time behavior very similar to that experienced in reed wind instrument playing. Multi-resonance vocal tract models are briefly considered and issues of real-time control are discussed.

1. BACKGROUND

The 1980s were an active period for acoustic investigation into the role and influence of a player's vocal tract in wind instrument performance [1, 2, 3, 4, 5]. While a few of these reports included suspect conclusions or demonstrated unfamiliarity with advanced performance practice techniques, a high level of understanding was achieved by the end of the decade.

Clinch et. al. [1] performed X-ray fluoroscopic examinations of vocal tract shape changes involved in the playing of the clarinet, soprano saxophone, and recorder. They noted a strong dependence of note quality on vocal tract shape and, somewhat curiously, concluded "that vocal tract resonant frequencies *must* match the frequency of the required notes in clarinet and saxophone performance."

Backus [3] made vocal tract impedance measurements and found peak values an order of magnitude less than the impedances of the clarinet air column resonances. He also experimented with a clarinet-like system arranged to sound using a vacuum mechanism located at its downstream end. He observed relatively little change in the resulting waveforms when either human or more sharply tuned resonance structures were placed around the vibrating reed/mouthpiece system. From these results, Backus concluded that "the player's vocal tract has a negligible influence on the instrument tone."

By assuming continuity of volume flow, Benade and Hoekje [2, 4, 5] showed that the pressure and flow relationships on each side of the reed can be written as

$$U = \frac{P_d}{Z_d} + \frac{P_d - P_u}{Z_r} \qquad\qquad -U = \frac{P_u}{Z_u} + \frac{P_u - P_d}{Z_r}, \quad (1)$$

where Z_u is the input impedance looking upstream from the reed into the player's windway, Z_d is the input impedance looking downstream from the reed into the instrument air column, and Z_r is the nonlinear acoustic impedance of the reed valve. The flow through the reed aperture can then be expressed in terms of the pressure difference $P_\Delta = P_u - P_d$ and the above equations solved as $-P_\Delta = ZU$ where

$$Z = \frac{Z_r(Z_d + Z_u)}{Z_r + Z_d + Z_u} = Z_r \parallel (Z_d + Z_u). \qquad (2)$$

The reed impedance plays a secondary role in this expression because it tends to be very large in comparison to the other impedances. If the upstream impedance (Z_u) is negligible, as was assumed for many years, the system can be accurately described in terms of the air column and reed impedances alone. On the other hand, it is clear that if significant impedance peaks occur in the upstream system, they can influence the behavior of the instrument in important ways. These authors made upstream impedance measurements and found that certain vocal tract configurations can produce strong upstream impedance peaks. In addition, they noted a number of ways in which upstream resonances could have considerable influence on the entrainment of the reed and the resulting sound spectra. With respect to the lack of earlier recognition within the acoustics community of the possible influences of a player's windway, Benade [4] noted that:

1. every player quickly learns to avoid windway configurations that might adversely affect the instrument response and/or produce undesirable multiphonics;
2. the audible effects of resonance alignment in the player's windway are rather subtle and not easily recognized in the resulting instrument spectrum;
3. the ability to make use of vocal tract resonances to strengthen or support instrument oscillations is a refinement that typically comes only with many years of performance experience.

In a later study by Wilson [6], upstream resonances were examined during clarinet performance of several musical phenomena. She found that the performer tends to align upstream resonances with the first or second harmonic of a sounding tone, "but that there were also a number of tones that did not have an airway resonance aligned with a harmonic." For pitchbend, a large-amplitude vocal tract resonance was used to control the playing frequency. When playing multiphonics, Wilson found that the performer creates a resonance that supports an oscillation at a linear combination of the audible pitch frequencies.

Sommerfeldt and Strong [7] presented a detailed time-domain simulation of a player-clarinet system which included a sixteen segment cylindrical tube approximation for the player's windway. They explored several vocal tract configurations and found some instances of upstream influence on the resulting sound spectra.

The present study seeks to investigate upstream resonance effects in a real-time synthesis environment. The emphasis here is on capturing the essential features of a generalized single-reed woodwind instrument and developing an upstream model which can be intuitively controlled to test upstream-downstream coupling and reed entrainment.

2. THE DOWNSTREAM MODEL

A combination of distributed and lumped system models are utilized in this study. Distributed models are implemented with digital waveguide (DW) techniques [8] which make use of digital delay-lines to efficiently simulate lossless traveling-wave propagation. Linear dispersion and attenuation are commuted and realized at discrete locations within a distributed structure. In the DW context, lumped system approximations are derived in terms of traveling-wave components and implemented with appropriately designed digital "scattering" filters.

2.1. The Instrument Air Column

The instrument air column is modeled as a single uniform waveguide of either cylindrical or conical shape and appropriately designed scattering junctions are applied at each of its ends. While more intricate air column structures can be modeled with DW techniques [9, 10, 11], such additional complexity is unnecessary for the purposes of this study.

The block diagram shown in Fig. 1 models traveling-wave propagation within a uniform air column structure. The single digital filter $\mathcal{R}(z)$ accounts for the combined frequency-dependent losses attributable to radiation, thermal heat conduction, and viscosity along the air column walls.

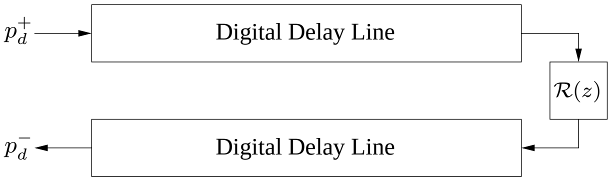

Figure 1: Generalized digital waveguide air column structure.

2.2. The Reed Junction

The single-reed woodwind excitation mechanism can be reasonably well modeled as a nonlinear spring because it is normally driven well below its resonance frequency. The flow through the aperture and the movement of the reed are controlled by the difference in pressures on the upstream and downstream sides of the reed channel, $p_\Delta = p_u - p_d$. Making use of the Bernoulli equation for static volume flow and assuming continuity of flow at the reed junction, a memory-less nonlinear function of p_Δ can easily be derived [12].

Using DW techniques, this characteristic is transformed into a nonlinear reflection function and implemented via a scattering junction as shown in Fig. 2. The pressure entering the downstream instrument air column is determined as:

$$\begin{aligned} p_d^+ &= p_d^- \cdot r(p_\Delta) + p_u^+ \left[1 - r(p_\Delta)\right] \\ &= p_u^+ - \left[p_u^+ - p_d^-\right] r(p_\Delta), \end{aligned} \tag{3}$$

where $r(p_\Delta)$ is the nonlinear reed reflection function. Details regarding the derivation of $r(p_\Delta)$ in the context of a traveling-wave, scattering theory approach are available elsewhere [13, 10]. Pressure scattering on the upstream side of the reed junction is given by

$$p_u^- = p_d^- - \left[p_u^+ - p_d^-\right] r(p_\Delta). \tag{4}$$

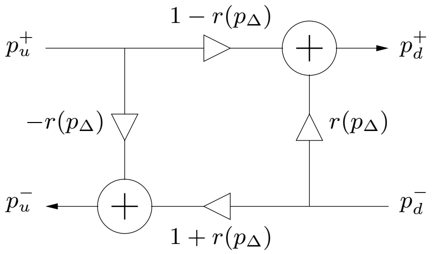

Figure 2: The reed scattering junction.

This study is concerned with the influence of upstream impedance maxima on the operation of *pressure-controlled* wind instrument excitation mechanisms. While a single-reed woodwind system is presented here, other appropriately designed pressure-controlled excitation models can be substituted, such as one based on the brass instrument lip valve. The conditions under which the upstream system might influence a *flow-controlled* mechanism, like that of a flute or recorder, are different and not considered here.

3. UPSTREAM WINDWAY MODELS

With a few exceptions [7, 14], most wind instrument simulations have assumed a constant or slowly varying pressure in the player's mouth and otherwise ignored possible upstream influences. Under these assumptions, the upstream system can be considered a large reservoir driven by a zero-frequency (DC) current source. An electrical circuit analog for such a system is shown in Fig. 3. The current source U_l represents the player's lungs, while flow resistance in the lungs and trachea is characterized by R_l. In general, the lung impedance varies over time based on the vocal fold configuration. The cavity impedance is given by $Z_c = -j\rho c^2/(V\omega)$, where ρ is the mass density of air, c is the speed of sound in air, V is the volume of the cavity, and ω is the radian frequency. The upstream resistance parameter R_u characterizes losses in the player's windway.

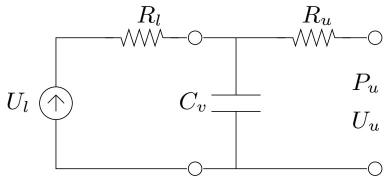

Figure 3: Electrical circuit analog for a traditional upstream windway system.

The impedance seen by the reed looking upstream is infinite for steady flow but relatively small at higher frequencies. Under these conditions, the reed is controlled by the oscillating pressure on its downstream side and the DC upstream pressure only.

3.1. Windway Resonances

The primary goal of this study was to investigate how upstream resonances might influence the resulting instrument sound and the oscillations of the reed valve. With this in mind, simple vocal tract characterizations having control parameters directly tied to resonance peak and bandwidth features were explored.

An upstream system with a single resonance is represented by the electrical circuit analog of Fig. 4. The impedance seen from the reed is characterized by peaks at DC (set with C_v) and at the resonance frequency, which is determined by the components L_1, C_1, and R_1. Despite the extreme simplicity of this characterization, wind instrument performers are typically making use of just a single resonance in their windway to influence the response of the reed.

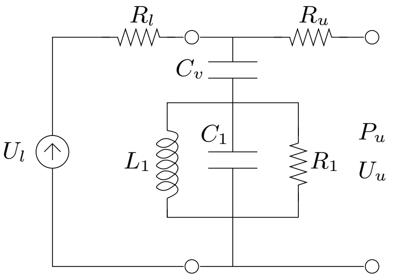

Figure 4: Electrical circuit analog for upstream windway with a single resonance.

Within the digital waveguide context, the lumped impedance representation of the upstream system is converted to a traveling-wave scattering junction expressed in terms of reflectances and transmittances. Figure 5 shows a representative reflectance characteristic when the lung and trachea impedance is assumed infinite.

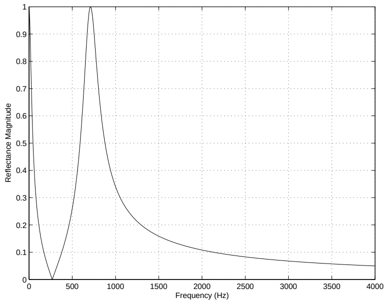

Figure 5: Upstream reflectance derived from the circuit of Fig. 4.

The complete system of Fig. 4 can be transformed to a traveling-wave scattering characterization using a transmission-matrix approach. If the series combination of the resonant circuit and volume capacitance are represented by an impedance Z_s and the upstream resistance by $Z_a = R_u$, the following matrix approach can be followed:

$$\begin{aligned} \begin{bmatrix} P_1 \\ U_1 \end{bmatrix} &= \begin{bmatrix} 1 & 0 \\ Z_s^{-1} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_a \\ 0 & 1 \end{bmatrix} \begin{bmatrix} P_2 \\ U_2 \end{bmatrix} \\ &= \begin{bmatrix} 1 & Z_a \\ Z_s^{-1} & 1+\frac{Z_a}{Zs} \end{bmatrix} \begin{bmatrix} P_2 \\ U_2 \end{bmatrix}, \end{aligned} \tag{5}$$

To render these relationships in the digital waveguide domain, it is necessary to transform the plane-wave physical variables of pressure and volume velocity to traveling-wave variables as

$$\begin{bmatrix} P_1 \\ U_1 \end{bmatrix} = \begin{bmatrix} P_1^+ + P_1^- \\ Z_0^{-1}\left(P_1^+ - P_1^-\right) \end{bmatrix}, \tag{6}$$

where Z_0 is the characteristic impedance of the section. Waveguide pressure variables on both sides of the upstream system are then related by an expression of the form

$$\begin{bmatrix} P_1^- \\ P_2^+ \end{bmatrix} = \begin{bmatrix} \mathcal{R}^- & \mathcal{T}^- \\ \mathcal{T}^+ & \mathcal{R}^+ \end{bmatrix} \begin{bmatrix} P_1^+ \\ P_2^- \end{bmatrix}. \tag{7}$$

The process of deriving appropriate discrete-time reflectance and transmittance filters is detailed elsewhere with respect to woodwind tonehole modeling [10]. For the system of Fig. 4, the resulting implementation requires four third-order digital filters.

A simplified, intuitive approach is illustrated by the block diagram of Fig. 6. A single second-order digital resonator is used to model the upstream resonance while the lung pressure component of the model is extracted and simply added to the reflected upstream pressure component. A coupling constant g is included to control the relative level of upstream influence. The unit delay shown in this signal path is necessary to avoid a delay-free loop through the digital resonance filter and reed scattering junction.

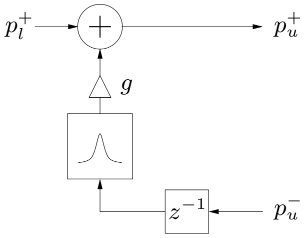

Figure 6: A simplified upstream resonance block diagram.

From this structure, it should be obvious that second-order digital resonators can be cascaded in series to simulate multiple upstream resonances. However, because vocal tract resonances will not typically have harmonic relationships, it is unlikely that a performer would be able to manipulate the upstream system in such a way that multiple upstream resonances could be used to reinforce multiple downstream resonances.

3.2. Piecewise Cylindrical Approximations

A distributed acoustic model of the vocal tract can be developed by approximating the dimensions of the upstream windway with a series of concatenated cylindrical pipe sections. In the digital waveguide context, each cylindrical section is efficiently implemented with a single digital delay-line and a one-multiply scattering junction. This approach was previously used to create an articulatory vocal tract model for the synthesis of singing [15].

With a model capable of accurately simulating arbitrary vocal tract profiles, it is possible to explore general windway shape trends and influences as reported by Clinch et. al. [1]. A multi-segment cylindrical model of the vocal tract was implemented for this study, though its use presented several challenges. In general, it is difficult to predict the way changes in vocal tract shape will affect the resonance structure of the upstream system. Further, the resulting parameter space is complex and requires a well developed, intuitive control interface. Finally, such complexity is unnecessary when one considers that the performer typically makes use of just a single windway resonance to influence the vibrations of the reed.

4. RESULTS AND OBSERVATIONS

The single resonance upstream implementation illustrated in Fig. 6 was combined with an existing digital waveguide saxophone model and the resulting instrument behavior was found to closely parallel that experienced when playing a real saxophone. For example, the first ten or so harmonics of a saxophone can be isolated through the use of vocal tract manipulations. By appropriately controlling the parameters of the upstream model, similar behavior can be demonstrated with the synthesis system. In addition, both the model and saxophone often require re-articulation of notes to break previous reed entrainment.

Figure 7 shows a pair of mouthpiece spectra from the synthesis model produced with and without an upstream resonance. When the upstream resonance was tuned to match the downstream third harmonic, the resulting vibrations of the reed became entrained at that frequency and the sound was heard to jump by a musical twelfth.

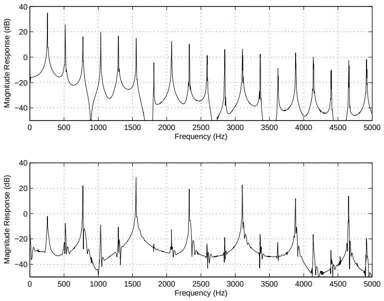

Figure 7: Mouthpiece spectra without upstream resonance (above) and with upstream resonance set to third harmonic frequency (below).

Some questions remain with respect to the role of a player's windway in wind instrument performance. In particular, the extent to which performers make use of vocal tract manipulations within "traditional" playing ranges or during rapid note sequences is unclear. The conclusions of Clinch et. al. [1] appear to overestimate these effects. Instead, observations by this author from saxophone performance experience tend to imply the possible use of broad upstream resonances to reinforce pitch regions, rather than specific notes. Further acoustic study is necessary to clarify these issues.

5. ACKNOWLEDGMENTS

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