Frequency Content of Breath Pressure and Implications for Use in Control

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ABSTRACT

The breath pressure signal applied to wind music instruments is generally considered to be a slowly varying function of time. In a context of music control, this assumption implies that a relatively low digital sample rate (100-200 Hz) is sufficient to capture and/or reproduce this signal. We tested this assumption by evaluating the frequency content in breath pressure, particularly during the use of extended performance techniques such as growling, humming, and flutter tonguing. Our results indicate frequency content in a breath pressure signal up to about 10 kHz, with especially significant energy within the first 1000 Hz. We further investigated the frequency response of several commercially available pressure sensors to assess their responsiveness to higher frequency breath signals. Though results were mixed, some devices were found capable of sensing frequencies up to at least 1.5 kHz. Finally, similar measurements were conducted with Yamaha WX11 and WX5 wind controllers and results suggest that their breath pressure outputs are sampled at about 320 Hz and 280 Hz, respectively.

Keywords

Breath Control, Wind Controller, Breath Sensors

1. INTRODUCTION AND BACKGROUND

The sounds produced by a wind music instrument are initiated and maintained via the application of air flow from a player's mouth to the input of the instrument. For a majority of wind instruments, it is the pressure inside the player's mouth, resulting from this air flow, that controls the vibrations of the "reed" mechanism and the subsequent oscillations of the air column[1]. Instruments such as recorders and flutes are, in contrast, controlled by the air jet *velocity*. No matter the underlying physics, however, it is the concept of *breath pressure* that players of all wind instruments *perceive* as the predominate control parameter. Through years of practice, performers develop an ability to precisely regulate their respiratory physiology, in conjunction with finger movements, to produce a myriad of musical effects.

Given the level of control demonstrated by wind instrument players, as well as the intimacy inherent in its use, breath pressure offers a natural parameter to be exploited by developers of human-computer interfaces. A few commercial music input devices have been developed which sense breath pressure, most notably wind controllers such as the Lyricon, Akai's EWI, and Yamaha's WX series of products [5]. A variety of non-commercial devices have also been reported [1, 2, 4, 7]. Most of these systems measure breath pressure with sensors based on the principles of a strain gauge. That is, an applied pressure deforms a diaphragm and this deformation is measured using electrical, mechanical, or optical components. In no case, however, has there been found a discussion of sensor frequency response or, for MIDI-based systems, a necessary discrete-time sample rate.

In general, there appears to be an expectation that the breath pressure used in wind instrument performance is a slowly varying function of time. Considering breath pressure as an "envelope" control for note events and estimating a maximum "note on" event rate (or a repetitive tonguing rate) by human performers of 20 Hz, one might be inclined to suggest as sufficient a discrete-time sample rate of perhaps 100 Hz (assuming five breakpoints per envelope and breakpoint interpolation by the sound processing system).

What is overlooked in this estimate, however, is the fact that wind instrument players make use of several techniques, such as flutter tonguing and growling, that effectively modulate the breath pressure signal at audio rates. If we wish to capture the full bandwidth of the breath pressure signal, it then becomes necessary to sample the breath pressure at significantly higher rates than first imagined. It is the purpose of this study to evaluate the frequency content of breath pressure, particularly in the context of "extended technique" playing, and to suggest an appropriate sample or control rate from measured data. Further, we evaluate the "frequency response" of several commercially available pressure sensors to determine their effectiveness in capturing the full bandwidth of a breath pressure signal. Finally, similar measurements are performed and reported for Yamaha WX11 and WX5 MIDI wind controllers.

2. BREATH PRESSURE IN PRACTICE

Breath pressure in wind instrument performance is expected to be nearly proportional to the amplitude envelope of an oscillatory note event. In the context of steady tone production, the pressure signal varies slowly in time except during the attack and release portions of the sound.

The most common use of breath pressure variation is to produce vibrato. By periodically varying diaphragm ten-

[1]Technically speaking, it is the difference in pressure between the mouth and the mouthpiece that controls the reed vibrations, though the player can only influence the former.

sion, players are able create a slow (4–6 Hz) modulation of the breath pressure. The breath pressure variations of particular interest in this study, however, are those used by musicians to achieve extended techniques, such as flutter tonguing and growling. Flutter tonguing is produced by vibrations of either the false vocal folds or the tongue under otherwise normal playing conditions. Flutter tongue rates are estimated to approach 50 Hz without excessive effort. Growling is produced by vibrations of the vocal folds and thus involves significantly greater frequency bandwidth. However, it is not possible to produce such vocalizations with the same flexibility and range as when singing without an instrument in one's mouth.

3. MEASUREMENTS

In most theoretical analyses of reed and lip mechanisms, pressures within the mouth and mouthpiece are considered independent. In practice, however, the vibrating "reed" is coupled to the mouth, inducing an oscillatory component of pressure which is distinct from that caused by variations of a player's respiratory physiology[2]. For this reason, our measurements must be conducted without causing vibrations of a reed. The data for the measurements discussed in this section was collected at a sample rate of 44100 Hz using a National Instruments LabVIEW system.

3.1 Breath Pressure Modulation

To estimate the frequency range of breath pressure modulation, a measurement was made while "growling" into a short plastic tube of small diameter (to approximate the air flow impedance under normal playing conditions). A miniature, low sensitivity DPA microphone, type 4062-FM, was inserted into the corner of the "player's" mouth to record the breath signal. Figure 1 shows a spectrogram of the measured signal. The growl began at a frequency of about 130 Hz and was swept to about 400 Hz over an eight second time period.

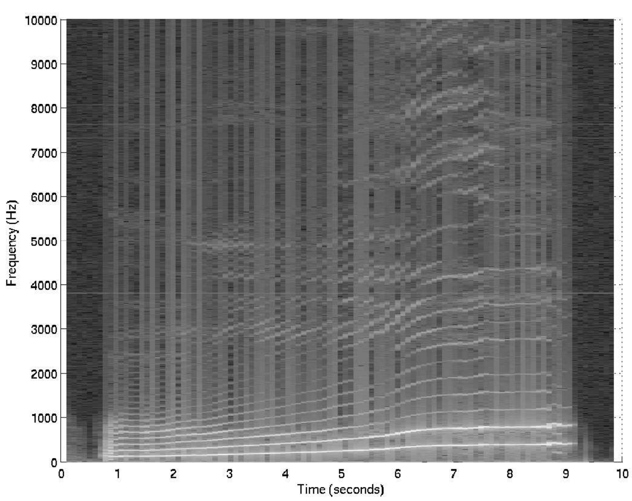

Figure 1: Spectrogram of pressure signal in mouth while growling, non-oscillatory conditions.

[2]The term "reed" is used here to refer to the general class of wind instrument excitation mechanisms, including air reeds.

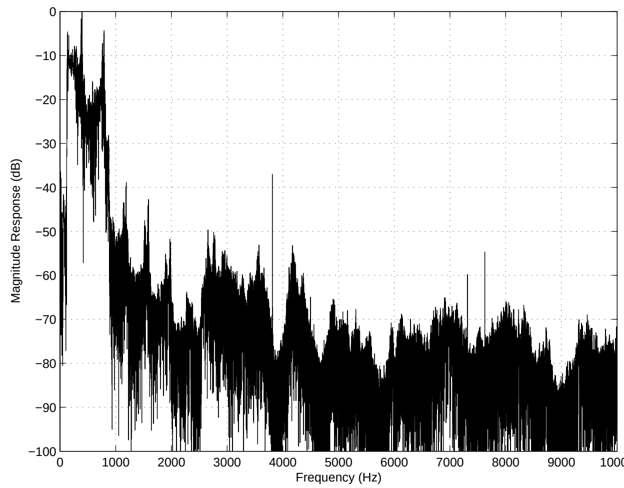

Figure 2: Single FFT of pressure signal in mouth while growling, non-oscillatory conditions.

From Fig. 1, the breath signal clearly exhibits harmonic energy up to 10 kHz. However, the most significant energy occurs within the first 1000 Hz, as evidenced by the spectrum plot of Fig. 2. The frequency components in the plots at 3812, 7314, and 7624 Hz are due to mechanical leakage into the computer measurement system.

3.2 Pressure Sensors

If the developer of an HCI device wishes to support breath pressure sensing over at least some of the extended frequency range demonstrated in the previous section, it is necessary to make use of suitable sensors, as well as appropriate discrete-time sample rates. One possible solution is to sense pressure with miniature microphones. However, microphones typically have very poor low frequency response, making them inappropriate for sensing the constant, or slowly varying, component of breath pressure. A large number of commercial pressure sensors are available for use in sensing gauge or differential pressure. For this study, we evaluated six such devices as listed in Table 1. Most of the sensors were purchased from either Digi-Key Corporation or Jameco Electronics. Freescale Semiconductor, formerly a part of Motorola Inc., provides free samples of many of its products, including the MPXV5010GC7U device tested here. All but the All Sensors 1" product sell for less than \$50 US. The device sensitivities varied between 0 – 5 pounds per square inch (PSI)[3].

There is no mention of frequency response in the data sheets for these sensors. For some products, mechanical "response time" values are provided. The Freescale data sheet defines this as "the time for an incremental change in the output to go from 10% to 90% of its final value when subjected to a specified step change in pressure."

To roughly estimate the frequency response of these sensors, we attached a plastic hose of 37.5 cm length to their pressure ports and hummed or growled through the tube while simultaneously recording the signal inside the mouth. The output voltage from the sensors was measured with the

[3]For reference, 1 kPa = 0.145 PSI = 4.021" H_2O = 102 mm H_2O = 0.01 bar.

Make	Model	Type	Range (kPa)	Response Time	Price	Frequency Response
Fujikura	XFPN-025KPGNW1	Gauge	0 – 25	2 msec	$25 US	Noisy and weak
Freescale	MPXV5010GC7U	Gauge	0 – 10	1 msec	$20 US	Good to 2.5 kHz
All Sensors	1 INCH-D-4V	Differential	0 – 0.249	NA	$88 US	Good to 1.5 kHz
All Sensors	4 INCH-GF-H-MINI	Gauge	0 – 1	NA	$38 US	Noisy and weak
Honeywell	SDX01G2	Gauge	0 – 6.9	100 μsec	$26 US	Poor
MSI Sensors	1451-005G-T	Gauge	0 – 34.5	1 msec	$16 US	Poor

Table 1: Evaluated commercial pressure sensor specifications.

LabVIEW system, as well as monitored on an oscilloscope to avoid clipping. The "hum" signal typically started around 140 Hz and increased to about 400 Hz. Results for the two All Sensors devices are shown in Fig. 3. Spectrograms for the Freescale and Fujikura sensors are shown in Fig. 4. While the attached tubing likely "colored" the results, it is still possible to derive general characteristics from these results.

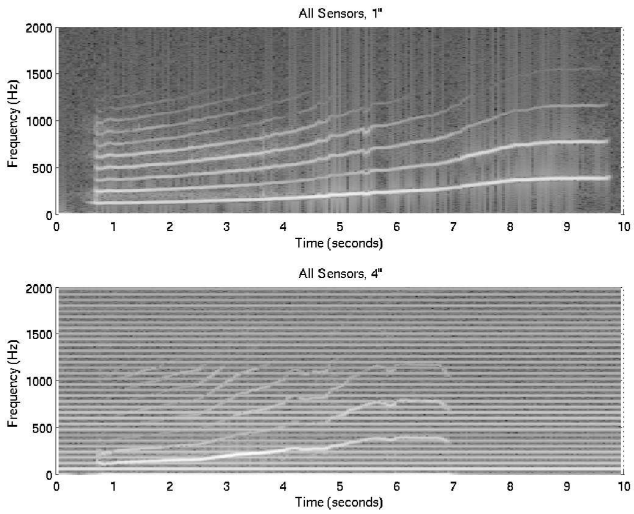

Figure 3: Pressure spectrograms as measured with All Sensors 1" and 4" devices during upward hum.

The Freescale and All Sensors 1" devices were found to measure frequency content up to 1500 – 2500 Hz. The All Sensors 4" and Fujikura sensors exhibited significant noise and their overall magnitude response was significantly weaker. Results for the Honeywell and MSI devices are not shown because they were found to have almost no "AC" response at all. Thus, available pressure sensors display significant differences in behavior that are not necessarily related to price. In terms of price and performance, the Freescale device was found superior.

3.3 Commercial Wind Controllers

A few wind controllers have been developed as commercial products, the most well known being Yamaha's WX and Akai's EWI series of instruments. The Akai controllers use analog circuitry, freeing them from the constraints of a discrete-time sample rate. The Yamaha wind controllers, on the other hand, are designed to output MIDI data and thus require sampling and discretization of sensor values.

The physical MIDI specification defines a unidirectional serial bit stream at 31250 bits per second, with 10 bits transmitted per byte. MIDI breath control messages are transmitted with a Control Change status byte and controller number two. In general, each breath control message requires three bytes, though in running status mode this can be reduced to two bytes. In an ideal scenario, MIDI transmission rates for breath control messages could reach almost 1.5 kHz, though practical considerations make maximum rates less than 1 kHz more likely. As a result, MIDI wind controllers can be expected to support no more than about 500 Hz of breath pressure bandwidth, no matter the constraints of the pressure sensor used.

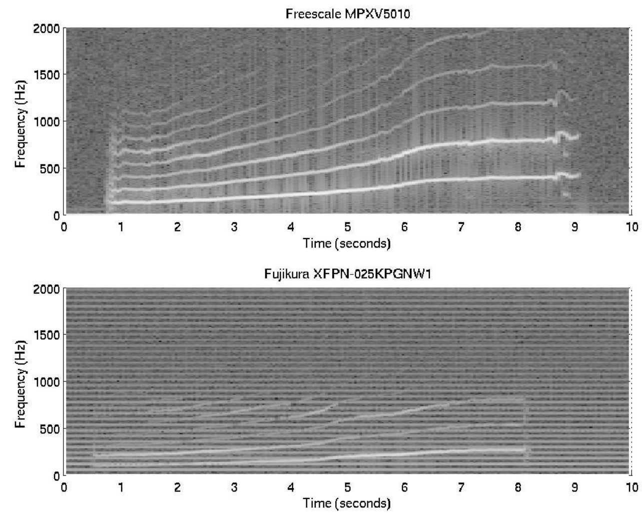

Figure 4: Pressure spectrograms as measured with Freescale and Fujikura sensors during upward hum.

This expectation was evaluated with Yamaha WX11 and WX5 MIDI wind controllers. A computer program was written using the Synthesis ToolKit in C++ (STK) to collect an incoming MIDI stream from the device and to write it to a Matlab MAT-file formatted data file for subsequent evaluation [3]. In particular, because MIDI events do not occur at regular intervals, it was necessary to resample the data on a uniform time grid, as well as filter out all but the breath pressure events.

An upward sweeping hum between about 100 – 200 Hz was performed on both controllers and the resulting MIDI data was subsequently analyzed. The incoming MIDI breath values were monitored during recording to avoid clipping at both the lower and upper range boundaries. The MIDI data was received on a Macintosh OS X computer using the CoreMIDI protocol. CoreMIDI makes use of a callback mechanism, though no maximum MIDI rate is mentioned in the documentation. The recorded data was resampled on a time grid corresponding to a sample rate of 1000 Hz and is shown in Fig. 5.

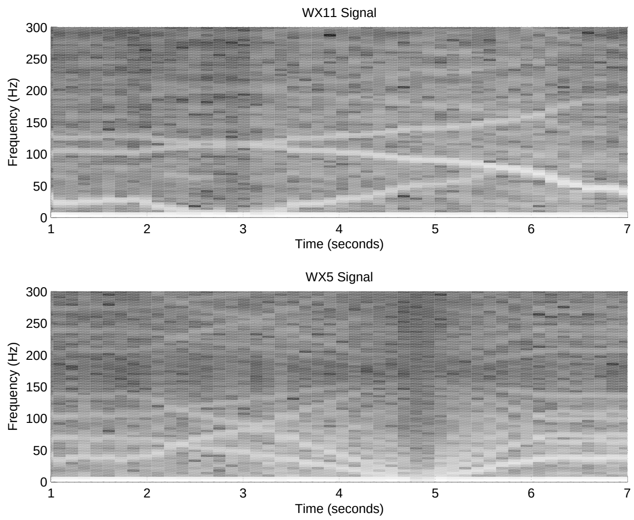

Figure 5: MIDI pressure signals from WX11 and WX5 wind controllers during upward hum.

From Fig. 5, the "hum" component that begins around 100 Hz is seen to "reflect" at about 160 Hz for the WX11 and around 140 Hz for the WX5. These rough estimates can be further verified by considering the second and third partial components of the modulation signal. In the case of the WX11, the second partial is aliased to a downward sweep from about 120 – 50 Hz and the third partial is aliased to a downward sweep from about 20 – 0 Hz, followed by a reflected upward sweep. A similar analysis can be made for the WX5 plot. From this, we can conclude that the WX11 and WX5 controllers implement sample rates of about 320 Hz and 280 Hz, respectively.

4. RESULTS AND CONCLUSIONS

The results of this study indicate that breath pressure signals can contain significant frequency content up to 1 kHz and beyond. The highest-frequency components result from vibrations of the vocal folds, most typically at a periodic rate with associated harmonics. These "vocalizations" subsequently modulate the oscillations of the air column under playing conditions. We have also analyzed several commercial pressure sensors to estimate frequency response and adequacy for use in sensing high-frequency breath pressure content. While most of these devices appear designed primarily for contexts involving slowly-varying pressures, we found that a few were capable of sensing frequency content up to at least 1.5 kHz. Finally, WX11 and WX5 MIDI wind controllers were evaluated and found to limit breath pressure signals to about 160 Hz and 140 Hz, respectively.

At this point, we cannot assess the frequency-domain magnitude or phase characteristics of pressure sensors in a rigorous manner. Informal tests indicate significant variations in magnitude response for all the devices and in many cases, significant noise content. In light of these limitations, a practical solution for sensing full-bandwidth breath pressure signals could involve the combined use of a traditional breath sensor and a miniature microphone. Another possible approach to achieving the effects of breath pressure modulation without actually sensing the associated high-frequency signal content was presented in [6]. In that case, modulation signals appropriate to flutter tonguing or growl effects were implemented in a physical modeling algorithm with low bandwidth controls exposed for performer interaction.

A question remains as to the importance in HCI contexts of higher-frequency breath pressure content. As was previously noted, breath pressure modulations are primarily associated with "extended techniques" and are not necessary for the general production of musical tones in wind instruments. That said, these authors feel that devices designed for HCI applications should strive to achieve a full range of possible sensory input. Restricting breath pressure control to slowly varying contexts will only continue the disconnect felt by many performers with respect to available music input devices.

5. ACKNOWLEDGMENTS

The authors would like to thank Kelly Braun and John Henderson for their help in acquiring measurements for this study. Support for this research was received from the Canadian Foundation for Innovation. As well, the WX11 MIDI wind controller used in this study was generously donated to the first author by the Yamaha Corporation in 1993.

6. REFERENCES

[1] G. T. Beauregard. Rethinking the design of wind controllers. Master's thesis, Dartmouth College, 1991.

[2] P. R. Cook. A meta-wind-instrument physical model, and a meta-controller for real time performance control. In *Proc. 1992 Int. Computer Music Conf.*, pages 273–276, San Jose, California, 1992. Comp. Music Assoc.

[3] P. R. Cook and G. P. Scavone. *Audio Anecdotes: A Cookbook of Audio Algorithms and Techniques*, chapter The Synthesis ToolKit (STK) in C++. A.K. Peters, Natick, MA, 2004.

[4] I. Fritz, 1997. http://home.earthlink.net/~ijfritz/.

[5] International Wind Synthesis Association. `http://windsynth.org/`.

[6] G. P. Scavone. Modeling and control of performance expression in digital waveguide models of woodwind instruments. In *Proc. 1996 Int. Computer Music Conf.*, pages 224–227, Hong Kong, 1996. Comp. Music Assoc.

[7] G. P. Scavone. THE PIPE: Explorations in Breath Control. In *Proceedings of the NIME-03 Conference on New Interfaces for Musical Expression, Montreal, Canada*, pages 15–18, May 2003.