ESTIMATING THE REED PULSE FROM CLARINET RECORDINGS

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ABSTRACT

In this work we estimate the volume flow *pulses* through a clarinet reed from recorded clarinet signal. The idea is similar to extracting glottal pulse sequences from recorded speech, however since the clarinet reed has little mass and generates significant reflection, the source-filter model used in speech processing invalid. Here, the clarinet is modeled as a pressure-controlled valve coupled to a bi-directional waveguide, with the output pressure seen as a linear time invariant transformation of reed volume flow. By noting that pressure waves will make two round trips from the mouthpiece to the bell and back for each reed pulse, a predictor is developed which operates on the recorded data in order to estimate the round-trip attenuation experienced by pressure waves in the instrument. Combining these losses with the direct measurements of the bell reflection function, a filter is developed which inverts the implied waveguide to reveal the reed volume flow pulses.

1. INTRODUCTION

Interactive virtual musical instruments require an input device that will allow for real-time, ergonomic and intuitive control of synthesis parameters. Many such devices fall from use before sufficient expertise can be gained to make them expressive and artistic tools. The result is that musicians are generally more virtuosic on acoustic instruments, likely in part because of the difference in time devoted to practice, but also, in part, because of the difference in response to user input, and haptic and auditory feedback. As an alternative therefore, researchers have explored the possibility of extracting control parameters directly from musical performance, where the performer may use an instrument with which s/he is sufficiently familiar to control some other virtual instrument.

For wind instruments, one of the primary ways in which a performer controls sound production, aside from changing pitch using instrument keys, is by changing the flow into the bore through alterations of blowing pressure and embouchure. In this work therefore, we present a technique by which the flow, or *reed pulse*, may be obtained from a recording of a clarinet, using acoustic measurements, and inverse filtering. Once the flow signal is isolated, it becomes a mapping problem to extract control parameters for a synthesis model.

The approach taken here is similar to that of estimating a glottal pulse sequence from recorded speech. This is commonly done via LPC, however Lu and Smith [1] presented a method where the formant filter and the glottal source are separately estimated. As the clarinet reed has a small mass and generates a significant reflection, the source-filter model used in speech processing is not valid here. Sterling et al. [2] attempt to extract clarinet control parameters, but could not invert their clarinet transfer function and thus used the amplitude envelope of the recorded sound to estimate blowing pressure. In van Walstijn et al. [4], a procedure is described for estimating parameters from separated traveling pressure waves, measured inside the instrument bore. In this work, we develop an expression for the transfer function from reed volume flow pulses to the sound produced by the clarinet. An expression for the inverse filter is given in terms of clarinet transmission, reflection and propagation losses, which are estimated from offline acoustic measurements and real-time processing of the recorded clarinet sound.

2. CLARINET MODEL AND PARAMETERS

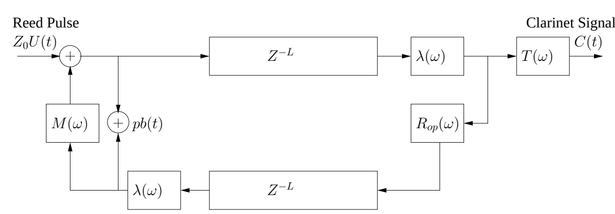

Figure 1. Waveguide model of a cylindrical tube with commuted propagation loss filters, $\lambda(\omega)$, at upper and lower delay line observation points, an open-end reflection filter $R_{op}(\omega)$ and corresponding transmission filter $T(\omega)$, and a reed (mouthpiece) reflection filter $M(\omega)$.

Blowing into the mouthpiece of a clarinet allows the player to control the reed's oscillation by creating a pressure difference across its surface. When the reed oscillates, it creates an alternating opening and closure to the bore, allowing airflow entry during the open phase and cutting it off during the closed phase. The effect is a periodic train of flow pulses, or the *reed pulse*, into the bore. The oscillation of the reed, and thus the periodicity of the reed pulse, is also dependent on the pressure traveling to and fro along the length of the bore, a pressure which is subject to frequency-dependent losses according to the bore's length, size, shape and termination.

The signal flow during performance may be seen following the classical waveguide structure shown in Figure 1. The initial position of the reed is open. An input mouth pressure of p_m creates a flow through the reed channel $U(t)$ after which the reed closes (though not necessarily completely). The flow is multiplied by the characteristic impedance of the bore Z_0 to create a positive input pressure pulse to the bore, which travels toward the bell along the bore length L while being subjected to various propagation losses $\lambda(\omega)$. Once the pressure reaches the bell, a part is inverted with transfer function R_{op} and sent propagating back to the mouthpiece, and a part is transmitted out the bell with transfer function $T(\omega)$. The reflected pressure is inverted, creating a negative pressure at the mouthpiece and further closing the reed. The negative pressure is reflected off the reed with transfer function $M(\omega)$ and is returned down the bore to the bell, again being subjected to propagation and reflection loss. The now positive pressure returned to the mouthpiece is sufficient to open the reed and allow for another airflow pulse. The result is that pressure waves will make two round trips from the mouthpiece to the bell and back for each reed pulse, as seen in Figure 2 (made lossless for improved visibility).

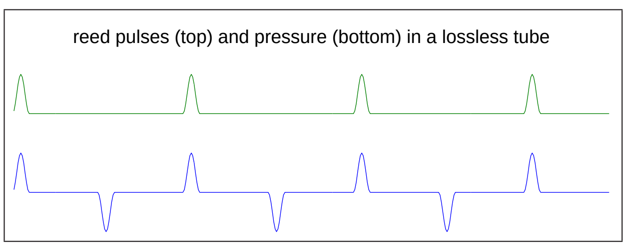

Figure 2. Pressure waves (bottom) will make two round trips from the mouthpiece to the bell and back for each flow reed pulse (top). The flow is therefore periodic, with a period corresponding to the bore pressure and thus also the recorded clarinet signal.

3. OBTAINING THE FLOW RESPONSE BY INVERSE FILTERING

Ignoring the time-varying component in the reed/mouthpiece reflection, the clarinet response to volume flow is given by

$$
\begin{aligned}
C(\omega) &= z^{-\tau}\lambda(\omega)T(\omega)[1+ \\
&\quad z^{-2\tau}\lambda^2(\omega)M(\omega)R(\omega)+ \\
&\quad z^{-4\tau}\lambda^4(\omega)M^2(\omega)R^2(\omega)+\ldots]U(\omega) \\
&= \frac{z^{-\tau}\lambda(\omega)T(\omega)}{1-z^{-2\tau}\lambda^2(\omega)M(\omega)R(\omega)}U(\omega) \\
&= H(\omega)U(\omega), \qquad (1)
\end{aligned}
$$

where $H(\omega)$ is the clarinet reed pulse transfer function. The flow response is then obtained by inverse filtering, that is

$$
\begin{aligned}
U(\omega) &= C(\omega)/H(\omega), \\
&= \frac{1-z^{-2\tau}\lambda^2(\omega)M(\omega)R(\omega)}{z^{-\tau}\lambda(\omega)T(\omega)}C(\omega) \\
&= G(\omega)C(\omega), \qquad (2)
\end{aligned}
$$

where the inverse filter is given by

$$G(\omega) = \frac{1-z^{-2\tau}\lambda^2(\omega)M(\omega)R(\omega)}{z^{-\tau}\lambda(\omega)T(\omega)}. \qquad (3)$$

The inverse filter therefore leaves us several unknowns: the reflection filter $R_{op}(\omega)$, the transmission filter $T(\omega)$, the reed reflection $M(\omega)$, and the propagation losses $\lambda(\omega)$. If we know $R_{op}(\omega)$, we may infer $T(\omega)$, since they are complementary. In the following, $M(\omega)$ is lumped with the unknown propagation loss, however in results not presented here it was seen to be 0.9 and reasonably independent of frequency and the reed opening area. To form the inverse filter in (3) therefore, we measure the clarinet bell reflection R_{op} directly, as described in Section 4, and the product $M(\omega)\lambda(\omega)$ is estimated directly from a recorded clarinet signal, as described in Section 5.

4. MEASURING THE REFLECTION FILTER

We begin by measuring a cylinder terminated at one end by the speaker and closed at the other (termination is with a piece of Lucite assumed to be perfectly reflective).

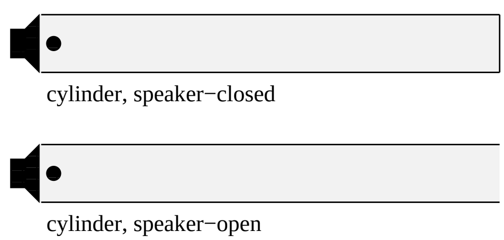

Figure 3. Measurement system, showing two tube structures, one with a closed end (top) and the other with an open (end). Each tube is terminated at the opposite end with a speaker providing a driving signal, along with a co-located microphone recording the response.

The responses from this measurement may be seen in Figure 4, with each echo L_n being comprised of the following transfer functions:

$$
\begin{aligned}
L_1 &= \sigma(\omega) & (4)\\
L_2 &= \sigma(\omega)\lambda^2(\omega)(1+\rho(\omega)) & (5)\\
L_3 &= \sigma(\omega)\lambda^4(\omega)\rho(\omega)(1+\rho(\omega)) & (6)
\end{aligned}
$$

where $\sigma(\omega)$ is the speaker transfer function, $\rho(\omega)$ is the reflection off the speaker, and $\lambda^2(\omega)$ is the round-trip wall-losses for a cylinder.

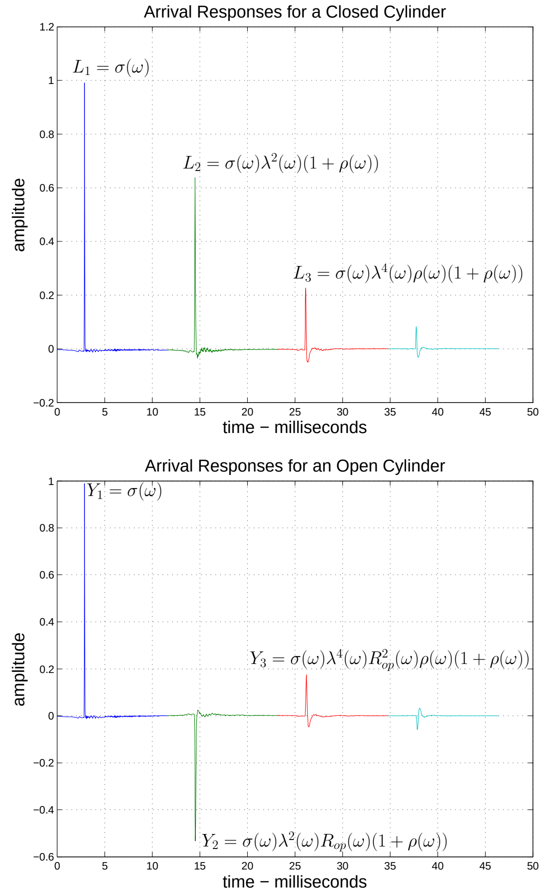

Figure 4. Measured impulse response for the closed (top) and open (bottom) cylinder showing individual arrivals. The open-end transfer function (or that of an appended bell) described by $R_{op}(\omega)$), may be isolated by comparison with the corresponding closed-end arrival. For example, $\hat{R}_{op}(\omega) = Y_2/L_2$.

For a rigidly terminated tube, the reflection at the end opposite the speaker is $R(\omega) = 1$. Changing this termination, either by simply opening the tube, or by appending some type of bell (as in Figure 5), will introduce a reflection in the response. The arrival responses for an open cylinder are seen in Figure 4 and given by

$$
\begin{aligned}
Y_1 &= \sigma(\omega) &(7)\\
Y_2 &= \sigma(\omega)\lambda^2(\omega)R_{op}(\omega)(1+\rho(\omega)) &(8)\\
Y_3 &= \sigma(\omega)\lambda^4(\omega)\rho(\omega)R_{op}^2(\omega)(1+\rho(\omega)), &(9)
\end{aligned}
$$

differing from the closed tube arrivals (4-6) in that Y_2 and Y_3 include the effect of the reflection $R_{op}(\omega)$, which may be estimated using the ratio of the second arrivals of the open and closed tube,

$$\hat{R}_{op}(\omega) = \frac{Y_2}{L_2}. \qquad (10)$$

Figure 5. Adapted measurement system, showing a clarinet bell appended to the measurement tube, allowing for measurement of the clarinet bell reflection filter.

Appending the bell of a clarinet to the tube (as shown in Figure 5) will similarly allow us to obtain its reflection function using (10). The reflection function and its associated impulse response are shown in Figure 6.

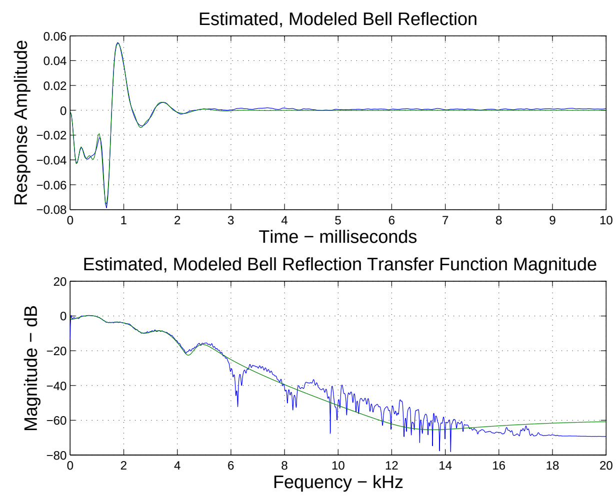

Figure 6. The clarinet bell reflection filter.

5. INFERRING PROPAGATION LOSSES

With a direct measurement of the reflection filter $R_{op}(\omega)$ and corresponding transmission $T(\omega)$, as well as an approximation for the reed reflection $M(\omega) = .9$, we are only in need of the propagation losses $\lambda(\omega)$ to form the inverse filter in (3).

In the presence of a periodic output $\tilde{C}(\omega)$, the copies of the clarinet response to prior reed pulses stack on top of each other, i.e., they are time aligned yielding

$$\tilde{C}(\omega) = z^{-\tau}\lambda(\omega)T(\omega)\left[\frac{1 + z^{-2\tau}\lambda^2(\omega)R(\omega)M(\omega)}{1-\lambda^4(\omega)R^2(\omega)M^2(\omega)}\right]\tilde{U}(\omega). \qquad (11)$$

Recall that for every reed pulse, there are two round trips from the mouthpiece to the bell and back again yielding a periodicity in the flow that corresponds to that of the pressure (see Figure 2), with the pressure showing two distinct halves: one where the pulse is positive and one where it is negative.

The '1' term in the numerator of (11) show contributions from mostly the first part of the period (initiated by the positive pulse), and the term $\lambda^2(\omega)R(\omega)M(\omega)$ shows mostly contributions from the second half of the period (initiated by the negative pulse). Taking their spectral ratio would yield an estimate of $\lambda(\omega)^2R(\omega)M(\omega)$.

The difficulty is that the first and second parts of the period do not contain disjoint contributions. They can, however, be separated by first considering their sum,

$$\tilde{\sigma}(\omega) = \lambda(\omega)T(\omega)\left[\frac{1+\lambda(\omega)^2R(\omega)M(\omega)}{1-\lambda^4(\omega)R^2(\omega)M^2(\omega)}\right]\tilde{U}(\omega)), \tag{12}$$

which creates an artificial 'echo' that cancels a portion of the feedback and yields

$$\tilde{\sigma}(\omega) = \frac{\lambda(\omega)T(\omega)\tilde{U}(\omega)}{1-\lambda^2(\omega)R(\omega)M(\omega)}. \tag{13}$$

Consider next, the difference between the first and second parts of the period:

$$\tilde{\delta}(\omega) = \frac{\lambda(\omega)T(\omega)\tilde{U}(\omega)}{1+\lambda^2(\omega)R(\omega)M(\omega)}. \tag{14}$$

The unknown round-trip transfer function can be found by examining the ratio of the sum and difference responses,

$$\rho = \frac{\tilde{\sigma}(\omega)}{\tilde{\delta}(\omega)} = \left[\frac{1+\lambda(\omega)^2R(\omega)M(\omega)}{1-\lambda(\omega)^2R(\omega)M(\omega)}\right], \tag{15}$$

and an estimate of $\eta = \lambda(\omega)^2R(\omega)M(\omega)$ is given by

$$\hat{\eta} = (\rho - 1)/(\rho + 1). \tag{16}$$

The estimator $\hat{\eta}$ reduces to the spectral ratio of the signal during first and second halves of the period. Every component of the output signal during the second half of the period has been filtered by $\lambda(\omega)^2R(\omega)M(\omega)$ compared to what they were during the first half of the period. A pitch detection algorithm must be used to find the period, and half periods may be found at zero crossings. Figure 7 shows an example of a clarinet signal and estimated reed pulse sequence.

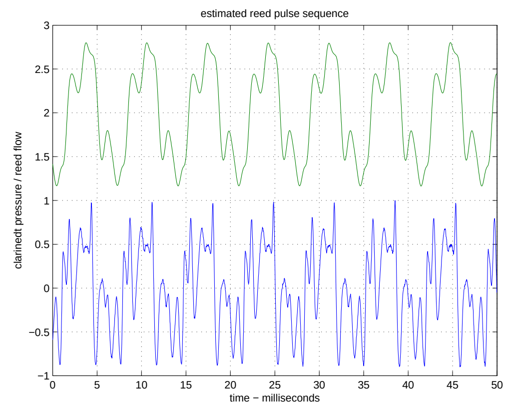

Figure 7. A clarinet signal (bottom) and estimated reed pulses (top).

6. CONCLUSION

In this work a method is presented for observing the *reed pulses*, from a clarinet recording during real-time performance. An inverse filter is formed to obtain the flow in response to a clarinet signal, but can be completed only by obtaining expressions for the bell reflection and the bore propagation losses. The reflection filter is obtained directly from a described measurement technique and the propagation loss is obtained by developing an estimator which assumes a periodic flow, with the period consisting of two distinct halves corresponding to positive and negative pulses in one period of the pressure signal. The estimator considers the ratio of the sum of the first and second halves to the difference of the first and second halves of the clarinet signal, yielding an expression which can be used, with knowledge of the bell reflection, to obtain the propagation losses and complete the inverse filter used to extract the reed pulses.

7. REFERENCES

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