EXPERIMENTAL INVESTIGATION OF DOPPLER SHIFT AND INFRASOUND GENERATION DURING WAVE PROPAGATION WITHIN THE BORE OF THE TROMBONE DURING SLIDE MOVEMENT

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ABSTRACT

During glissando playing in the trombone the length of the approximately cylindrical slide section within the bore is altered while waves are propagating. Slide movements of 2 metres per second are not unusual. The simplest way to visualise the effect is in terms of the slide being represented by a moving reflector, resulting in a (small but measurable) Doppler shift in the wave coming from the mouthpiece before it arrives at the bell for instance. An additional effect is to be observed in terms of the volume of air within the instrument changing telescopically, leading to a localised change in DC pressure (and a resulting flow) which generates infrasound components within the bore and also impacts on the sound velocities for forward and backward going waves. Lastly there will be sections of bore with moving walls which could introduce additional mean flow effects and excitation of (mostly evanescent) transverse modes of vibration.

In this study experimental data is presented showing the pressures measured by microphones mounted in the mouthpiece, in the water key (in the slide section) and at the bell of a trombone while slide movements are performed. Some measurements were performed using a fixed excitation frequency provided by a loudspeaker mounted onto the mouthpiece. Moving the slide results in changes in both the amplitude and frequency of the signal being measured by microphones (in spite of the input signal being produced by the loudspeaker being fixed in frequency). Infrasound components were also detected inside the instrument bore. Frequency tracking of audio was combined with optical tracking of slide movement to provide evidence concerning the nature of the physics of wave propagation within the dynamically changing trombone bore and conclusions drawn concerning any implications for perception and synthesis.

1. INTRODUCTION

The slide of a trombone's primary function is to allow the player to change the length of the instrument in order to change the resonant frequencies available. Movements of the slide can be done in between sounding notes so that the bore has a static length during production of individual notes in many cases. A characteristic use of the instrument is to play during slide movement, however, and this facilitates powerful glissando and portamento techniques.

The mouthpiece (where the lips act as a valve to gate the pressure in the mouth to provide a source of acoustic excitation) and the bell are both stationary during such glissando playing, but the distance that acoustic waves must travel between these points changes due to the slide section increasing in length telescopically. From this point of view the forward going waves must undergo a change in frequency or Doppler shift due to the delay time for travel between the two points changing dynamically. Measurements of the motion of the slide in trombone playing suggest that speeds of around 2 m/s are sometimes exceeded [1] and peak velocities tend to be roughly proportion to the total distance travelled [2] and this results in measurable Doppler shifts.

Another consequence of slide motion is that the volume of the air column changes by a significant fraction, resulting in the production of significant quantities of low frequency (including infrasonic) pressure and flow within the bore.

Here differential pressure sensors are mounted in the mouthpiece and in the water key (in the slide section) of a trombone and a microphone is mounted in front of the bell. In some of the experiments the only source of acoustic energy was through the movement of the slide, while in other measurements a fixed excitation frequency was input using a loudspeaker mounted onto the mouthpiece end of the bore. Both infrasound components, generated by slide movement, and Doppler shifting of traveling waves were measured. These were compared to modelling based on optical tracking of slide movement in order to illuminate the nature of the physics of wave propagation within the dynamically changing trombone bore and draw conclusions concerning perception and synthesis.

2. APPARATUS

The experimental apparatus is shown in schematic form in figure 1. The trombone was a King Trombone with the bell partially cut off. Sensor Technics HCXM020D6V differential pressure transducers were used to measure the pressure inside the bore. Each transducer has two ports, one open to the outside air and one coupled to the air inside the instrument's bore via a 5cm long rubber pipe. The microphone located in front of the bell of the trombone was a Brüel & Kjær model 4192 microphone connected to a 2669 model signal conditioner and Nexus preamp. Data acquisition was achieved using a WaveBook/516E with WaveView 7.15.19 software. A JBL model 2446H, 8 Ohms, compression driver loudspeaker was used along with a Sherwood AX3030RA power amp. Slide position was measured using a Baumer OADM 20I4471 laser distance sensor. The position data required digital low pass filtering and time domain

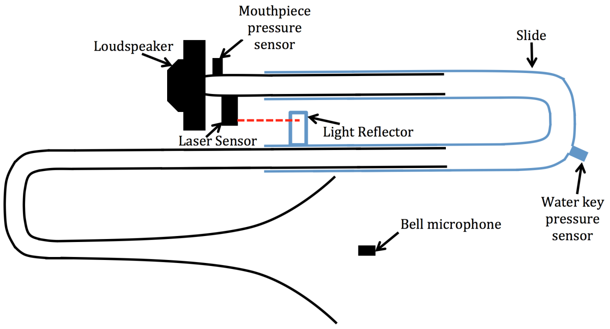

Figure 1: Schematic of the experimental apparatus including the trombone with a loudspeaker coupled in place of the mouthpiece. Blue is used to indicate the moving slide (and the light reflector and water key pressure sensor mounted on it).

interpolation to smooth high frequency noise and to upsample to an audio sample rate to act as an input for theoretical modelling. This was achieved by truncating and zero padding in the frequency domain. All calculations and plots were performed in MATLAB. Experiments were preformed in the anechoic chamber at the University of Edinburgh.

3. THEORY

3.1. Doppler shifting

The sound wave emitted by the loudspeaker must travel to the end of the slide and back again before reaching the bell section. In doing so it acts rather like a moving reflector. While the sound is not literally reflected to the source, it is redirected through 180 degrees as it propagated through the slide and thus arrives at the bell section with a time delay which depends on the time varying position of the slide. Making the approximation that the speed of sound is constant, it may be expected that the frequency of the wave received at the bell, f, is Doppler shifted according to the equation for active sonar[3]:

$$f = f_0 \left(\frac{c - 2v}{c} \right) \tag{1}$$

where f_0 is the frequency of the wave emitted by the source, v being the velocity of the slide (defining positive velocities for increasing bore length) and c is the speed of sound.

3.2. Pressure pumping

If we assume that the changes in air volume within the bore are so fast that no heat energy is exchanged with the walls and, for the moment, pretend that no energy escapes by propagation then, when the slide moves in the manner of a pump, an adiabatic change in pressure may be calculated. The initial absolute pressure and volume in the slide (P_0 and V_0) are related to the absolute pressure and volume in the slide after an approximately instantaneous change (P_1 and V_0) by:

$$P_1 = P_0 \left(\frac{V_0}{V_1} \right)^{\gamma}, \tag{2}$$

where γ is the adiabatic constant (equal to 1.4 for adiabatic gases). If the new volume is $V_1 = V_0 + dV$ and since we are considering a close to instantaneous change, the fractional change of volume in the slide will be small ($dV \ll V_0$) and we may use the binomial approximation to get

$$P_1 = P_0 \left(1 + \frac{dV}{V_0} \right)^{-\gamma} \approx P_0 \left(1 - \gamma \left(\frac{dV}{V_0} \right) \right). \tag{3}$$

Assuming that the change occurred in a time duration of t_s, we have a change of volume of $dV = 2vt_sS$ where again v is the velocity of the slide and S is the cross sectional area within the slide. The change in pressure is thus:

$$dP = P_1 - P_0 \approx -\gamma P_0 \left(\frac{2vt_sS}{V_0} \right). \tag{4}$$

So far we have ignored propagation in this analysis. In the time t_s, the pressure created will actually spread by propagation to a volume ct_sS (breaking the accuracy of the adiabatic assumption). To the first approximation, the pressure that will be generated in the volume V_0 will be given by dP multiplied by the ratio of pressure that remains $V_0/(ct_sS)$:

$$p_{gen} \approx dP \left(\frac{V_0}{ct_sS} \right) \approx -\gamma P_0 \left(\frac{2v}{c} \right) \tag{5}$$

The speed of sound itself is $c = \sqrt{P_0\gamma/\rho}$ where ρ is the equilibrium density of air so this is:

$$p_{gen} \approx -2v\rho c. \tag{6}$$

If a slide was able to achieve a velocity of 2 m/s close to instantaneously (after starting from atmospheric pressure at $P_0 \approx 10^5$), this indicates pressure changes of around -1.7 kPa. Typical fast slide movements, however, accelerate over the course of around 0.1 seconds and, since sound travels around 34 m in that time, reflection from the end of the trombone must be taken into account. In practice this significantly reduces the size of the observed pressure changes.

3.2.1. Waveguide model

Waveguide treatments of the trombone include the work of Smyth and Scott[4] while the use of varying delay times for modelling glissandos during slide motion is discussed in Vergez and Rodet[5]. These concentrate on the acoustic source from the lips and its interaction with the instrument, ignoring the effect of pump generated low frequency components. Since the pressure variations produced by the pumping action of the slide typically occur over the course of 0.1 seconds, we expect that signals of the order of 10 Hz will be produced. This is much lower than the first resonance of the trombone bore and thus the reflection at the bell is close to -1 for the generated pressures. We can therefore approximate the behaviour of the bore at this frequency in terms of a cylinder open at the bell and closed at the loudspeaker end. If we assume that the generated pressure is produced at the end of the slide such that the pressure sensor in the water key measures an initial forward going wave of amplitude $p_{gen}/2$ and that this, and an initial backward going wave of equal amplitude, will reverberate within the instrument then the pressure measured should be:

$$\begin{aligned} p_s(n) \quad = \quad & \frac{1}{2}\Big(p_{gen}(n) + l.p_{gen}(n - N_l) \\ & + r.p_{gen}(n - N_r) + l.r.p_{gen}(n - (N_l + N_r)\Big) \\ & + l.r.p_s\left(n - (N_l + N_r)\right), \end{aligned} \tag{7}$$

where p_s is the predicted acoustic pressure at the water key, n is the time domain sample number, l is the scalar reflection coefficient at the loudspeaker end (approximated as being $l = 1$),

r is the scalar reflection coefficient at the bell (approximated by $r = -0.95$), N_l is the (time varying) number of samples in the time domain for a round trip from the water key to the loudspeaker and back and N_r is the (time varying) number of samples for a round trip from the water key to the bell and back. This feedback equation can be run in the time domain by initialising p_s to zeros and calculating p_{gen} by putting the time varying slide velocity (calculated using the slide displacement data) into equation 5.

4. RESULTS

4.1. No source (other than slide movement)

Figure 2 shows the resulting bore pressure and movement data when the slide is moved from a large extension to low extension (as would be done during an upward glissando). A fairly large amplitude, low frequency pressure signal is produced (with the only source of energy being the compression of the air due to the pumping action of the slide movement). Also shown is the theoretical pressure signal at the water key using the simplified waveguide model given in equation 7. It may be noted that the main result of including reverberation within the bore of the instrument for the generated sound is to make any initial forward going wave (proportional to the negative of the slide velocity) followed after a time delay by its negative, meaning that the pressure buildup is loosely proportional to the negative of the acceleration of the slide (rather than its velocity).

Figure 3 shows the spectra of the pressure signals for the same experiment at the mouthpiece (blue) and water key (green). The spectra for the same microphones in the absence of slide movement are also shown to illustrate the noise floor. It should be noted that the low frequency pressure signal produced by the pumping action of the slide stands significantly clear of the noise floor below 100 Hz, giving over 115 dB re. 20μPa in the range between 0 and 3 Hz for this experiment. No clear pressure signal was observed above noise floor outside the bell (partly because the low frequency component is largely reflected by a close to negative one reflection coefficient as it approaches the bell).

Figure 4 shows the experimentally measured slide movement data and experimentally measured pressures in the bore along with the prediction from the cylindrical waveguide model for a slide movement corresponding to a downward then upward glissando (also with no source of acoustic energy other than the slide movement). Again the pressure build up is loosely proportional to the negative of the slide acceleration.

4.2. Constant frequency sine wave source

The experiment was repeated but with the addition of a constant, high frequency (nominally 10 kHz) sine wave source being played using the loudspeaker coupled to the mouthpiece side of the instrument. This high frequency was chosen because it is well above the cut-off frequency of the horn and so experiences minimal reflection in the bore, thus allowing the Doppler shift for a forward going wave to be measured without significant interference from reverberations within the bore. It is also below the cutoff frequency for higher mode propagation within the cylindrical sections of the bore.

Figure 5 shows the results when the slide movement (in the upper plot) is moving from small to large extension (as would occur for a downward glissando) with the resulting frequency tracking signal for the microphone in front of the bell shown in the lower plot in blue as a ratio to the initial frequency

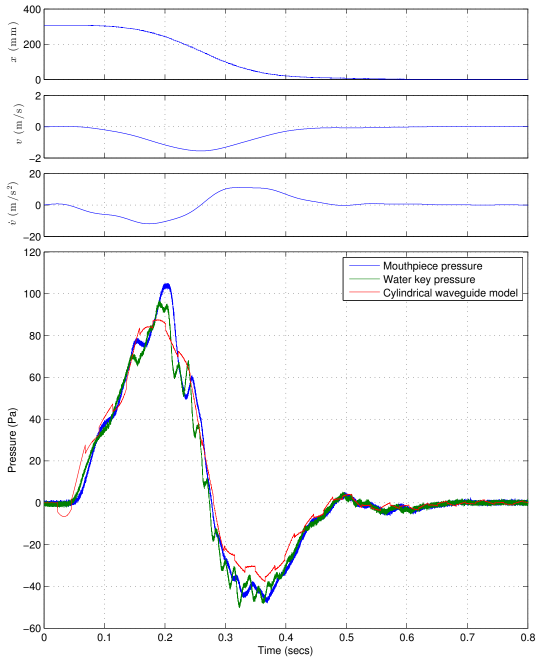

Figure 2: Slide displacement is shown in the top plot, slide velocity in the second highest plot, slide acceleration in the third plot and with the resulting bore pressure measured at the mouthpiece area and in the water key shown in the lower plot in blue and green respectively. The only energy input is provided by slide movement (in this case corresponding to an upward glissando). The red line shows the cylindrical waveguide model for the pressure build up as calculated entirely using the slide position data.

(which corresponds to the constant frequency emitted by the loudspeaker). Frequency tracking was performed by high pass filtering the bell microphone signal (Hanning filter with cut-off frequency 800 Hz), then calculating the frequency using zero crossings (using the same equations as in Kemp et al [6]) and finally averaging over 21 zero crossings in order to minimise the effects of noise. The theoretical Doppler shift for a moving reflector is shown in green as calculated directly from the slide displacement data and equation 1. It is clear that the frequency measured in front of the bell reduces during an outward slide movement and the slide acts as a moving reflector to the first approximation.

Figure 6 shows the spectra measured at the mouthpiece position (blue), water key (green) and outside the bell (red) during the same slide movement experiment as in figure 5, along with the corresponding spectra measured with the same source playing but without slide motion. The Doppler shifts observed at the water key position are roughly half of those measured outside the bell. This arises because the water key is mounted in the moving slide section and is therefore acting as a moving receiver. No Doppler shift is observed at the mouthpiece as the Doppler shifted signal (chosen to be high in frequency) was almost all transmitted from the bore due to the cut-off frequency of the bell.

The corresponding plots for a downwards then upwards glis-

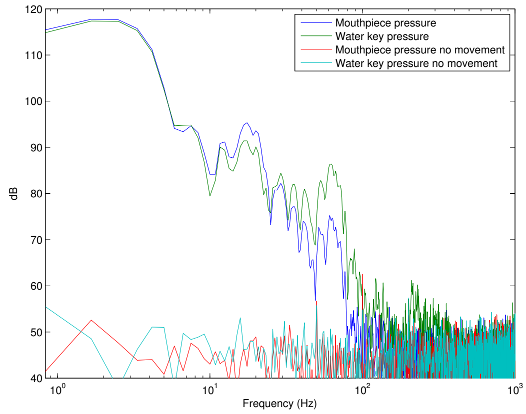

Figure 3: Spectra (with logarithmic frequency scale) for the bore pressure measured at the mouthpiece area (blue), in the water key (green) are shown during the same slide movement shown in figure 2. The only energy input is through moving the slide. Also shown are the spectra for the microphones during no slide movement (showing the noise floor).

sando are shown in figures 7 and 8. It is clear that both positive and negative Doppler shifts are present in this case.

5. DISCUSSION AND CONSEQUENCE FOR PLAYING AND SYNTHESIS

5.1. Pressure and lips

It is clear from figure 2 that during the initial stages of an upward glissando (when the slide is accelerating) the DC pressure in the mouthpiece will seem to increase (typically by the order of 100 Pa for a fast glissando) and this may be perceptible effect on the player, particularly if playing very quietly. The player will need to increase their mouth/supply pressure a little if they want to maintain the same overpressure (or pressure difference between the mouth and mouthpiece) while the slide is accelerating towards their lips. Correspondingly they may have to slightly reduce their mouth/supply pressure if they want to maintain the same overpressure during the deceleration at the end of an upward glissando. The reverse should be true for a downward glissando (with the initial acceleration requiring a slight drop in pressure etc.).

5.2. Doppler shift, glissando and slurs

When slurring to a new pitch in brass instruments without a slide, a new frequency must be instigated by the lips and the reverberant energy within the instrument will be sounding at the frequency of the previous note. The resulting forces can cause beating during the transient and split notes. In the trombone, on the other hand, the reverberant energy within the instrument is Doppler shifted, meaning that when the slide is moved, the lips can follow the frequency of the incoming pressure waves in order to play a glissando or slur to a new note with the same mode number. This is an easier task than on brass instruments without a slide.

The opposite extreme for the trombone is when a “cross grain slur” is required. This technique involves swapping mode number in order to make an upward pitch jump simultaneously with lengthening the instrument using the slide, or creating a downward pitch jump while shortening the instrument using the

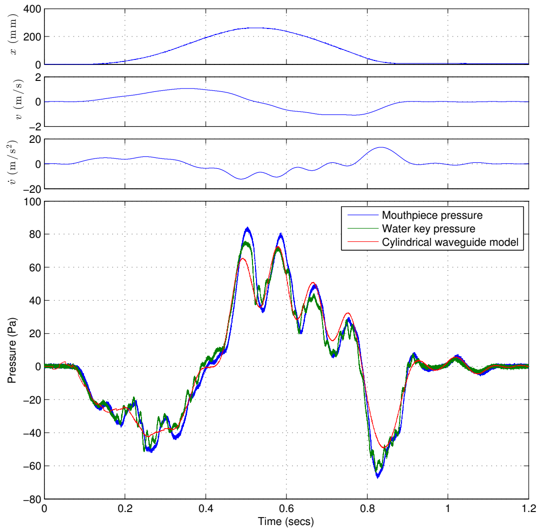

Figure 4: Slide displacement is shown in the top plot, slide velocity in the second highest plot, slide acceleration in the third plot and with the resulting bore pressure measured at the mouthpiece area and in the water key shown in the lower plot in blue and green respectively. The only energy input is provided by slide movement (in this case corresponding to a downward then upward glissando). The red line shows the cylindrical waveguide model for the pressure build up as calculated entirely using the slide position data.

slide. In these cases the task is especially difficult because not only does a new lip frequency have to be established on the instrument, but the reverberant energy which interferes with the lips is Doppler shifted in the wrong direction.

5.3. Acoustic velocity and mean flow

The pressure created by the motion of the slide will experience positive amplitude pressure reflection at the mouthpiece end, which is equivalent to a negative reflection for the acoustic velocity wave, leading to a cancellation of the velocity at the mouthpiece side of the slide. At the bell, on the other hand, the pressure travelling waves are reflected negatively, and this is equivalent to a positive velocity travelling wave reflection, meaning that the velocity wave is reinforced rather than cancelled.

This agrees with an intuitive visualisation of mean flow. In the case of a constant slide velocity, v, a steady mean flow of approximately $-2v$ is to be expected between the bell and slide necessary to prevent massive changes of DC pressure within the instrument during the large volume fraction changes. For the case of a $v \approx -2$ m/s slide motion, this implies that the peak mean flow to be expected would be approximately $-2v \approx 4$ m/s. Using the characteristic impedance of plane waves the difference between the pressures of the forward and backward going pressure waves would of the order of $2v\rho c \approx 1.7$ kPa. This is the value of the total generated pressure derived by a different route in equation 6, half of which is expected to propagate forward and half backward along the bore before the reflections occur. Given that the acoustic velocity in the pipe can be de-

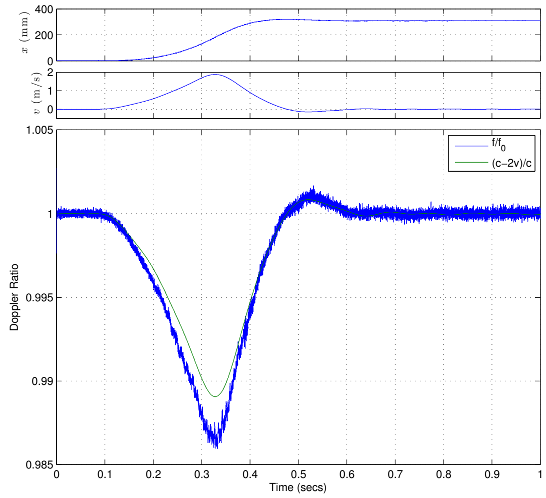

Figure 5: This experiment features a slide displacement, shown in the upper graph, that corresponds to a downward glissando with the slide velocity shown in the second graph. The measured Doppler shift ratio, f/f_0, shown in blue in the lower graph, is obtained by frequency tracking the signal measured in front of the bell and dividing by the source frequency. The theoretical Doppler shift for a moving reflector, $(c - 2v)/c$, is given in green.

duced from the characteristic impedance:

$$p^+ - p^- = u\rho c \approx -2v\rho c \approx 1.7kPa, \qquad (8)$$

(in the case of a slide velocity of -2 m/s) where u is the acoustic particle velocity, p^+ and p^- are the forward and backward going acoustic pressure traveling waves respectively. It is clear that p^+ is therefore positive and peaks at just over 1.7/2 kPa = 850 Pa and p^-, being close to -1 times this value, reaches close to -850 Pa. When the slide is accelerating there is a significant imbalance between absolute values of the (velocity dependent) forward going and (delayed) backward going wave (hence the measured pressure signal of the order of $p^+ + p^- \approx 100$ Pa seen in figure 2).

5.4. Implications for synthesis

Doppler shifts are a natural consequence of having a varying delay time in the bore and these are already implicit in any waveguide model that incorporates a varying delay time when slide movement is modelled. More sophisticated treatments discussing the 3D wave equation under slide movement would be interesting although the experiments suggest that corrections involved would be slight. The low frequency sound generated by the acceleration of the slide may have an impact on the behaviour of lip models when playing at relatively quiet dynamics and fast glissandos and could be added into trombone models for completeness.

6. ACKNOWLEDGEMENTS

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European

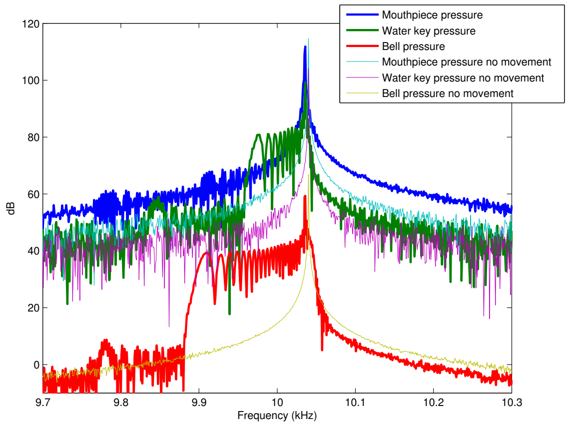

Figure 6: Spectra (around the frequency of the constant frequency input sine wave) for the bore pressure measured at the mouthpiece area (blue), in the water key (green) and outside the bell (red) during the same slide movement shown in figure 5. Also shown are the spectra for the microphones during no slide movement.

Union's Seventh Framework Programme FP7/2007-2013/ under REA grant agreement No. 605867 supporting the BATWOMAN ITN Project.

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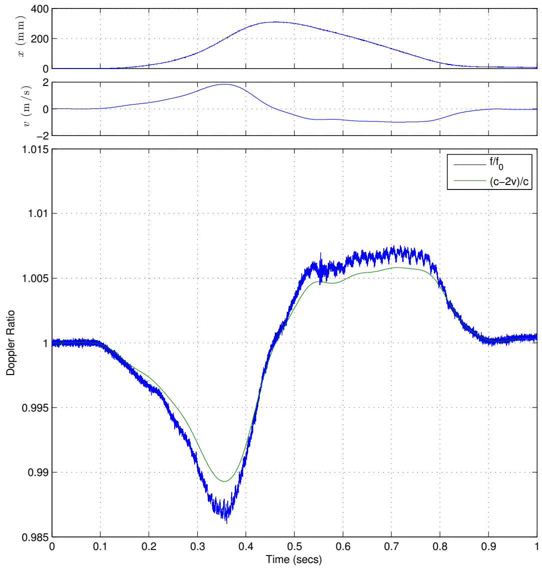

Figure 7: This experiment features a slide displacement, shown in the upper graph, that corresponds to a downward glissando then upward with the slide velocity shown in the second graph. The measured Doppler shift ratio, f/f_0 is shown in blue in the lower graph and the theoretical Doppler shift for a moving reflector, $(c - 2v)/c$ is shown in green.

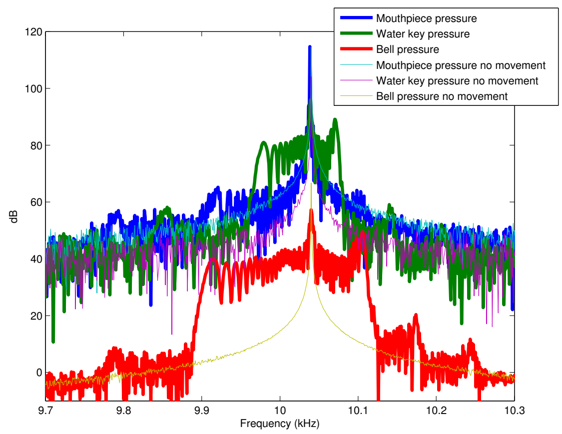

Figure 8: Spectra (around the frequency of the constant frequency input sine wave) for the bore pressure measured at the mouthpiece area (blue), in the water key (green) and outside the bell (red) during the same slide movement shown in figure 7. Also shown are the spectra for the microphones during no slide movement.