THE INFLUENCE OF MOUTHPIECE CUP SHAPE ON "BRASSINESS"

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ABSTRACT

The degree of spectral enrichment of brass-instrument tone due to non-linear propagation in the instrument depends not only on the amplitude of the sound, but also on the maximum rate of change of the sound pressure in the mouthpiece. A skilled player has some control over the latter, but the internal contour of the mouthpiece is also very important. Judging from the sounds produced, a deep funnel-shaped (horn-like) mouthpiece encourages a less steep waveform than does a shallow bowl-shaped (trumpet-like) mouthpiece. This paper opens with a review of the physics of finite-amplitude sound propagation in a flaring tube, and how this has led to the definition of a "brassiness potential" that predicts the relative degree of spectral enrichment for various brass instruments. The remainder focuses on the influence of the mouthpiece. Internal (within the mouthpiece) and external (beyond the bell) measurements of sound pressure and spectrum have been made for a trumpet played with both a conventional trumpet mouthpiece and a flugelhorn mouthpiece.

1. BRASSINESS POTENTIAL

1.1. Large-amplitude plane waves

Consider the propagation of a large-amplitude plane wave in a lossless cylindrical tube [1]. Suppose the initial wave shape is sinusoidal, as shown in Figure 1. The velocity imparted to the air by the sound wave carries the sound along with it. Thus, dx/dt, the propagation speed at x relative to a fixed observer, is the sum of c, the sound speed re the moving air, and u, the particle velocity:

$$\frac{dx}{dt} = c + u \tag{1}$$

Additionally, the sound pressure alters the local temperature, increasing c where the air is compressed and decreasing it where the air is rarefied. In air, this increases the effect of convection alone by about 20%:

$$\frac{dx}{dt} = c_0 + 1.2u \tag{2}$$

where c_0 is the small-signal value of the speed of sound, or about 345 m/sec under playing conditions.

The speed of the wave as a whole is c_0, but those parts where the particle velocity u is positive move faster

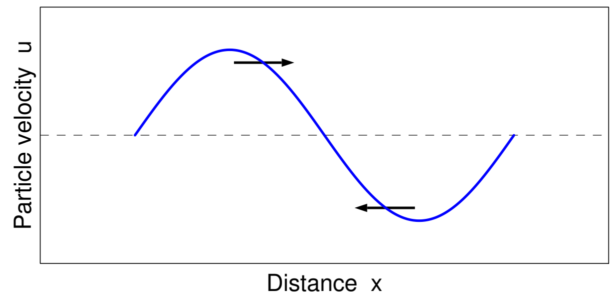

Figure 1: One cycle of the initial sine wave. The sound is propagating from left to right. The arrows indicate the direction of particle velocity.

than c_0 and those parts where u is negative move slower than c_0. This causes the waveform to steepen between a positive peak and the negative peak just ahead of it, as shown in Figure 2. Eventually, the rate of change of the waveform becomes infinite and a shock wave is formed. Figure 3 shows the distorted sine wave at that point.

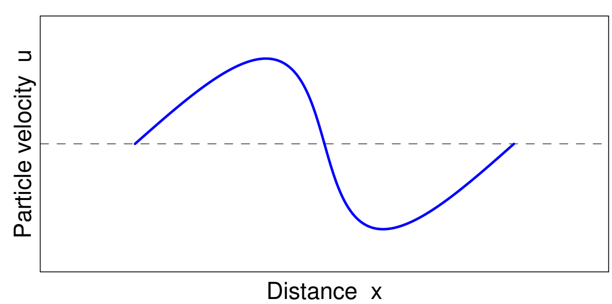

Figure 2: The wave shape at 0.6 times the shock-formation distance.

As the wave propagates beyond the shock formation distance, the shock grows and the waveform eventually assumes a sawtooth shape. Figure 4 shows the wave shape a little beyond the initial formation of the shock.

1.2. Large amplitude sound in a flaring horn

As the sound energy spreads across the increasing cross-section of an outwardly-flaring horn, the particle velocity decreases. If we neglect losses within the horn and assume that the sound energy is spread uniformly across

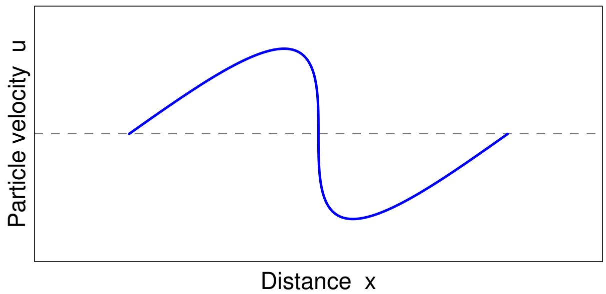

Figure 3: The wave shape exactly at the shock-formation distance.

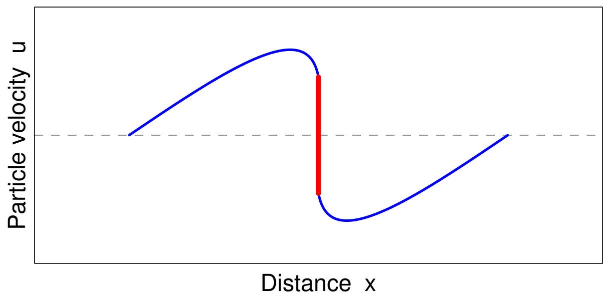

Figure 4: The wave shape at 1.1 times the shock-formation distance. The shock wave is shown with a heavier line (in red, if viewed in color).

the tube, conservation of energy leads to

$$\frac{u(x)}{u_0} = \frac{D_0}{D(x)} \tag{3}$$

where $D(x)$ and $u(x)$ are bore diameter and particle velocity at position x. D_0 and u_0 are $D(x)$ and $u(x)$ at a reference point, normally the input end.

The sound speed for the various parts of the waveform is changed accordingly. Equation 2 for a plane wave in a cylindrical tube now becomes

$$\frac{dx}{dt} = c_0 + 1.2\frac{D_0 u_0}{D(x)} \tag{4}$$

For the same amount of nonlinear distortion, the sound must travel farther in an outward-flaring horn than in a cylindrical tube, "stretching" the coordinate x.

Figure 5 compares an unstretched cylinder with the stretched x coordinates of a relatively narrow trumpet bell and a more rapidly-expanding flugelhorn bell. Given the same particle velocity injected at the small end, all three ducts have the same nonlinear distortion.

Equation 4 can be integrated over the whole length of an instrument to give the length of a cylindrical tube with the same nonlinear distortion as the instrument. Since all brass instruments flare outwards, it is clear that the length of the cylinder will be less than the length of the instrument.

The *brassiness potential* B is defined as the ratio of the length of the cylinder to the equivalent conical length

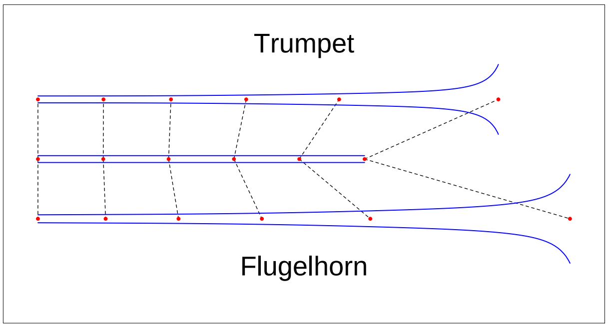

Figure 5: Three ducts with the same total distortion. At the top is a Vincent Bach model 37 B♭ trumpet bell, in the center a cylindrical tube, and at the bottom the final portion of a Salvation Army St. Albans flugelhorn bell. The dashed lines connect intermediate points at which the distortion is the same in all three ducts.

of the instrument[1].

The brassiness potential B is thus a dimensionless number lying between zero and unity. It is higher for "narrow" instruments like the trumpet and trombone, and lower for "wide" instruments like the flugelhorn and euphonium. Larger values of B mean greater nonlinear distortion and therefore a greater tendency for the timbre to acquire a brassy edge at louder dynamics.

The brassiness potential B has proven to be a useful parameter for establishing what might be termed an "acoustic kinship" among instruments, as shown in Figure 6.

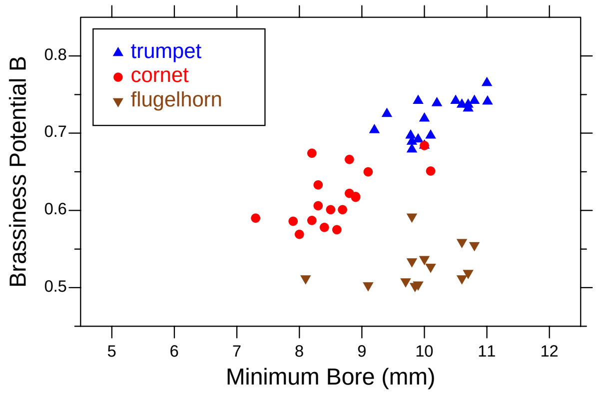

Figure 6: A scatter plot of brassiness potential B vs. minimum bore diameter for some trumpets, cornets, and flugelhorns. (Adapted from [2].)

[1] The *equivalent conical length* is the length of a cone, complete to the vertex, whose lowest resonance frequency matches the nominal fundamental frequency of the instrument. It is generally slightly longer than the physical length of the instrument.

2. THE EFFECT OF THE MOUTHPIECE

2.1. The experimental setup

An S. E. Shires $B\flat$ trumpet was played with both a normal trumpet mouthpiece and a flugelhorn mouthpiece (see Figure 7). Both mouthpieces were made by Denis Wick and had identical rims. Sound pressure in the mouthpiece was measured with an Endevco 8510-B2 piezoresistive pressure transducer mounted flush with the interior surface of the mouthpiece cup.

Figure 7: The two mouthpieces tested, together with wax castings of the cup shapes. The flugelhorn mouthpiece is on the left, the trumpet mouthpiece on the right.

Sound pressure external to the instrument was measured with an electret microphone positioned on the bell axis 60 cm from the plane of the bell rim. The external microphone was mounted on an aluminum rod attached to the lower valve caps on the trumpet, so that its position relative to the trumpet was fixed.

After passing through a preamplifier (built by the author), the two signals were digitized by a USB sound card (M-Audio Transit) whose output was recorded on a MacBook Pro computer at a 44.1 kHz sample rate and 16-bit resolution using the Amadeus Pro sound editing program.

The recordings were made in a moderately dead room (but by no means anechoic). However, the external microphone was close enough to the trumpet that the direct sound very strongly dominated the reverberant field. Moving the playing position within the room produced no discernible change in the recorded signal.

A skilled brass player can exercise a good deal of control over timbre [3]. In order to eliminate this as much as possible, during the tests the player listened to moderately loud pink noise through MP3 player ear buds worn beneath sound-isolating earmuffs. The masking noise level was high enough that vocal communication, even at shouting level, was not possible. Although the masking noise was quite disconcerting, the player was able to perform as requested.

2.2. Data analysis

Three pitches were recorded: $B\flat_3$, F_4, and $B\flat_4$ (the second, third, and fourth harmonics of the open $B\flat$ trumpet). Of these, only F_4 could be played comfortably over a wide dynamic range.

Although the player had stated in advance that he thought he would be quite comfortable playing on the two test mouthpieces, this proved not to be the case. Because the mouthpieces are somewhat narrower than his current favorites, he had difficulty producing a stable $B\flat_3$, particularly on the trumpet mouthpiece. For this reason, data taken for $B\flat_3$ will not be shown here.

Not surprisingly, the acoustic parameters of the flugelhorn mouthpiece did not match the trumpet very well. There was a pronounced tendency to play progressively flatter as the playing pitch rose. The interval between F_4 and $B\flat_4$ played on the flugelhorn mouthpiece was 12 cents smaller than on the trumpet mouthpiece. Even so, the $B\flat_4$ data were reasonably consistent with the F_4 data.

The analysis software was written in Python and was inspired by parts of Beauchamp's SNDAN package [4]. Every two periods of the fundamental frequency, the program analyzes a window four periods wide. Each data point was taken from a slow *diminuendo* and therefore is an essentially steady tone over the four-period duration of the analysis window.

The parameter used here to characterize the spectrum is the *average frequency* [5], defined as

$$f_{av} = \frac{\sum_{k=1}^{N} f_k |A_k|^2}{\sum_{k=1}^{N} |A_k|^2} \tag{5}$$

where f_k and A_k are the frequency and Fourier coefficient of the kth harmonic of the windowed signal, f_1 being the fundamental frequency[2]. This calculation included harmonics up to 90% of the Nyquist frequency; that is, $f_N = N f_1 \simeq 0.9 f_{Nyquist}$.

A higher value of f_{av} means stronger higher harmonics, and corresponds to a brighter or brassier timbre.

In the following figures, "internal" refers to the signal from the mouthpiece pressure transducer, "external" to the signal from the microphone on the bell axis.

Figure 9 shows how the average frequency f_{av} of the radiated sound varies with playing level. It should come as no surprise that f_{av} for the trumpet mouthpiece is consistently higher than for the flugelhorn mouthpiece.

Above approximately 45 dB, the rate at which f_{av} increases with playing level is substantially greater than at lower levels. It can be inferred from this that only above 45 dB is finite-amplitude distortion the dominant factor determining the timbre.

[2]The average frequency is the center of gravity of the *power spectrum*; it is a close cousin of spectral centroid as defined by Beauchamp, which is the center of gravity of the *amplitude* of the spectrum.

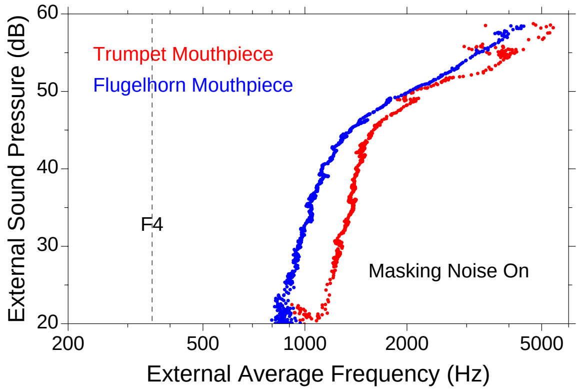

Figure 8: External sound pressure vs. external average frequency for F_4. The dB reference level is arbitrary.

At softer levels, it should be noted that the ratio of f_{av} for the two mouthpieces is very nearly constant. For these mouthpieces, this ratio is very close to the square root of the ratio of the mouthpiece cup volumes, as determined by weighing the wax castings shown in Figure 7. This suggests that at low playing levels, f_{av} is close to a resonance formed by the shunt compliance of the mouthpiece cup volume and a series mass "seen" by the mouthpiece cup looking into the instrument.

A shown in Section 1.1, a shock wave will form first at the point on the waveform where the initial slope is maximum. Hence, it has been found fruitful to use the maximum value of dp/dt, denoted by $\dot{p}_{max}$, as a measure of signal strength in the mouthpiece.

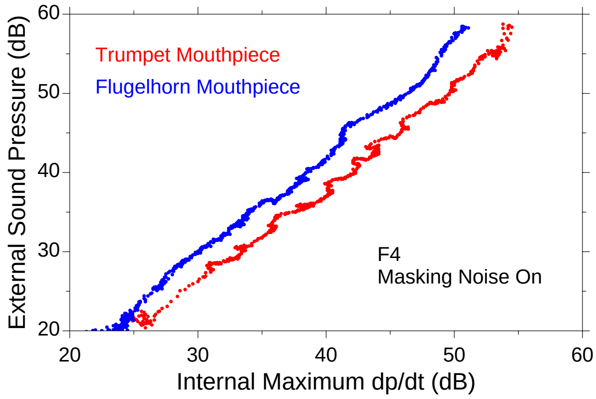

Figure 9: External sound pressure vs. maximum internal sound pressure derivative for F_4. The dB reference levels are arbitrary.

Figure 9 shows how $\dot{p}_{max}$ varies with the external sound pressure. It is interesting that (in dB), the relationship is nearly a straight line. The slope is not unity; a 1 dB change in $\dot{p}_{max}$ corresponds to a change of roughly 1.3 dB in the external sound pressure. For a given $\dot{p}_{max}$, more energy is stored in the compliance of the larger flugelhorn cup than in the smaller trumpet cup. Thus the flugelhorn mouthpiece produces the greater external sound pressure.

3. CONCLUSIONS

Analysis of a relatively simple model of large-amplitude sound propagation in a flaring horn has led to the definition of a brassiness potential B derived from the dimensions of a brass instrument. B quantifies the amount of spectral enrichment that will occur at loud playing levels due to finite-amplitude distortion. It has proven useful in providing an acoustic dimension along which to rank-order brass instruments.

The measurements under playing conditions using two radically different mouthpieces on the same trumpet suggest that, to first order, mouthpiece cup volume is a key parameter. The experiment was flawed in that the flugelhorn mouthpiece seriously perturbed the intonation of the trumpet. There are mouthpieces made for trumpet that are intended to imitate flugelhorn tone quality (and still play in tune!). It might be instructive to repeat the experiment using one of these, provided a satisfactory trumpet mouthpiece is available with an identical rim. In the absence of a pair of suitable commercially-made mouthpieces, it would be possible (given the proper resources) to fabricate special experimental mouthpieces.

4. ACKNOWLEDGEMENT

The author wishes to thank his son, Robinson Pyle, not only for playing the trumpet for the tests, but also for donating the two mouthpieces, and especially for suggesting that loud masking noise would inhibit his ability to modify the timbre so as to fit his preconceptions of what it "ought" to be.

5. REFERENCES

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