Spectral Analysis of the French Horn and the Hand-in-Bell Effect

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ABSTRACT

With the goal of investigating the effects of hand-in-bell playing of the French Horn, a technique was developed to quickly and accurately measure the input impedance of the instrument to determine intonation and playability of resonant modes. This technique is a continuation of previous work done by Professor Steve Errede and Dave Pignotti on the impedance spectra of trumpets and other wind instruments, but uses the HP3562A spectrum analyzer to achieve much lower measurement times at the cost of increased noise. This allows for measurements to be made using a genuine player's hand technique *in situ*. Specifically, the effect of hand muting the instrument, or "hand stopping" was investigated in an attempt to clear up some of the confusion about transposition and the use of this technique.

I.   Background and Introduction

As with other brass instruments, the French Horn is played by vibrating the player's lips against the mouthpiece. Playable notes on the horn must "lock in" to provide musically useful pitches with correct intonation, and these notes correspond to resonant modes of the instrument; brass players refer to these notes as "partials", and they are also referred to as harmonics or resonant modes. The ability to access many partials for each key combination accounts for the relatively low number of valves. Many modern French Horns are in fact "double" horns, in that they consist of a horn in the key of F and a horn in the key of Bb together, switchable by a thumb-operated valve. The valves of the French Horn,

as with other brass instruments, change the length of the air column, effectively changing the key of the instrument. The valves allow the player to access notes that are in between partials by switching to another harmonic series of partials in a different key. A "transposition" refers to an adjustment in key by the player using the valves of the
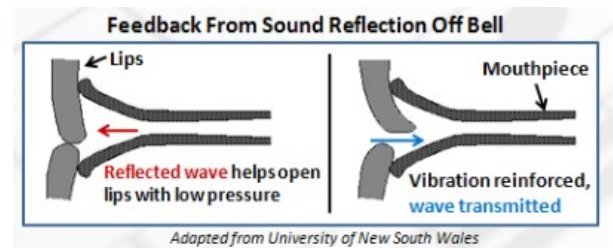

Figure 1: Typical hand position for playing the French Horn. Slightly cupping the hand closed lowers the pitch.

instrument, effectively moving all notes up or down by the same amount of pitch. The French Horn is the only brass instrument where the player inserts his or her hand into the flared end of the instrument (the "bell") during normal play. The hand is cupped slightly, but the end of the instrument is mostly open to allow sufficient projection of sound. A photo of this technique is shown in Figure 1. One of the benefits of this technique is that it allows the horn player to adjust intonation while playing; cupping the hand (slightly closing off the bell) lowers the pitch of the instrument without having to adjust tuning slides (Farkas 12).

Also unlike other brass instruments, the French Horn typically plays up to about the 16th resonance in its normal playing range; other brass instruments only play up to about the 8th resonance. Since musical instruments are designed to function on an approximate harmonic series, where each resonance is an integer multiple of the fundamental, the spacing between successively higher resonances decreases. This means that the horn player requires the instrument's partials to be "pronounced and distinct" to achieve reasonable accuracy in the upper range of notes (Backus[2] 273).

The placement of the player's hand serves two functions, both vital to the playability of the horn. First, the hand causes upper resonances to decrease in pitch, effectively bringing the usually sharp higher notes more in line with standard tuning. This intonation effect is due to the added acoustical

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mass the hand creates at the end of the air column as it is pushed farther into the bell, lowering the frequencies of the system, which can be thought of as an approximate Helmholtz resonator (Backus[2] 275). The second effect of the hand placement inside the bell is the increase in playability of the upper resonances of the instrument; this is where the problem of accuracy in the upper range is addressed. As with other brass instrument musicians, the French Horn player relies on acoustical feedback to reinforce the "buzzing" made by the lips to drive the instrument. This mechanism is shown in Figure 2, whereby sound waves reflecting off of the bell and back up to the lips reinforce the lip vibration; this is essential for a played note to comfortably "lock in" (Wolfe). Having the player's hand in the bell cuts down on radiation of high-frequency harmonics, and helps them reflect to build up stronger standing

Figure 2: Player's vibrating lips are reinforced by acoustic feedback from wave reflection off of the bell.

waves between the bell and player's mouth. Thus, with the hand in the bell, the horn player can effectively and accurately utilize resonances even exceeding the 16th order above the fundamental (Rossing et al. 235).

An advanced technique used by French Horn players involves closing off the end of the bell with the hand, effectively muting the horn to produce a sound unique to the instrument. This is known as "stopping" the instrument, and a photo of the technique is shown in Figure 3. This technique requires on-the-fly transposition by the player to compensate for the shifting of all the partials that occurs when the bell is closed off. Typical horn pedagogy instructs that transposition of a semitone downward is necessary (Rider 163). This implies that the player is compensating for raised partials by lowering them with transposition; however, as was previously mentioned, cupping the hand closed in the bell *lowers* the pitch of the instrument.

Herein lies the apparent contradiction in the hand-stopping technique: If a player begins closing

the bell by cupping his hand, he will notice that the pitch drops. However, the player is taught to transpose *down* while the bell is completely closed off, as though stopping actually *raised* the pitch. To add to the confusion, some horn players claim that transposing up actually does work for certain stopped notes. So does hand stopping raise or lower the pitches of the horn's partials? Clearly there is something more complicated going on when the stopping technique is used.

Figure 3: The "hand-stopping" technique of muting the French Horn. The bell is sealed off by the player's cupped hand.

The goal of the research described in this thesis was to measure the frequencies and relative playability of the resonant modes of the French Horn, in order to observe how they change when the hand-in-bell techniques are applied. A better understanding of the effects of playing techniques can be invaluable in shaping the way future students are taught. In order to quantify the response of the horn, an electrical analogy is helpful. Recall that playable notes on the horn correspond to frequencies at which wave reflection occurs off the bell and back up the instrument. In an electrical transmission line, signal reflection occurs when the line's characteristic impedance and that of the load are not complex conjugates (Kudeki and Munson 106). This situation can be applied in analogy to a sound field such as that inside the French Horn: the analog for voltage is pressure, and the analog for current is the longitudinal component of the velocity of the air particles. This analogy is shown below in Figure 4. In other words, the air column of the horn itself acts as the acoustic transmission line, while the outside air acts as the load. Since the instrument may respond with a nonzero phase component, the pressure and particle velocity must be considered complex in nature to adequately describe the sound field. Thus, in

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direct analogy to Ohm's Law for electrical circuits, one may define a complex acoustical impedance, mismatches in which between a source and load cause wave reflection back up the instrument.
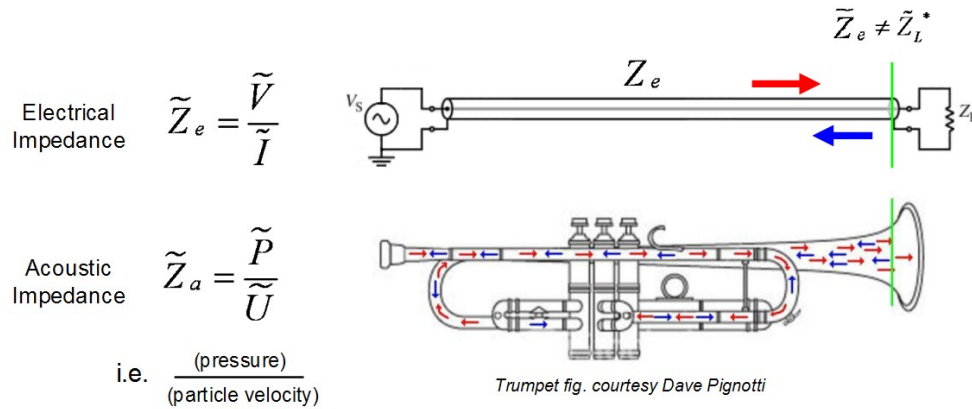

Figure 4: The brass instrument as an analog to the electrical transmission line, with correspondingly defined acoustic impedance to measure wave reflection (blue) at source/load impedance mismatch (green line). Red represents the incident wave or electrical signal.

P stands for pressure, and U_l stands for the longitudinal component of the particle velocity. This defines the complex *specific* acoustic impedance, since it is independent of volume. Since playable notes on the French Horn correspond to frequencies at which standing waves occur, it follows that maxima in the acoustical impedance at the mouthpiece will correspond to these notes. The frequency of a particular maximum corresponds to the frequency of the playable note, and the peak height gives information as to the stability or "playability" of that partial. Since French Horn players have to worry about partials becoming closer together in the upper range, it is important that the peaks at higher frequencies be pronounced; in other words, the playability of a partial can be determined by the height of that partial's impedance peak *in comparison to the adjacent minima*.

Previous work on measuring the hand-in-bell effect using input impedance was most notably performed by John Backus in 1974. However, Backus did not use a real horn player's hand technique for the measurements, but a lump of plasticene in the approximate location of the hand. Also, Backus

used a No. 13 rubber stopper to close off the bell of the horn for the stopped horn measurements (Backus[7]). Backus' results showed that the lump of plasticene did indeed lower the higher resonances to match more closely with the harmonic series, as well as strengthening the higher resonances by raising their impedance peaks. His results also showed that stopping the horn served to lower the resonances, and had the added effect of attenuating the second harmonic. The goal of this thesis was to see how Backus' results compare to measurements done *in situ* with a real horn player's hand in the bell, and it was found that results with a real hand compared qualitatively very well with Backus' findings. Backus' results for the French Horn are summarized below in Figure 5. The effect of the "hand" in the bell corresponded with expectations; increased definition and lower frequency in upper range peaks. Backus also found that "stopping" the horn caused the peaks to move downward rather than upward, and also attenuated the second harmonic peak significantly. These results are consistent with those presented in this thesis with the use of a real horn player's hand.
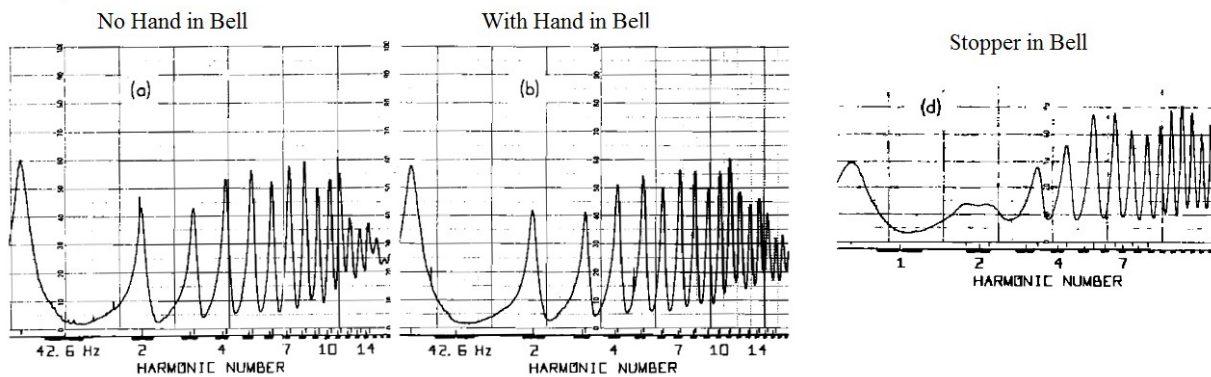

Figure 5: Summary of Backus' results for input impedance measurements of the Conn 8D French Horn. Backus found that the addition of the hand in the bell increased the peak definition (note playability) in the upper range, as well as lowering the pitch somewhat. He also found that simulating hand-stopping shifted impedance peaks downward, and attenuated the second harmonic substantially.

At the University of Illinois at Urbana-Champaign Music Physics lab, Professor Steve Errede and former thesis student David Pignotti have developed a more modern version of the brass instrument input impedance measurement technique, based off Backus' work. Pignotti was able to

measure the input impedance of his Bach trumpet using two Knowles Acoustic microphones to measure pressure and particle velocity, four lock-in amplifiers, and 8 analog/digital converters on a data acquisition card (Pignotti). The trumpet was placed inside a box lined with acoustic foam to attenuate background 1/f noise from building ventilation, and the instrument's air column was driven sinusoidally by a piezoelectric transducer connected to a function generator. However, due to the large amount of averaging required to remove background noise, and the large settling time of the lock-in amplifiers, measurement time took in excess of 8 hours, which is far too long to have a French Horn player apply correct hand technique to the instrument. Thus the measurements described in this paper use methods derived from Pignotti and Errede's method, with an emphasis on reduction of measurement time. The largest change from Pignotti's method is the use of an HP3562A spectrum analyzer in place of the lock-ins and the ADCs. The lower settling time of the spectrum analyzer, coupled with greatly reduced averaging, should drastically reduce measurement times. In this way, a seasoned French Horn player will be able to reach into the box and apply his hand technique to the bell while the measurement is being taken.

II.   Experimental Procedure

The microphone used to measure the complex pressure was the Knowles Acoustic FG-23329 sub-miniature electret condenser microphone. This microphone was coupled capacitively to an 11x gain non-inverting op-amp preamplifier designed by Professor Errede, which is shown in Figure 5. This preamp was designed to make the effective frequency and phase response of the microphone as flat as possible, which was verified by simulation to be true in the audible frequency range (Errede 8).

To measure the longitudinal component of the particle velocity inside the mouthpiece, a Knowles Acoustic EK-23132 sub-miniature electret condenser microphone was modified by removing the back

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plate. The back was replaced with a very fine-mesh copper screen electrically connected to the microphone case to act as an RFI/EMI shield. This allows the microphone to measure differential pressure in one dimension, as the removal of the back plate destroys the omnidirectionality. Taking advantage of Euler's equation for inviscid fluid flow, shown below in Equation 1, the longitudinal particle velocity can be expressed as an integral of the differential pressure in the longitudinal dimension (Equation 2). Accordingly, the microphone's signal is integrated in time by designing the preamplifier circuit as an integrating op-amp circuit.

$$\frac{\partial \tilde{u}_z(\vec{r},t)}{\partial t} = -\frac{1}{\rho_o}\frac{\Delta_z \tilde{p}(\vec{r},t)}{\Delta z} \tag{1}$$

$$u_z(z,t) = -\frac{1}{\rho_o}\int_{-\infty}^{t}\frac{\partial p(z,t')}{\partial z}dt' \tag{2}$$

Thus the modified microphone and 11x gain integrating preamplifier together measure the longitudinal component of the particle velocity. Once again, the combination of the differential pressure microphone and the integrating preamplifier circuit provide a flat frequency and phase response in the audible frequency range. Shown below in Figure 6 is the preamplifier circuit for the particle velocity mic, with the microphone
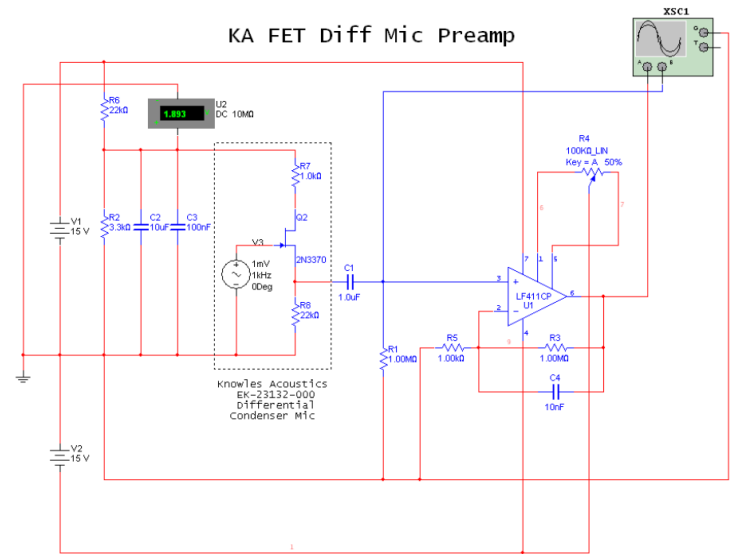

Figure 6: Preamplifier circuit for the differential pressure microphone. Coupled with the integrating op-amp circuit, this microphone effectively measures one-dimensional particle velocity. This preamp allows for a flat microphone response in the audible frequency range.

represented by the circuit in the gray box. The pressure mic preamp circuit is identical to the circuit in Figure 6, but without the capacitor labeled C4.

Both microphones were placed through holes drilled in the sides of the instrument's mouthpiece, and were placed close together in the center of the mouthpiece's volume. This placement assures that the impedance will be calculated from pressure and velocity measurements that are essentially taken at the same spacial point. The broad face of the particle-velocity microphone is pointed perpendicular to the airflow, and the piezoelectric transducer is affixed over the mouthpiece using cyanoacrylate glue. This is diagrammed in Figure 7 with the transducer removed to show microphone placement, and in Figure 8 with the transducer attached. The mouthpiece holes are sealed around the microphones with apiezon putty.
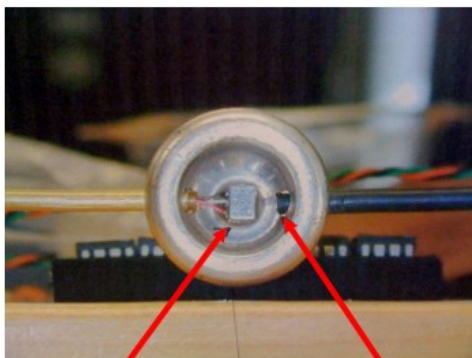
Particle velocity
(dP integrated in t)   Pressure

Figure 7: Particle velocity and pressure microphones shown inside the mouthpiece, facing "down" the direction of airflow into the horn.
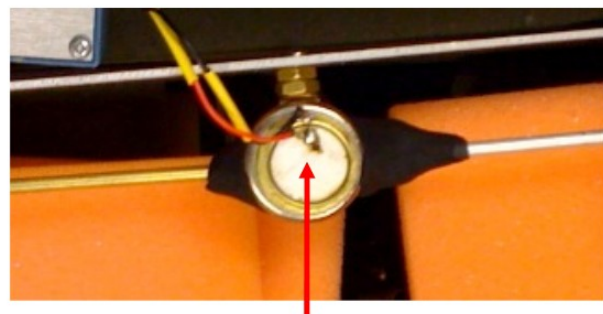
Piezoelectric driver

Figure 8: Both microphones situated inside the mouthpiece with the piezoelectric transducer affixed and openings sealed with apiezon

The outputs from each microphone's respective preamplifier are each connected to their own input channel on the HP3562A, and the piezoelectric transducer is connected to the "source" output channel via a 30x voltage amplifier. It is important to note that driving the piezoelectric transducer at more than about 35 V amplitude caused saturation in the FETs inside the microphones, resulting in

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distortion of the signal; this created an effective limit as to how strongly the horn could be driven by the transducer. The HP3562A is placed in "swept-sine" mode, which drives the piezoelectric transducer sinusoidally and measures the microphones' outputs phase-locked to the driving phase of the source channel. Thus the measurements of pressure and particle velocity are complex in nature, whose phases are with respect to the driving phase of the instrument's air column. The HP3562A is programmed, via the "Math" menu, to calculate the complex ratio of the channels, effectively calculating the acoustic impedance as a function of the piezoelectric tranducer's driving frequency.

However, it was realized that the "source" channel was not effectively buffered from the piezoelectric transducer, and that this was impairing the ability of the HP3562A to drive the transducer at a constant-amplitude sinusoidal voltage. In other words, the piezoelectric transducer was loading down the "source" output channel of the HP3562A, so a unity-gain buffer amplifier was designed with a large (50MΩ) input impedance and an output impedance of only a few Ohms to rectify this problem. The circuit design for this unity-gain buffer is shown in Figure 9. Shown in Figure 10 is a full diagram of the experimental setup between the HP3562A spectrum analyzer and the mouthpiece of the French Horn.
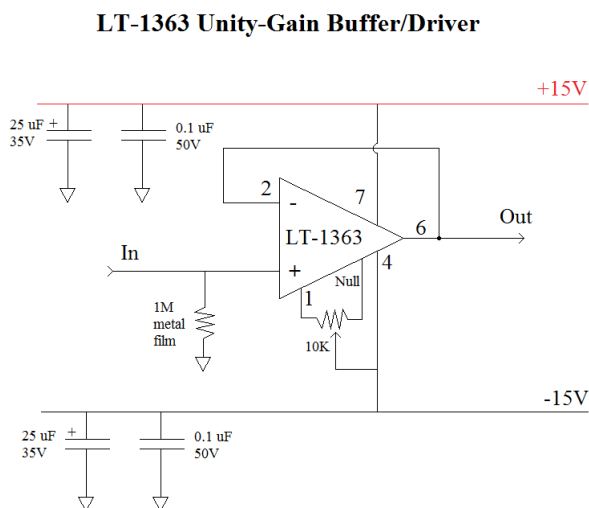
LT-1363 Unity-Gain Buffer/Driver

Figure 9: Buffer circuit used to keep the piezoelectric transducer from loading down the "source" output, ensuring constant-amplitude sinusoidal voltage signal to the transducer
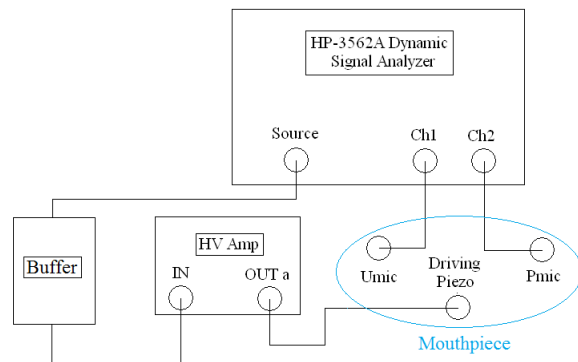

Figure 10: Diagram of the experimental setup between the Spectrum Analyzer and the French Horn mouthpiece (blue oval)

The HP3562A was programmed to do swept-sine measurement of the mouthpiece impedance over a frequency range of 20Hz to 820 Hz, which is approximately the playable range of the French Horn. Data was taken at the maximum of 801 points, resulting in a resolution of about 1Hz per data point. The table of calculated impedance as a function of driving frequency was stored in the memory of the HP3562A, and downloaded onto a PC for analysis via IEEE 488, or "GP-IB" interface. Custom-written drivers and a Matlab script were required to download and parse the data from the device's memory, and the data were then plotted in Excel.

A photograph of the experimental setup is shown in Figure 11, with the entire French Horn and microphones/preamps all inside a foam-lined box to attenuate the 1/f background noise from the ventilation system. The same Conn 8D model double French Horn was used for all measurements. The top of the box is open, and a model hand is used to show the position of the French Horn player's own hand.

Figure 11: Entire French Horn and microphone apparatus enclosed in foam-lined box to suppress 1/f background noise, with model hand to show where player's hand goes during measurements

Before a measurement was taken, the horn player would reach inside the box and set his hand in the correct playing technique, with the box as closed as possible, and data acquisition was initiated once the hand position was set. Without any averaging, which slightly increased the amount of noise in the data, measurement times were on the order of 10 minutes.

For consistency, comparisons of hand technique effects on input impedance were made with all four of the valves on the instrument in their "neutral" positions (called the "F side"). Changing valve positions effectively changes the length, and thus the key, of the horn; the effect of the hand position is

present in all valve combinations, so taking all measurements in the F side is sufficient for the purposes of this project.

The data was downloaded from the HP3562A in pairs of real/imaginary RMS voltages that were proportional to the complex acoustic impedance. However, to measure the impedance in proper acoustic Ohms, scaling corrections needed to be applied to the data to account for the sensitivity of the microphones. Microphone sensitivity was measured by placing the microphone in a 1.0 KHz sinusoidal free-air sound field with a sound pressure level (SPL) of 94.0 dB. This sound field was set by a NIST-calibrated SPL meter using C-weighting in close proximity to the microphone. The RMS output voltage amplitude from the microphone preamplifier was then measured using a true RMS digital multimeter. This sensitivity is effectively constant over the relevant frequency range, so a constant scaling factor was applied to each microphone's data. The resulting calculated acoustical impedance after corrections was in true acoustic ohms, and the magnitude of the impedance was calculated from the real/imaginary pairs. Since this paper is only interested in impedance magnitudes, phase corrections were not applied. Very detailed information on the properties and calibration of these microphones can be found in Dave Pignotti's senior thesis appendix (Pignotti).

III.   Results and Discussion

Shown in Figure 12 is a comparison of the input impedance of the horn with no hand in the bell (blue) and with the hand in the bell in normal playing position (orange). Recall that peaks in the impedance curves correspond to the playable "partials" on the instrument. The effect of the hand in the bell is much more pronounced at higher frequencies, and congruent with Backus' results.
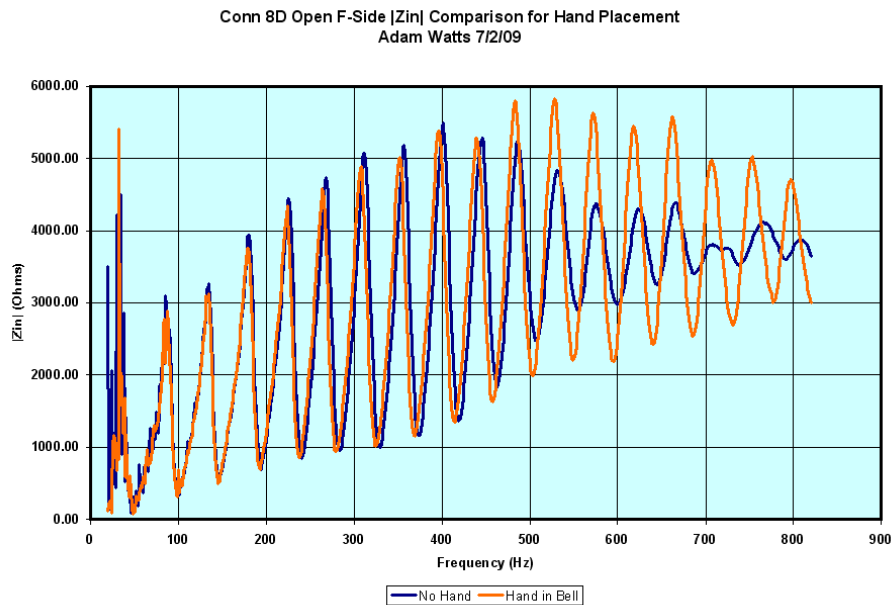

Figure 12: Input impedance of the French Horn as a function of excitation frequency of the air column via the mouthpiece. The comparison is made for no hand in the bell (blue) and normal hand playing position (orange). The addition of the hand has a pronounced effect on higher notes (curve peaks), increasing note stability (peak height) and lowering note pitch (frequency). The first peak is known to be due to 1/f ventilation noise.

The orange curve in Figure 12 demonstrates a significant increase in peak height in the upper range of the instrument, as well as reduced minima; as discussed earlier, this corresponds to a significant increase in "playability" of the upper partials due to the introduction of the hand in the bell. The frequency locations of the upper peaks have also apparently shifted downward due to the hand, but there is almost no perceptible change in the lower range. This result is not surprising, as the effect of the normal playing hand position is generally agreed upon amongst players; this data merely serves to

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reinforce that intuition, as well as to lend credence to the data Backus took with the plasticene

simulation hand, with which the presented data agrees very well. To sum up the results, the addition of

the hand in normal playing position inside the bell indeed serves to both lower the pitch and increase

the stability of the upper partials of the French Horn; this effect is apparently not present in the lower

range of the horn.

Shown in Figure 13 is the input impedance curve for hand-stopped French Horn (orange),

which is compared to normal playing hand position (blue). Once again, the first peak is due to 1/f noise

in the lab.
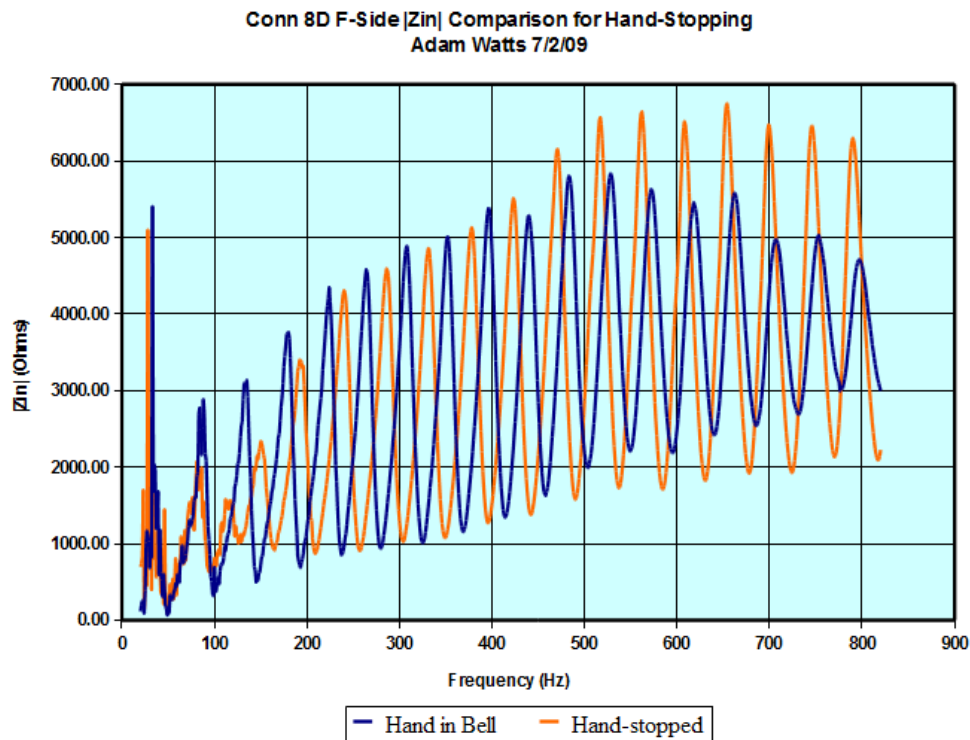
Figure 13: Comparison of impedance curve for French Horn, normal hand position versus hand-stopped. As with Backus' results, the data shows a diminished second harmonic peak, as well as an overall downward peak shift. It is worth nothing that the pitch shift is not even throughout the horn's range.

As Backus found with his rubber-stopper technique, there is a diminished second harmonic peak

after the addition of the hand-stopping compared to normal playing position. There is also a downward

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shift in all peaks due to the presence of the stopping, which confirms Backus' results. This appears to shed some light on the controversy: evidently, hand-stopping does lower the partials in pitch, and most horn players are transposing downward because they end up playing the *next higher partial* without realizing it. However, while horn players are taught to transpose down a semitone while hand-stopping, the frequency shift shown in Figure 14 does not appear to be constant in frequency. Indeed, it appears that the partials shift more drastically in the middle range of the instrument, and that there is barely any pitch change in the upper partials due to stopping.

To further investigate the frequency-dependent nature of the partial dropping due to the stopping technique, the frequencies of the impedance maxima were calculated by Matlab script. The frequency difference for each partial due to hand stopping are plotted in Figure 14. Since humans perceive pitch logarithmically, frequency changes are more accurately portrayed in cents, which are proportional to the logarithm of frequency ratios. The frequency change in cents between two pitches is defined as

$1200*\log_2(freq1/freq2)$.
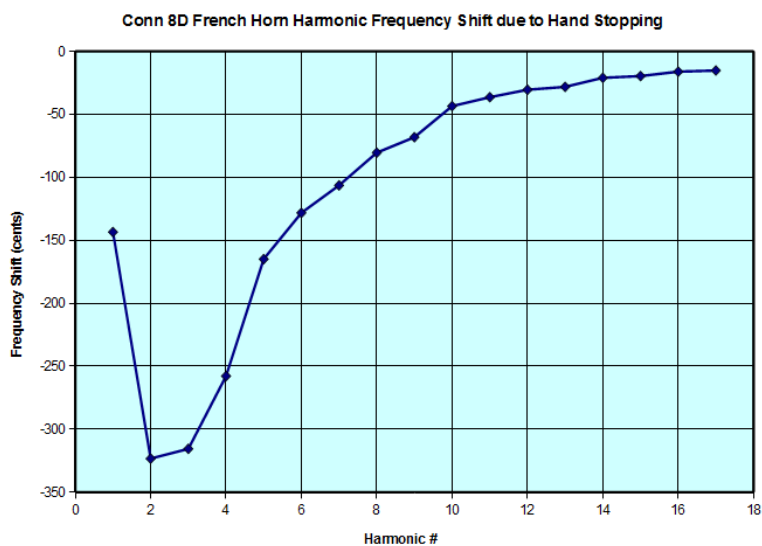
Representing frequency changes in

Figure 14: Frequency change for each partial on the French Horn due to hand-stopping. The effect is clearly not constant over the horn's range, and only shifts by a semitone (100 cents) in the middle range.

cents automatically accounts for the fact that the partials on the horn naturally get closer together in frequency in the upper range; this is an artifact of the logarithmic nature of human pitch perception, so using cents "normalizes" this effect out.

It is clear from the data that the pitch change due to hand stopping is not constant over the range of the instrument. As previously mentioned in the introduction, typical horn pedagogy instructs

transposition of a semitone (100 cents) while stopping; however, the data only shows a semitone change in pitch for the middle range of the instrument. In fact, there is very little pitch change at all in the upper range, and certainly not enough difference to warrant transposition.

III.   Conclusions

The new technique adapted from the previous work of Dave Pignotti and Professor Errede has enabled a measurement of the input impedance of the French Horn that is quick enough to warrant the use of a genuine horn player's hand technique in the bell of the instrument. This data qualitatively supports the work done by Backus to investigate the effect of normal hand-in-bell playing, as well as his conclusions about the nature of the hand-stopping muting technique.

The normal playing hand technique of the French Horn player, wherein the hand is cupped inside the bell end of the instrument, serves to help the player access the high frequency resonant modes, or partials, of the horn. The hand helps reflect higher frequency waves back up to the player's mouth, reinforcing the buzzing of the lips and increasing the stability of the note. This effect is supported by the data presented in this paper, as well as Backus' data with the hand simulation, in that impedance peaks became more pronounced and defined in the upper range when the hand was added. The cupped hand also lowers the pitch of the higher notes, bringing them more into line with the harmonic series, and thus more in tune. The data in this paper supports this by showing that the peaks of the impedance curve, which correspond to playable notes, shifted downward in pitch in the upper range once the hand was added.

The data presented in this paper also was able to confirm ideas presented by Backus involving "hand-stopping" horn technique, or the closing off of the bell with the player's hand. Hand-stopping the horn inexorably changes the frequencies of the partials, but the exact nature of this change has been steeped in controversy. The apparent controversy between the nature of partial-shifting due to hand-stopping centers around the question of the direction of the shift; players disagree as to whether partials

are shifting up or down, because there is reportedly mixed success with transposing in either direction to compensate for the shift. However, Backus' data using a rubber stopped in the bell, further supported by the data in this thesis using a real hand, suggests that the partials are indeed lowered by the addition of a stopping mechanism. The confusion arises because apparently many players are inadvertently playing the next partial up from the note they want while stopping, and transposing downward to compensate. This situation explains why most horn teachers instruct to transpose down a semitone while playing stopped horn; they are encouraging their students to play the next partial up and to compensate downward with the instrument's valves.

However, the data in this paper (to wit, Figure 15) shows that the partials do not drop a consistent amount due to stopping throughout the horn's range. Rather, it appears that hand stopping drops the pitch of the horn's partials substantially more than a semitone (100 cents) in the lower range, but hardly drops the pitch at all in the upper range. This could be a problem for horn students that are taught to transpose down a semitone all the time; if they are trying to play in the upper range, they will end up over-compensating. Apparently the rule to transpose down a semitone while stopping is only valid in the middle range of the instrument. This could have wide-ranging implications on how this particular technique is taught; armed with the data in this paper, horn teachers could begin showing that an all-encompassing transposition rule is oversimplifying the hand-stopping phenomenon.

It is important to realize that the implications of the measurements made in this paper are much farther-reaching than resolving a small controversy in extremely specialized musician pedagogy. Measurements of the input impedance of a wind instrument effectively shows the researcher where every note lies on the instrument, and how relatively stable each note is. The researcher could take an impedance spectrum measurement, then change some variable about the instrument's design, and take another impedance measurement to see how the note placement was affected. In theory, if one were able to construct an impedance spectrum that represents an "ideal" instrument, he or she could work

backwards to design the instrument to match those specifications. With the drastically reduced measurement times using the method presented in this paper, instrument designers and repairers could see the effects of their work within minutes of making them.

Future work along these lines involves the proliferation of this measurement technique to small instrument shops, with a focus on reduced cost. The HP3562A is by no means inexpensive, and it is likely unreasonable a cost for most shops to take on. However, it could be possible to make the same measurements using a standard (or perhaps slightly upgraded) sound card that is found in every personal computer. Modern PCs have sound cards that often provide very high resolution (16-bit) analog to digital conversion, and are designed to function well in the audible frequency range. The stereo microphone input of a PC sound card could receive both the pressure and particle velocity microphone signals simultaneously, one in the left channel and one in the right. Furthermore, the speaker output of the sound card could be used instead to drive the piezoelectric transducer that excites the instrument's air column, allowing for careful measurements to be made that are phase-locked to the driving frequency, just like this paper shows for the HP3562A. The catch is that these sound cards are probably much less precise than the spectrum analyzer, but it is worth investigating the feasibility of the inexpensive proliferation of this wide-reaching measurement tool.

An important question that still needs to be answered about this sort of measurement is whether the swept-sine excitation of the instrument's air column is a good approximation of real playing. While the sound pressure levels generated by the piezoelectric driver are barely audible, levels inside the mouthpiece during actual playing can be in excess of 120 dB (the pain threshold). In fact, Euler's equation for inviscid fluid flow, which allowed us to calculated particle velocity by integrating differential pressure, fall apart at sound pressure levels higher than 120 dB. It is a big challenge to get lab quality microphones that can handle such high pressure levels; regardless, more work needs to be done making measurements *in situ* with the player driving the instrument naturally

Acknowledgments

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