Acoustic Harmonicity and Input Impedance for Various Bb Trumpet Mutes

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ABSTRACT

There are many various types and grades of mutes used by trumpet players in concert settings, and many “myths” and misconceptions about their effects on timbre, intonation and playability. The sound output produced with each of the various mutes (including Straight, Cup, Harmon, Plunger and Practice) was recorded and run through a phase-sensitive wave analysis program to determine the phase relations, frequencies, and amplitudes of the most prominent harmonics, giving insight into tone and timbre differences of each mute. With pressure and differential pressure microphones measuring complex pressure and particle velocity within the cup of a trumpet mouthpiece, the input impedances of the trumpet can be calculated across a range of frequencies by exciting the air column with a piezoelectric transducer attached to the rim of the mouthpiece. This data was collected for each of the various mutes and compared to data without a mute, to quantify each mute’s effect on the intonation and playability of the trumpet.

I. Introduction

The trumpet is considered a brass instrument, sounded by the “buzzing” of one’s lips within the confines of a small metal mouthpiece “cup.” Therefore, the trumpet, like all brass instruments, is known as a “lip-reed” instrument, in which the opening-and-closing of lips create pressure waves that propagate down the air column of the instrument, exiting by radiating only at the bell-shaped exit of the horn. Through centuries of refining designs, the trumpet that we know today acts very well as a 1-D harmonic oscillator, creating a harmonic series of integer multiples of the fundamental frequency of the horn. The harmonic content of the horn is thus very important in creating its timbre.

The entire trumpet acts as an open-ended standing wave tube in which pressure waves reflect off of the impedance mismatches at the open ends, creating counter-propagating waves. These waves send back “information” to the player’s lips, in a way of reinforcing them to vibrate at a certain frequency to produce pressure waves that form the pitch the player intends. This "reinforcing" information can be best described by the input impedance of the instrument across a range of frequencies. In general terms, acoustic impedance is the resistance of a fluid to incoming pressure waves. It can be calculated as the ratio of complex pressure to complex particle velocity at a given space and time in a fluid.

Therefore, in a trumpet mouthpiece, if the pressure and particle velocity can be calculated in a phase-sensitive manner across a range of frequencies, input impedance curves can be drawn to show what frequencies create "peaks" of input impedance of the wave tube. These peaks are therefore the maximum points of resistance in the mouthpiece, which means that the lips feel the most reinforcing information from the pressure wave reflections. Therefore, these "peaks" are actually the frequencies of the playable notes of the trumpet for that given valve combination. Because the sound only emanates from the bell of the horn (something that separates the brass family from other lip-reed woodwind instruments), the quality of the sound can be tempered with the addition of an obstacle at the bell end in the form of a *mute*. If one compares the curves between these different exit conditions, the shifting of peaks will point out the intonation changes and the relative heights of the peaks will point out the differences in playability. It is with these principles that the second part of this investigation takes place in comparing and contrasting the input impedances of various mutes for a trumpet.

Out of the multitudes of mutes made for trumpets the three most common are the "straight mute," the "cup mute" and the "Harmon mute." Straight mutes are by far the most widely used mutes, being called for in almost any genre of music from symphonic to jazz. It is known for its "nasally" and biting sound that seems to make the trumpet more "articulate." It is a very simple design, being conical in shape and having one end open, pointing into the trumpet. It is secured in the horn's bell by three thick corks, which leave gaps around the bell's exit, giving it an "open" or suspended sort of attachment. It is widely considered by both trumpet players and band conductors alike that the addition of a straight mute causes the horn to play "high," or sharp compared to what it would play without a mute.

Another very popular mute is a derivative of the straight mute, the “cup mute.” In the simplest of designs, this can be a flanged “cup” attached to the end of a straight mute. Supposedly because of the added cone to the end of the mute, the sound is quite different than the straight mute; it is less “nasally” and sounds deeper. It is also secured in an “open”/suspended manner like the straight mute. However, the added cone changes the pitch so that musicians tend to think that the cup mute “lowers” the tone of the instrument, making it more flat.

Harmon mutes, or “wah-wah” mutes as they are more semantically called, are not used as commonly as straight or cup mutes, but are still quite popular in certain genres of music, especially jazz. They are comprised of a large, open metallic bulb, with the option of using a “stem,” or pipe-like insert, to adjust the tone of the sound. They are secured differently than cup or straight mutes, in that there is a single thin cork layer completely surrounding the tip of the mute so that it completely closes or “seals” the end of the bell.

Another type of mute becoming more popular recently is the “practice mute.” They are completely “closed” in attachment like the Harmon mute, and are meant for practicing purposes only, not concert settings. Players will typically use these only when it is necessary to not disturb others, as they significantly reduce the sound produced by the horn, while therefore increasing the resistance to playing, which some believe makes it easier to play certain partials. Players have differing feelings about how these mutes affect tone and quality of playing. However, the most popular brand of practice mute is the “Silent Brass” System, created by Yamaha, and will be discussed later in this report.

Although there are certain generalizations about the effects of mutes on a trumpet’s intonation and playability, mute manufacturers try to claim that the mutes are designed and manufactured to play in-tune. Leblanc Corporation claims that their “Alessi-Vacchiano Mello-Mute” (which will be discussed later) “is acoustically built to play in tune” (MusiciansFriend.com), while Yamaha quotes that their Silent Brass mute has “excellent intonation – very accurate tuning in every range.” Yamaha also states that the practice mute has “low resistance – the blow feels free,” as if to state that the playability of different notes is not affected by the addition of the mute. These claims will be investigated through this report.

II. Experimental Setup & Procedure

Mutes

I chose to analyze mutes from each of the above types and compare them laterally to different styles/prices of mutes in their respective categories. For straight mutes, I chose to analyze the Humes & Berg 101 Stone-Lined Straight Mute (MSRP: $21.00, seen in Figure 1) with the Denis Wick DW5531 (MSRP: $65.99, Figure 4) and the Tom Crown Aluminum and Copper ended straight mutes (MSRP: $57 & $62, Figures 2 & 3). For cup mutes, I chose the counterpart of the Humes & Berg straight mute, the Humes & Berg 102 Stone-Lined Cup Mute (MSRP: $36.00, Figure 5), and the Denis Wick DW5531 again (Figure 6), because it transforms into a cup mute by sliding on a cone sheath. For Harmon mutes, I chose the Leblanc “Alessi-Vacchiano” 3001 (MSRP: $61.00, Figure 7) and the Jo-Ral TPT-2C Bubble (MSRP: $92.99, Figure 8). With the prices varying so widely between these mutes, there must be a quantitative difference in timbre, intonation or playability that creates need for people to purchase the more expensive of the mutes. I only chose to analyze one practice mute, the Yamaha “Silent Brass” PM-7 (MSRP: $84.00, Figure 10), because I wanted to see the differences in playing between a practice mute and no-mute at all.

Trumpet and Mouthpiece

For all of the experiments, I used my Bach Stradivarius Bb Trumpet, Model 37. For the harmonic analysis portion, I played on a Blessing 5C mouthpiece, but for the input impedance experiment, in order to not damage the sensitive microphones, a modified Bach 7C mouthpiece was used. I do not foresee a large difference in the results since the cups are very similar in size, and any differences should not be necessary to note since I will be looking at trends more than actual numerical comparisons.

Harmonic Analysis of the Mutes

To analyze the harmonic contents of the different mutes and playing styles, I, with the help of Steve Errede, recorded myself playing a concert F4 (for Bb Trumpet, a G4) pitch on each of the 12 mutes styles, listed below:

1. No mute
2. Straight mute – Humes & Berg
3. Straight mute – Tom Crown, Aluminum end
4. Straight mute – Tom Crown, Copper end
5. Straight mute – Denis Wick
6. Cup mute – Humes & Berg
7. Cup mute – Denis Wick
8. Harmon mute – no stem, Leblanc Vacchiano
9. Harmon mute – no stem, Jo-Ral
10. Harmon mute – with stem, Leblanc Vacchiano
11. Harmon mute – with stem, Jo-Ral
12. Practice mute – Yamaha "Silent Brass"

These sounds were recorded through a Peavey PVM-45 hypercardiod dynamic microphone, into a Marantz Professional PMD671 recording device, set at a recording level of "3.0" (except for the practice mute #12 that was recorded at a max-level of "10.0" due to the quiet nature of the mute).

With these tones played and recorded to the best of my ability at the same distance from the microphone, dynamic, articulation, amount of air, and without correcting the pitch, they were transferred to a computer and run through a MATLAB program developed by a former research student in the UIUC Physics Department, Joe Yasi[1]. This phase-sensitive software is able to determine the phase relations, frequencies, and amplitudes of the most prominent harmonics, giving insight into tone and timbre differences of each mute as will be seen in the next section.

Input Impedance Analysis

In order to gather mouthpiece input impedance data for the trumpet with various mutes, we needed recorded devices capable or measuring complex pressure and particle velocities within a small space. Thanks to a former research student's thesis work on the "Acoustic Impedance of a Bb Trumpet," [2] I was able to use a similar setup for this experiment. To measure pressure in the mouthpiece, I used an electret omni-directional pressure microphone, a 0.1” Knowles Acoustics FG-23329. To measure particle velocity, I used a RadioShack type 270-090 electret condenser microphone, modified[2] to have an open-diaphragm to measure differential pressure, combined with an integrating op-amp that gives it the ability to measure signals proportional to complex particle velocity (assuming Euler’s approximations for inviscid flow hold true). These microphones were inserted into a Bach 7C mouthpiece (as seen and mentioned in Pignotti’s[2] report). A piezoelectric transducer was affixed to the lip of the mouthpiece to gently excite the air column, making sure that the intensity of the vibrating membrane did not exceed 94-dB in which certain inviscid flow and non-linear approximations would not hold true.

By putting the trumpet in a large wooden box padded with foam strips to simulate an anechoic chamber, the transducer could be hooked up to an amplified swept-sine source at a level of 500 mV before amplification, spanning a frequency range of 2 kHz between 20 and 2020 Hz.. The microphones were hooked up to a spectrum analyzer to measure RMS V^2 output signals over the frequency range, and the complex quantities of pressure and particle velocity were then divided to yield the dimensionless input impedance of the mouthpiece. These dimensionless values could then be converted to Acoustic Ohms by multiplying them by conversion factors found by measuring the sensitivity of the microphones in a known free-field sound field. This data was all run through a MATLAB program modified by myself to help more easily convert the numerical values into useful data in the form of Microsoft Excel charts.

III. Results and Discussion

Harmonic Analysis of the Mutes

The MATLAB program developed by Yasi allowed the output of harmonic amplitude and relative phase charts (seen in Appendix B).

Simply viewing the harmonic amplitudes of using no mutes in the trumpet, it can be seen that the fundamental (1st harmonic) is lower than the 2nd harmonic, which is a common feature for trumpets. It also has notably strong 2nd, 3rd and 4th harmonics before decaying out the higher ones. The decay is smooth and steady (on a logarithmic scale) as seen in the harmonic range Figures in Appendix B. The phase shifts of the harmonics relative to the fundamental are also worth noting, seen in the Appendix.

Comparing these to the figures for straight mutes, one can note that the H&B and DW straight mutes both exhibit very similar harmonic behavior, showing a common trend in straight mutes. The first 4 harmonics are quite low, especially the 4th, until the higher harmonics (5 and higher) become rapidly stronger, in the DW case more than 5x the fundamental amplitude (in dB). This increase in strength of the higher harmonics while diminishing the lower harmonics gives tones a brighter, more "nasally" sound, seen in straight mutes, therefore this makes sense. The TC mutes similarly have decreased low harmonics (1 through 3), but both the aluminum and copper TC mutes have *very* high 4th harmonics, unlike the first two straight mutes. The aluminum's 5th harmonic very low and the 6th and 7th harmonics are strong, yet the copper's 5th and higher harmonics are less prominent. This could create a more "biting" sound from the aluminum backed TC mute, compared to the copper mute. The choice between the two may be for varying styles of music or for musicians of different taste. The phase relations of the H&B and DW straight mutes are also very similar, not providing much sense for a difference in timbre between the two, yet the DW is much more expensive (albeit because it is made of metal and includes a cup-mute cone). This may prove that the cheaper H&B mute is a fine substitute for the more professional looking DW mute, while the TC mutes provide a different shaped straight mute with different timbre qualities for different musician's tastes.

The H&B and DW cup mutes also showed a very similar resemblance. Their harmonic amplitudes were very similar in trends, have an increasingly strong 1st, 2nd and 3rd harmonics but much diminished 4th and higher harmonics. This shows that the cup mutes are in fact smoother in sound, to say, more mellow than the biting higher harmonics of the straight mutes. The cone indeed does add a buffer for these higher harmonics. However, there may be possible differences in timbre and tone quality due to the phase differences between the two, although it is hard to describe phase as something even a trained listener can hear. The phase relations of the H&B cup mute are very similar to the relations of having no-mute in, which begs the question that maybe the varying phase structure of the DW mute is what is desired in a cup mute.

For Harmon mutes with no stem, there is a very characteristic structure seen in the harmonic amplitudes of both the cheap Vacchiano and the more expensive Jo-Ral.

Without a stem, both of these mutes produce very strong low harmonics with a large dip in the 4th or 5th harmonic, creating a very mellow and subdued sound. There is then a strange up-and-down decay for the higher harmonics. The Vacchiano's decay in higher harmonics is much less smooth than is the Jo-Ral, which seems to even have a possible secondary formant region 2500-3500 Hz. This may be a desired quality in Harmon mutes. Looking into their phase structures, the two are very similar indeed, yet it is interesting to notice that the 2nd harmonic is nearly in-phase with the fundamental for both mutes. This may relate to a less brassy sound produced by the no-stem Harmons, since even the no-mute data shows a 2nd harmonic that is almost 180 degrees out of phase with the fundamental.

With stems added however, the harmonic structure changes significantly, decreasing the low harmonics such as the 1st through 3rd but increasing the higher harmonics like the 4th through 6th, with a definite strongest 4th harmonic. This produces a more brassy sound as is easily noted by replacing the stem into the mute. The phase structure is also noticeable since the 2nd harmonic is now more out of phase (indicating a more brassy feature?) while the 4th harmonic, the new strongest harmonic for both mutes, is not placed in similar relative phase to the fundamental for both mutes. This may account for a difference in the mute quality.

The Silent Brass mute shows a very strange harmonic structure with a very strong fundamental yet very weak 3rd harmonic. The 4th harmonic then picks up to be almost as strong as the 2nd, yet the decay afterward is quite rapid. The entire harmonic range is not very smooth in decay or in pattern at all, meaning that the sound heard should be quite strange compared to a trumpet's normal feature. This is true if one has heard the Silent Brass mute, especially since it is NOT meant for listening purposes; it is purely meant as a practice mute, in fact to NOT be heard by passer-bys. This may account for why the harmonic structure is quite different than other mutes (including a strangely high 13th harmonic…), because it is not a desirable tone to have in a trumpet.

Input Impedance Analysis

As seen in the input impedance curve for a non-muted trumpet (first Figure of Appendix C), one will note the great decrease in definitive peaks in input impedance above 1400 Hz. This is why we define “playability” as the effective “ease” of playing certain pitches based on the strength of the “reinforcing” reflection waves. If there is a lack of peaks yet high input impedance, this means that it may be possible to play a pitch in that region correctly, yet the note itself will not “slot” correctly, and will therefore be hard to “play” easily, thus showing a lack of “playability.”

Playability is a dimensionless quantity that we have defined as a ratio of the height of a peak to the average of the valleys surrounding it:

$$\text{Playability (-)} = \left(|Z_{peak}| \Big/ Avg\left[|Z_{valleys}|\right] \right)$$

Intonation can then be defined as the location of the peaks of the impedance curve relative to a fixed tuning scale or a control set of data (which for this experiment is the no-mute data mentioned previously). To define intonation of a “slotted” peak, it is best to work in the musical units of “cents,” or fractions of a semi-tone in equal temperament tuning. There are 12 semitones per octave in equal temperament, and if each of these is divided into 100 cents (meaning each perfectly in-tune note is $\pm$ 50 cents from its nominal value), the intonation between two frequencies can be calculated as:

$$\text{Intonation (cents)} = 1200 \times \log_{10}\left(f \big/ f_{control} \right)$$

A good musician can discern between around 20 cents difference around a nominal value, so that will be a criteria in judging the in-tune qualities of a mute.

These quantities of playability and intonation are of great importance in brass instruments, and will help answer questions relating to the effects that mutes have on intonation and playability of the horn itself.

These differences in intonation and playability between the no-mute scenario and muted scenarios are shown in Appendix C. The yellow graphs show the comparison of input impedance curves, but the intonation and playability graphs that follow are more important in realizing the mute’s effects on the trumpet and the player.

For the straight mutes, the expensive ones (DW, TC-Al, TC-Cu) are mostly in tune or at very most less than 20 cents sharp in the playable range described in a Table in Appendix A. However, the cheaper H&B straight mute is less consistent in its tuning compared to no-mute, and in fact runs generally flat! The playability of the expensive mutes seem to follow a very tight and similar trend of being less playable at low pitches but getting increasingly more and more playable through higher frequencies, and although the H&B straight mute follows the same basic pattern, it does not conform as tightly to this trend as do the others, being more inconsistent throughout the playable range.

For cup mutes, the expensive DW mute is only outside of the 20 cent region for C5, but for the rest of the playable range between 200-900 Hz, it is “perfectly” in-tune (according to the resolution of the spectrum analyzer)! The H&B mute is much less consistent and flat for most of the playable range, only really getting in-tune for high notes above a Grand C. The playability for both of these cup mutes is also notable, since the H&B is consistently less playable than the DW cup mute is.

For Harmon mutes, with or without stem, their impedance peaks intonation never goes flat. Both stemmed versions of the mute are very similar in trends, being “perfectly” in-tune for almost all of the playable range, but the non-stemmed mutes are more out of tune. Yet still, the more expensive no-stem Jo-Ral is in general in tune more times throughout the playable spectrum than is the cheaper no-stem Vacchiano. In fact, it stays within the 20 cent range for the entire spectrum, meaning it still has good intonation properties. Both mutes with and without stems follow the same trends of playability, hitting low points at E5 and increasing in playability into the higher playable range, yet the Vacchiano mute is almost always at a lower playability than the more expensive Jo-Ral.

The Silent Mute is the last to be analyzed, and is only compared to the no-mute control data. It can be seen in the yellow comparison chart that throughout the entire harmonic spectrum of the trumpet, the peaks line up quite nicely in terms of frequency (meaning good intonation, especially within the playable range), yet once out of the playable range into the altissimo range, the no-mute peaks cease to exists, making it hard to slot notes up there, but with a Silent Mute, these peaks do not decrease very much at all! These huge peaks create a much more playable upper-register, most likely due to the strong reflections of pressure waves reinforcing the player’s lips. Looking at the intonation chart, intonation with the Silent Brass mute never goes flat, and even rarely goes sharp within the playing range. However, the playability chart suggests that with this mute in, notes are much more playable, or at least “slot” easy, especially in the upper-register.

IV. Conclusions

Harmonic Analysis

In general, the harmonicity of the individual mutes showed a great characterization of families of mutes. For straight mutes, this meant stronger higher harmonics, resulting in a brassier sound, while for cup mutes, the cone added a buffer for these higher harmonics and increased the lower ones, creating a mellower tone. Harmon mutes without a stem were very strong in low harmonics, especially the fundamental, but once the stem was added, the higher harmonics once again rose, making a more brassy sound. The practice mute showed a very strange harmonic structure and even had strong peaks at the 13^{th} harmonic, which proves that it is not a mute that is meant to be enjoyed for listening’s sake, but more so just for practicing with to reduce the volume emitted by the horn. As far as expensive versus cheap mutes, there were not too many noticeable differences in the harmonic structure of the mutes, and if any, it could be related to the consistency and decay of the harmonic range.

Intonation

By analyzing the intonation of mutes with the input impedance setup, the expensive straight mutes were in-tune more than a fair amount, and if not in-tune perfectly, then they were always sharp, similar to the original hypothesis that straight mutes play sharp. However, the cheaper H&B mute played in-tune much less than the more expensive straights, and was often flat!

The cup mutes always played flat if not in-tune (same as hypothesis), but the expensive one (DW) was almost perfectly in-tune the entire playable range. It maybe worth it to fork out the extra money for that one!

As for Harmon mutes, the stem greatly enhanced the intonation ability of the mutes, getting them to nearly perfect intonation relative to the control data without a mute. This may correlate to the fact that the stem also greatly increased the higher harmonics, possibly providing the higher energy partials for stability, but more tests would need to be run to prove this correlation. Even without the stems though, the more expensive Harmon mute (Jo-Ral) was very much in-tune, unlike the inexpensive counterpart, the Vacchiano. In general however, the Harmon mutes played sharp if not in tune.

The Silent Brass mute was very much in-tune throughout the playable range, except for the two lowest notes being somewhat sharp. This corresponds to Yamaha's claim of "very accurate tuning," even in the altissimo ranges above a Grand C, where the mute is still within the 20 cent region of being "in-tune."

For playability, basic trends were seen for each type of mute. In general, all the mutes increased in playability in the upper-registers of the playable range, but the "closed"/sealed mutes got to playabilities near 10, while the "open"/suspended mutes only got playabilities maxed at less than 6 (dimensionless values)! This shows that the closed-off nature of the sealed mutes reflects more pressure waves, and this causes increases in impedance that allow for better "information" being sent to the lips, for better pitch slotting. The cheaper mutes were *always* less playable than the expensive counterparts, and definitely less consistent in trends, which show financial need for better mutes for more professional players. The Silent Brass DID increase in playability significantly throughout the playable range, especially in the upper-register, which is not true to what Yamaha claimed as "low resistance" playing.

In general, the more expensive mutes may not have as many noticeable harmonic differences (or at least not many able to be concretely described by amplitudes and phases), but the more expensive mutes did definitely show better consistency in intonation and playability compared to the cheaper mutes.

V. Future Recommendations

More analysis can be done with the data provided, especially that concerning phase relations for the harmonic structures of the muted sounds. Investigations into physically why the mutes cause the harmonic, intonation and playability differences (based on geometric features, etc) would give a better understanding of these mutes as a whole as well.

Time was not warranted for doing deep analysis of the effects of a plunger on the trumpet's harmonics, tone and playability, but data was taken for a plunger mute being open, closed (for playing) and fully closed. This can be looked into in the future.

As far as input impedance testing, more resolute testing might create better (or more accurate) data on peaks involving intonation and playability. This can be seen in the final Figure of Appendix C, which shows the no-mute data of 4/15 compared to the no-mute data of 4/27, but with a small frequency span. The spectrum analyzer can only store up to 800 bins of data, so for a 2 kHz span, the resolution is only 2.5 Hz. With a span of 800 Hz (200-1000 Hz range), the resolution becomes 1 Hz, which is shown in the final Figure as having higher peaks that the original data does not show.

VI. Acknowledgments

I would like to thank Steve Errede for his continued help and use of resources towards me in completing this project. I would also like to thank the University of Illinois Department of Physics for the resources that they provide as a department.

VII. References

[1] J. Yasi, "An Algorithm for Extracting the Relative Phase of Harmonics from a Periodic Digital Signal" (unpublished) <http://online.physics.uiuc.edu/courses/phys199pom/NSF_REU_Reports/2004_reu/Joe_Yasi_Final_Paper.pdf>.

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