Acoustical Investigations of the French Horn
and the Effects of the Hand in the Bell

Phys498POM Spring 2009
Adam Watts

Introduction:

The purpose of this experiment was to investigate the effects of the characteristic playing technique of the French Horn wherein the player's hand is placed strategically inside the bell of the instrument. Much of this experiment dealt with verifying quantitatively what I have come to learn intuitively about the instrument through years of playing. Specifically, I looked at the input impedance of my Conn 8D double French Horn to determine the frequencies of playable notes on the instrument: maxima peaks in input impedance correspond to stable playable notes. Measurements of the input impedance were made over a frequency range of about 30Hz-1kHz on both the open (all valves open) F side and the open Bb side of the instrument, both with and without a “hand” in the bell. A synthetic hand was crafted into the characteristic shape of a typical horn player's hand, and was used to simulate the normal playing position while data was taken. The frequencies of input impedance maxima were compared to standard A440 equal temperament to determine intonation, and these data were then compared for the cases of hand vs. no hand.

Theory:

I was motivated to investigate this by a master class I attended, during which the instructor pointed out that having the hand in the bell of the horn made the Bb side more in-tune in the middle-upper register, and helped the player accurately hit the higher modes (also known as “partials”) in the instrument's range. Before this class, the only effect of the hand I knew of was that I could adjust my intonation quickly by either opening up or cupping closed my hand position. This intonation effect is due to the added acoustical mass the hand creates at the end of the air column as it is pushed further into the bell, lowering the frequencies of the system, which can be thought of as an approximate Helmholtz resonator (Backus 275). The other effect can be measured by looking at the magnitude of the input impedance at these frequencies. 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; in other words, sound waves reflecting off of the bell and back up the leadpipe are essential for a played note to comfortably “lock in”. 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 waves between the bell and player's mouth; this increases the height of the resonant peaks at high frequencies, thus making them easier to play (Backus 275). One might note that this same technique would be helpful, and indeed necessary for all brass instruments playing at high frequencies; however, this hand-in-bell technique is only present consistently with the French Horn. This is because unlike the other brass instruments that play up to about the 8th resonance mode, the French Horn uses modes up to an octave higher (16th mode) in regular playing; this requires that the high resonances of the instrument be “pronounced and distinct” (Backus 273). This is precisely what the hand in the bell accomplishes: the technique allows the French Horn to be played accurately in its upper register by making the high frequency resonant modes more pronounced.

Since this high frequency effect relies on reflected waves from the bell, as previously described, it can be attributed to impedance mismatch between the air column of the instrument and the surrounding air near the bell. Just as with electrical transmission systems, impedance mismatch between the transmission line and the load results in reflected waves back down the line. This is a result best summarized by the maximum power transfer theorem, in that maximum power is transferred between transmission line and load when the impedance of one is matched to the complex conjugate of the other (Kudeki and Munson 106). Since the acoustical impedance of free air is frequency-independent, and approximately 420 acoustical Ohms, maximum wave reflection will occur at peaks in the instrument's input impedance above 420 acoustical Ohms. Therefore, the frequencies of these maxima in input impedance will directly correspond to stable playable notes on the Horn. Moreover, in order for the hand in the bell to strengthen the high frequency modes as discussed above, we should see correspondingly larger peaks in input impedance at higher frequencies with the hand in the bell.

To measure the input impedance of the instrument, another electrical analogy is helpful, albeit a more quantitative one than the transmission line analogy. The ubiquitous Ohm's law for electrical circuits can be generalized for acoustics; whereas complex electrical impedance is the quotient of complex voltage to complex current, complex acoustical impedance is the quotient of complex pressure to the complex particle velocity (Olson 63). Thus, our experimental setup needs to measure the complex pressure and complex particle velocity at the input of the instrument (inside the mouthpiece) as a function of frequencies in the instrument's playable range. Computing the complex quotient of the pressure to the particle velocity for each frequency will map out the input impedance as a function of frequency for the French Horn, and maxima peaks in this graph will correspond to playable notes for that valve combination.

Experiment:

To carry out this measurement, I used a technique developed by Professor Steve Errede along with Dave Pignotti, Brendan Sullivan, Marguerite Brown, and Nicole Pfiester, as well as countless other students over the years. The instrument is excited by a sinusoidal force from a piezoelectric transducer affixed to the mouthpiece (shown at the top of Figure 1). To measure the pressure inside the mouthpiece, a hole is drilled into the side and an electret condenser microphone is inserted inside (Errede 5). To measure particle velocity, however, a differential pressure microphone is used, and the resulting signal is integrated in time to arrive at the particle velocity; this is possible because of Euler's formula for inviscid fluid flow, whereby the time derivative of the particle velocity is proportional to the gradient of the pressure (Errede 9). Since we need to know what the *complex* quantities are in order to compute the full impedance of the instrument, two Stanford Research SR-830 Lock-In Amplifier are used to simultaneously measure the in-phase and quadrature (90 degrees out of phase with the driving source) voltage signals from the microphones, effectively letting us measure the real and imaginary components of the particle velocity and pressure. It should be noted that while the complex particle velocity is a vector field, and thus should be measured in three planes for completeness, we are only measuring the particle velocity in the longitudinal direction, since this is the wave propagation direction and is the only component that will contribute to this impedance measurement. Also, while the impedance measured is a complex quantity, it is the *magnitude* of the input impedance in which we are interested.

To simulate the player's hand inside the bell of the instrument, I used a latex kitchen glove filled with hot dogs in the fingers (to approximate the density of real fingers) and thick sponge in the palm. This slightly unorthodox solution is pictured below in Figure 1. The simulation hand is carefully shaped such that the palm cups and the fingers curl slightly, approximating the “hand-shake” shape necessary for a good horn playing hand position. At the top of the picture, the two microphones are visible protruding from opposite ends of the mouthpiece. The entire apparatus is enclosed in a box lined with foam to try to approximate a free-field environment.

Figure 1: Measurement apparatus with simulation hand in bell

The calculation of the complex acoustical impedance is carried out in software by a Matlab program that records, computes, and graphs parameters including real and imaginary components, as well as magnitude and phase data for pressure, particle velocity, and impedance as a function of frequency. Data was taken in steps of 1 Hz from 29.5 Hz to 1.5 kHz for the sinusoidal driving frequency, on both the open F and Bb sides of the horn, with both the hand present in the bell and not present.

Data Analysis:

Shown below in Figure 1 is a comparison of the magnitude of the input impedance of the F-side of the horn before and after the hand is inserted into the bell. The blue trace represents the horn without the hand, and the magenta trace represents the horn with the hand in the bell. Note that due to 1/f noise present in the lab, we did not scan lower than 29.5 Hz, and thus did not measure the fundamental of the F-side of the horn.

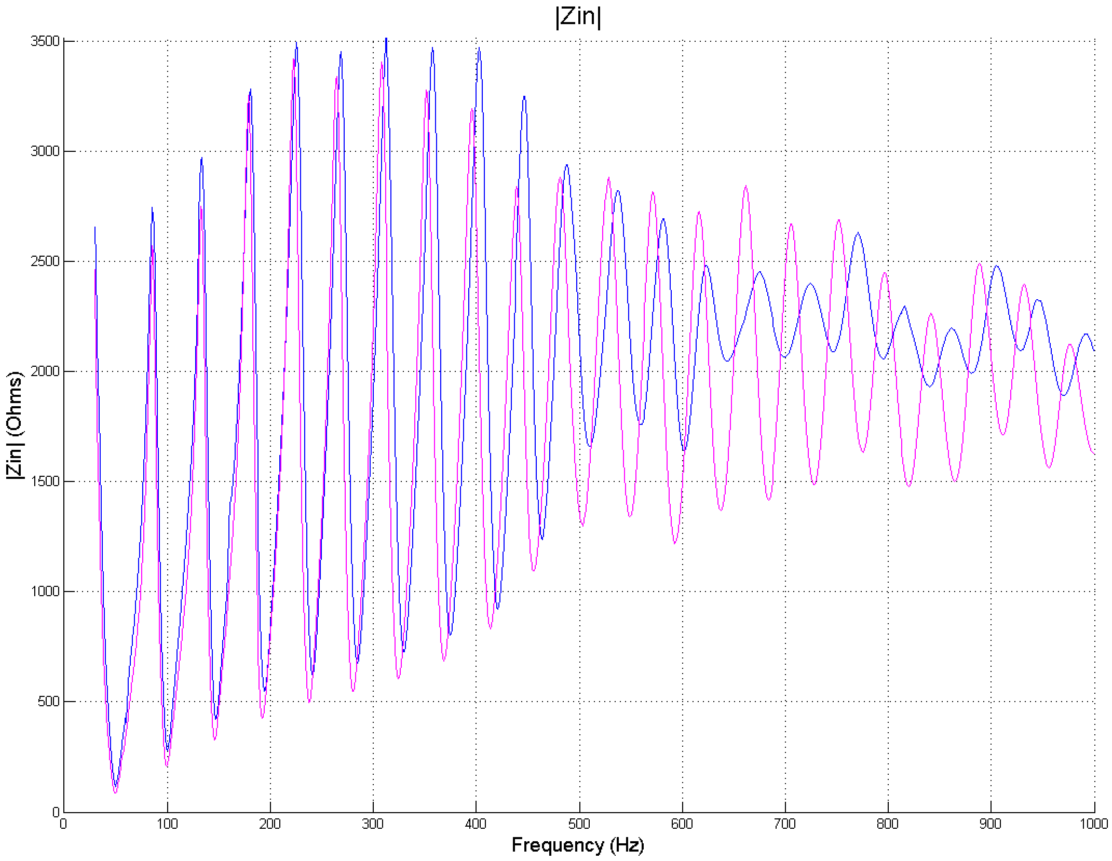
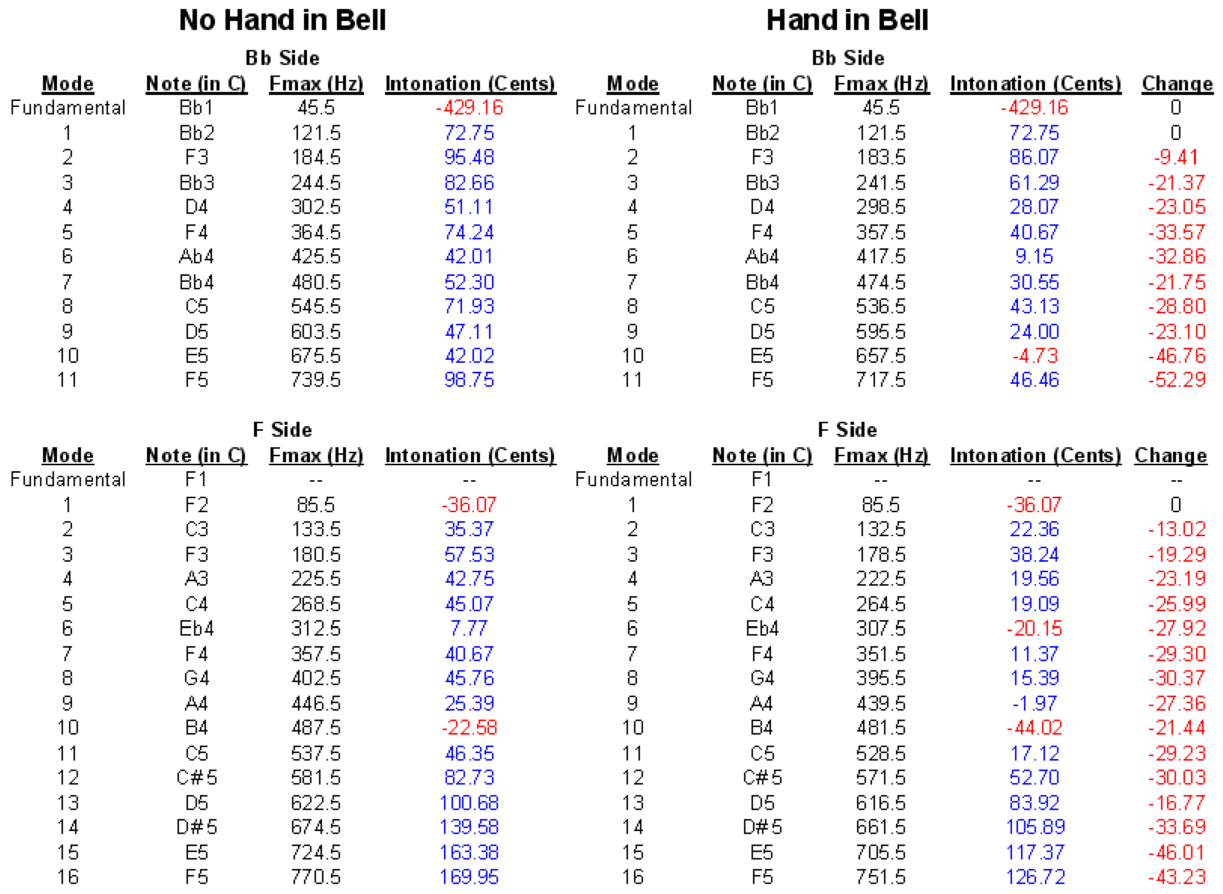


Figure 2: Comparison of |Zin| on F-side of Conn 8D French Horn with no hand (blue) and hand (magenta) in the bell.

I have summarized the frequencies of input impedance maxima in Table 1 below, and have compared the frequencies of the peaks to standard A440 equal temperament to give an idea as to the relative tuning of each partial (i.e. mode) of the instrument. Note again that we were not able to detect the fundamental resonance for the F side, so it is left blank in the tables. It is also important to note that while we actually measured over the entire audio spectrum (20Hz-20kHz), I am only showing resonances that are in the playable range of the instrument (~29.5Hz – 1kHz). To summarize the intonation effects of the hand in the bell, the frequency changes in input impedance maxima are listed as well in Table 1.



	No Hand in Bell				Hand in Bell			
		Bb Side				Bb Side		
Mode	**Note (in C)**	**Fmax (Hz)**	**Intonation (Cents)**	**Mode**	**Note (in C)**	**Fmax (Hz)**	**Intonation (Cents)**	**Change**
Fundamental	Bb1	45.5	-429.16	Fundamental	Bb1	45.5	-429.16	0
1	Bb2	121.5	72.75	1	Bb2	121.5	72.75	0
2	F3	184.5	95.48	2	F3	183.5	86.07	-9.41
3	Bb3	244.5	82.66	3	Bb3	241.5	61.29	-21.37
4	D4	302.5	51.11	4	D4	298.5	28.07	-23.05
5	F4	364.5	74.24	5	F4	357.5	40.67	-33.57
6	Ab4	425.5	42.01	6	Ab4	417.5	9.15	-32.86
7	Bb4	480.5	52.30	7	Bb4	474.5	30.55	-21.75
8	C5	545.5	71.93	8	C5	536.5	43.13	-28.80
9	D5	603.5	47.11	9	D5	595.5	24.00	-23.10
10	E5	675.5	42.02	10	E5	657.5	-4.73	-46.76
11	F5	739.5	98.75	11	F5	717.5	46.46	-52.29

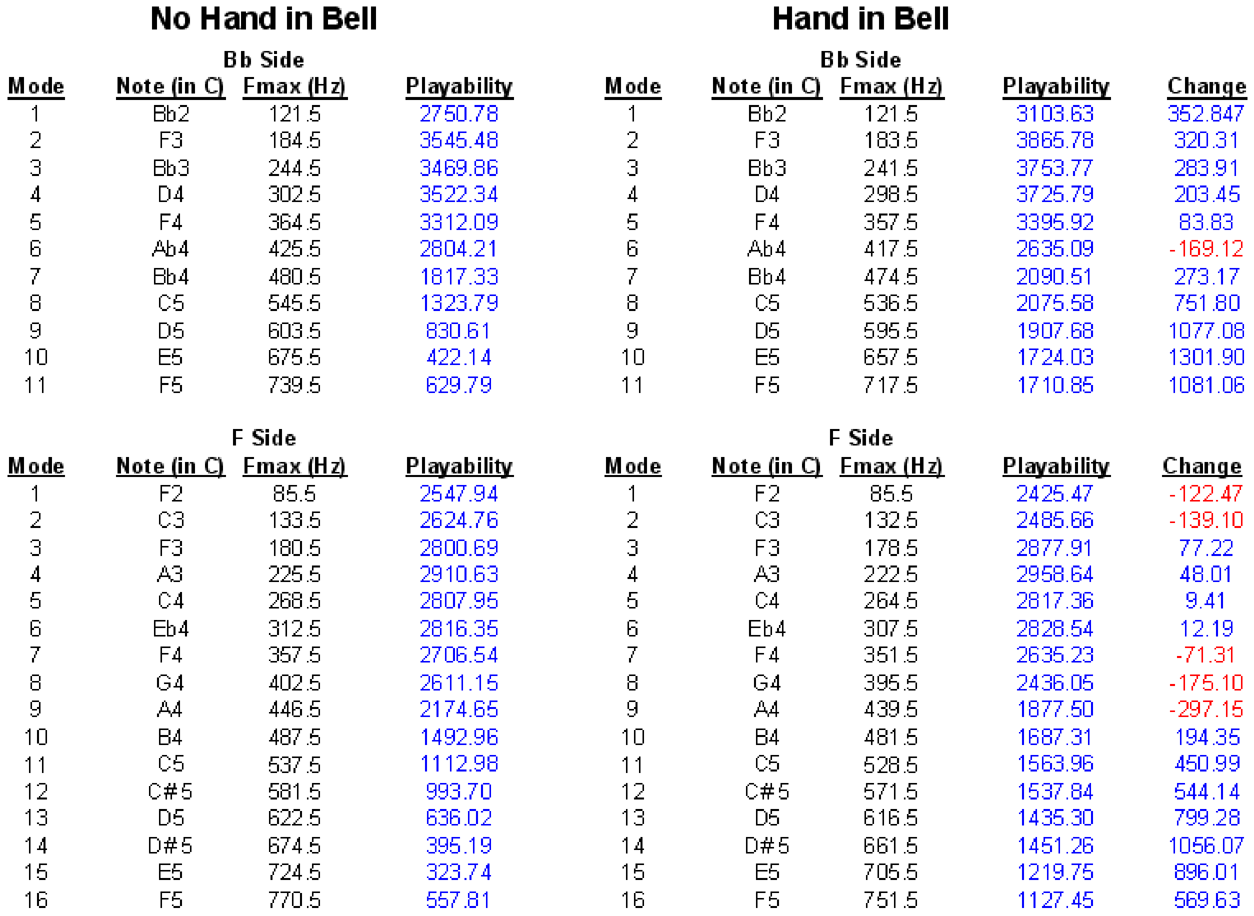
		F Side				F Side		
Mode	**Note (in C)**	**Fmax (Hz)**	**Intonation (Cents)**	**Mode**	**Note (in C)**	**Fmax (Hz)**	**Intonation (Cents)**	**Change**
Fundamental	F1	--	--	Fundamental	F1	--	--	--
1	F2	85.5	-36.07	1	F2	85.5	-36.07	0
2	C3	133.5	35.37	2	C3	132.5	22.36	-13.02
3	F3	180.5	57.53	3	F3	178.5	38.24	-19.29
4	A3	225.5	42.75	4	A3	222.5	19.56	-23.19
5	C4	268.5	45.07	5	C4	264.5	19.09	-25.99
6	Eb4	312.5	7.77	6	Eb4	307.5	-20.15	-27.92
7	F4	357.5	40.67	7	F4	351.5	11.37	-29.30
8	G4	402.5	45.76	8	G4	395.5	15.39	-30.37
9	A4	446.5	25.39	9	A4	439.5	-1.97	-27.36
10	B4	487.5	-22.58	10	B4	481.5	-44.02	-21.44
11	C5	537.5	46.35	11	C5	528.5	17.12	-29.23
12	C#5	581.5	82.73	12	C#5	571.5	52.70	-30.03
13	D5	622.5	100.68	13	D5	616.5	83.92	-16.77
14	D#5	674.5	139.58	14	D#5	661.5	105.89	-33.69
15	E5	724.5	163.38	15	E5	705.5	117.37	-46.01
16	F5	770.5	169.95	16	F5	751.5	126.72	-43.23

Table 1: Summary of input impedance maxima frequencies of Conn 8D French Horn, the corresponding intonation compared to A440 equal temperament (in cents), and the change due to the presence of the hand in the bell.

Note that the 11th harmonics for all four setups represent a deviation from the expected "harmonic series" once the hand is inserted into the bell. The 11th harmonic is lowered enough that it can be considered a semi-tone lower, so rather than representing the "tritone" pitch in the series, the

11th harmonic is now more diatonic and useful to the horn player.

Similarly, I compare the relative *strengths* of the playable notes by looking at the difference in heights of the impedance maxima and minima as a function of frequency. For this comparison, I paired each maximum with its successive and preceding minima and computed Zin(max) – <Zin(minima)> (i.e. average). This shows the relative ease with which the note can be played, with a larger "peak-to-min" value representing a stronger note on the instrument. This data is shown below in Table 2.



No Hand in Bell				Hand in Bell				
	Bb Side				Bb Side			
Mode	Note (in C)	Fmax (Hz)	Playability	Mode	Note (in C)	Fmax (Hz)	Playability	Change
1	Bb2	121.5	2750.78	1	Bb2	121.5	3103.63	352.847
2	F3	184.5	3545.48	2	F3	183.5	3865.78	320.31
3	Bb3	244.5	3469.86	3	Bb3	241.5	3753.77	283.91
4	D4	302.5	3522.34	4	D4	298.5	3725.79	203.45
5	F4	364.5	3312.09	5	F4	357.5	3395.92	83.83
6	Ab4	425.5	2804.21	6	Ab4	417.5	2635.09	-169.12
7	Bb4	480.5	1817.33	7	Bb4	474.5	2090.51	273.17
8	C5	545.5	1323.79	8	C5	536.5	2075.58	751.80
9	D5	603.5	830.61	9	D5	595.5	1907.68	1077.08
10	E5	675.5	422.14	10	E5	657.5	1724.03	1301.90
11	F5	739.5	629.79	11	F5	717.5	1710.85	1081.06

	F Side				F Side			
Mode	Note (in C)	Fmax (Hz)	Playability	Mode	Note (in C)	Fmax (Hz)	Playability	Change
1	F2	85.5	2547.94	1	F2	85.5	2425.47	-122.47
2	C3	133.5	2624.76	2	C3	132.5	2485.66	-139.10
3	F3	180.5	2800.69	3	F3	178.5	2877.91	77.22
4	A3	225.5	2910.63	4	A3	222.5	2958.64	48.01
5	C4	268.5	2807.95	5	C4	264.5	2817.36	9.41
6	Eb4	312.5	2816.35	6	Eb4	307.5	2828.54	12.19
7	F4	357.5	2706.54	7	F4	351.5	2635.23	-71.31
8	G4	402.5	2611.15	8	G4	395.5	2436.05	-175.10
9	A4	446.5	2174.65	9	A4	439.5	1877.50	-297.15
10	B4	487.5	1492.96	10	B4	481.5	1687.31	194.35
11	C5	537.5	1112.98	11	C5	528.5	1563.96	450.99
12	C#5	581.5	993.70	12	C#5	571.5	1537.84	544.14
13	D5	622.5	636.02	13	D5	616.5	1435.30	799.28
14	D#5	674.5	395.19	14	D#5	661.5	1451.26	1056.07
15	E5	724.5	323.74	15	E5	705.5	1219.75	896.01
16	F5	770.5	557.81	16	F5	751.5	1127.45	569.63

For both the intonation and relative note "strength", it is evident that the effect of the hand in the bell is more pronounced on the Bb side of the instrument, which is probably something most French Horn players know about intuitively. As expected, the pitch of the playable notes on the instrument for the open F and Bb sides decreased as the hand was inserted into the bell, and this effect is more pronounced at higher modes (as predicted by Backus). Furthermore, all but one partial on the Bb side of the instrument became “stronger”, i.e. easier to play, once the hand was inserted, which agrees well with the explanation from the horn master class I mentioned at the beginning of the paper. This effect is more pronounced on the Bb side, especially at higher modes.

Conclusion:

By measuring the magnitude of the complex acoustical impedance at the input of my French Horn, I was able to show how the simulation hand in the bell affected the strength and intonation of the partials of the instrument. As far as intonation, it was clear that adding the hand in the bell lowered the frequencies of almost every resonance, especially on the Bb side, which completely agrees with my intuition from playing the instrument. The hand lowered the higher harmonics the most, which is to be expected from Backus’ explanation mentioned earlier.

Similarly, the relative playability of the partials on the open (all vales up) F and Bb side of the horn was measured by calculating the impedance difference between successive maxima and minima in the input impedance of the horn. The data shows that almost all of the partials of the open Bb side of the horn increased in playability strength due to the insertion of the hand in the bell, and that the effect was not as pronounced on the open F side. This again agrees well with my playing intuition of the instrument, as it is my experience that the hand in the bell increases the stability of the Bb side of the horn, especially at higher frequencies.

Further research using these techniques will be used to examine the effect of full hand closure in the bell, also known as “hand-stopping”. The effects investigated in this paper would also be worthwhile to study using other measurement techniques, such as spectral analysis, to verify results. While the results in this paper agree with my own intuition as a player, it should be noted that the method of exciting the air column of the horn is not equivalent to playing the instrument. The sound pressure level inside the mouthpiece during normal playing easily exceeds 100 dB, while the strength of the piezoelectric driver used in this experiment is much weaker. Inherent nonlinearities in the instrument as such high sound pressure levels during normal playing would undoubtedly have an effect on the modes of the instrument’s air column. Further research using a sinusoidal driving force of comparable sound pressure level to a player’s lips is needed. It should also be noted that while the driving force in this experiment was sinusoidal (i.e. monochromatic), this is not so in the case of a player's lips driving the instrument. However, the force from the player's lips will be a sum of sinusoidal driving forces, so it is possible that in the linear regime of the medium, sweeping through monochromatic driving frequencies as we did in this paper is an acceptable way to excite the air column. Again, further research into this is needed to determine the accuracy of monochromatically exciting the air column of the instrument.

Works Cited

Backus, John. *The Acoustical Foundations of Music, Second Edition.* Pg. 273, 275. W. W. Norton & Company, New York 1977.

Errede, Steve. “UIUC Phys498POM Lecture 13 part 1”. Pg. 5,9.

Kudeki, Erhan and Munson, David. *Analog Signals and Systems.* Pg. 106. Pearson Education, Inc. New Jersey 2007.

Olson, Harry F. *Music, Physics, and Engineering, Second Edition.* Pg. 63. Dover Publications, Inc. New York 1967.