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The effect of hand and mute on the impedance spectra of the horn

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ABSTRACT

The effects of different horn players' hand shapes and positions, and the effects of different mutes were quantified by the input impedance spectrum *Z* and related to players' and listeners' perceptions. *Z* was measured using a three microphone, two calibration technique for combinations of a horn with three different hands, four different practice mutes and representative fingerings, complete for some sets. The hands were casts of real players' hands which could be reinserted with a typical reproducibility in the magnitude and frequency of peaks in *Z* of 0.1 dB and 0.4 Hz rms variation in independent measurements. Different hand configurations showed reproducible, measurable changes in *Z*, with an rms difference in the amplitude and frequency of the impedance peaks 1 to 20 of up to 0.8 dB and 0.6 Hz, respectively. The relative magnitudes and the harmonicity of the peaks were measurably different for practice mutes compared to that for an average hand. Frequency differences in the *Z* spectrum correlated well with player's perceptions of the intonation of the instrument.

INTRODUCTION

An important part of playing the horn is the placement of the player's right hand in the bell of the instrument. Players note that different hand positions and shapes affect the pitch, loudness and timbre of notes played – and use the effects musically. Hand positions and shapes are also expected to affect transfer functions, including the input impedance spectrum Z. Backus (1976), Benade (1976) and Widholm (1988) have shown that without the hand in the bell, impedance peaks above 450 Hz are greatly diminished in magnitude and disappear entirely above 750 Hz. The frequencies of peaks in Z strongly influence playing pitches (1), and the magnitudes of the peaks, as well as the harmonicity of sets of peaks, have some correlation with ease of playing particular notes. Although horn players do not generally play notes above 700 Hz (sounding F5), they are often asked to play notes between 450 and 550 Hz (A4 to D5). Further, impedance peaks falling near higher harmonics of the notes played are involved in the playing regime. These observations all suggest that the measured changes in *Z* due to hand shape and position could be related to players' assessments of playability and other properties of the instrument-hand combination.

An important accessory for a horn player is a practice mute: a mute designed not for performance, but to make practice less disturbing for neighbours and cohabitants. Practice mutes range from elaborate models incorporating a feedback system to the player via headphones, to improvised arrangements. As players often spend many hours with such mutes, ideally the performance of a horn with such a mute should approximate that of the horn played normally with a hand. Of course, an object whose purpose is to diminish radiation from the bell will usually affect reflection back into the bore, so effects on the impedance spectrum are expected.

The relation between impedance peaks and playing frequency for a lip-reed instrument has previously been investigated using simplified models (e.g. Fletcher, 1993). For acoustic loads having a sharp resonance with large acoustic impedance, the operating frequency is close to the impedance peak. But what is the acoustic load? Benade (1985) made a simple model of the load on an autonomous valve using continuity of volume flow and assuming that the acoustic pressures on the up- and down-stream sides of the valve acted on equal area. He showed that the impedance loading the reed (Z_{load}) is

$$Z_{load} = (Z_{tract} + Z_{bore}) \parallel Z_{reed}. \quad (1)$$

Further approximations are also commonly made: firstly, that the impedance of the reed (Z_{reed}) is very much larger than that of the vocal tract (Z_{tract}) and the bore (Z_{bore}), giving the effective load as approximately the series impedance $Z_{tract} + Z_{bore}$; secondly, that Z_{tract} is very much smaller than Z_{bore}, giving the simplest model, in which the effective load is simply Z_{bore}. The playing frequency, based on a simple model for autonomous oscillators (Fletcher, 1993), depends on the impedance of the acoustic load, the valve's geometry and natural frequency, and the applied pressure. Few experiments have investigated the acoustic load for lip reeds. Chen, Smith & Wolfe (2009) measured the three components independently and showed that clarinet-player-reed systems operate very close to the peak in (1) under some conditions. So far, published measurements of the impedance of players' vocal tracts for lip-reed instruments during performance appear to be confined to the didjeridu (Tarnopolsky et al., 2005, 2006).

However, model studies and some unpublished results using trombones show a small but musically important effect due to the impedance of the vocal tract (Wolfe et al., 2003).

In the present study, the impedances of the reed and vocal tract were not measured, but it is expected that they vary considerably over the range of the instrument. It is also quite likely that players adjust them, either consciously or subconsciously, to control tuning and perhaps timbre, although these were not investigated. For comparisons among hands and mutes however, we expect that neglecting such variations will, at worst, result in the differences measured being underestimates of the effects that might be measured in the absence of the auditory feedback which is inevitably used by musicians.

To date, in the literature, there are no studies investigating the impedance spectra of the horn with different hands or practice mutes in the bell (although Chick et al. (2004) measured the accuracy of replacing the same hand in the bell). This study aims to begin to address this gap and also correlate findings with players' subjective responses of playing with different hands and practice mutes.

MATERIALS AND METHODS

The horn used was a professional model Yamaha 668 double horn and the mouthpiece was a Marcinkiewicz Model No. 7. The practice mutes measured were Yamaha Silent Brass (practice mute 1), Denis Wick practice mute (practice mute 2), Humes & Berg Stonlined Sh! Sh! Practice mute (practice mute 3), and Trumcor Stealth #5 (practice mute 4).

Replica Hands

Replicas of the right hands of three horn players were cast in Perma-Gel, a commercially available synthetic ballistics gelatin. The replica hands were designed to imitate the exact shape and playing position of an individual player's hand (Figure 1) and to approximate the acoustic properties of a human hand. These were positioned in the bell using a system of stays mounted to the bell in marked positions (Figure 2). Replica hands were used, rather than actual players' hands, to control for shape and position, and to allow for many Z measurements to be made with no geometrical changes.

Figure 1. Replica of a horn player's right hand in playing position. It was made from synthetic ballistics gelatin.

Impedance Measurements

Acoustic impedance measurements were made using the three microphone, two calibration technique (Dickens, Smith & Wolfe, 2007). Measurements were made with representative fingerings (complete for some sets) on both sides of the horn (F and Bb) with various practice mutes or replica hands in the bell (Figure 2).

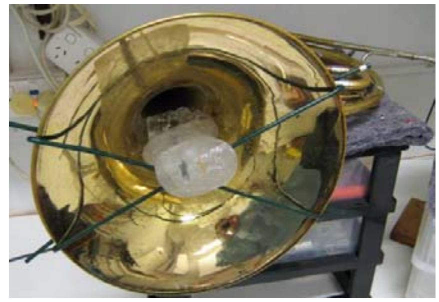

Figure 2. Replica hand in (rotated) playing position in the bell of the horn.

Recordings of Horn Players

Seven professional horn players were recorded playing the horn with each of the three replica hands and four practice mutes. All players had experience in national symphony or opera orchestras. The horn player was seated, with the edge of the bell resting on the palm of the right hand to support the horn. The sound was recorded using one Rhode NT3 microphone placed behind the player at a distance of approximately one radius from the bell of the horn and another placed close to and over the player's head.

Player Surveys

Each of the seven horn players also completed a player survey. In response to playing with each of the replica hands and practice mutes, they were asked to make judgements on the quality of sound, intonation, and ease of playing (Figure 3) compared to playing with their own mouthpiece and hand.

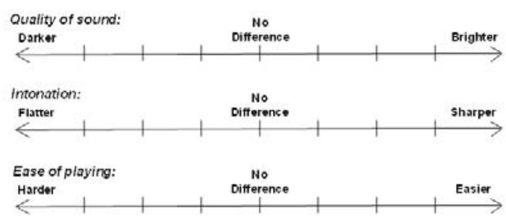

Figure 3. Example of scales used in player survey.

RESULTS AND DISCUSSION

Setups

Multiple acoustic impedance measurements made for each of the replica hands showed that they could be reinserted in the bell with a typical reproducibility in the peaks of 1.6% average error in magnitude and 0.2% average error in frequency. This level of reproducibility is important as the differences in the impedance spectra between different hands and different mutes are relatively small. The differences in both amplitudes and frequencies of the resonance peaks become greater near and above the cutoff frequency of the bell (around 500 Hz). The external radius of curvature of the flaring bore decreases rapidly near the bell so, for lower frequencies, reflection occurs in narrower parts of the bore, before reaching the hand. This is demonstrated by the difference in impedance spectra between a horn with a hand in the bell (normal playing position) and a horn with no hand in the bell (Figures 4 and 5).

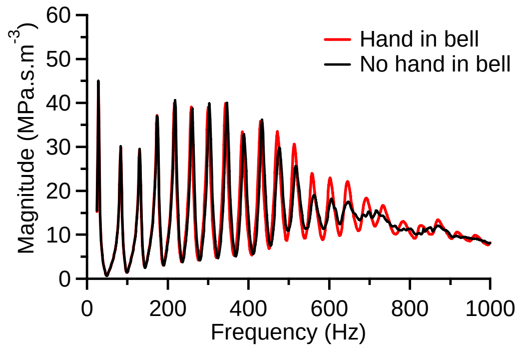

Figure 4. Impedance spectra for the open F horn with and without hand in bell, illustrating the effect of the hand on the cutoff frequency of the bell.

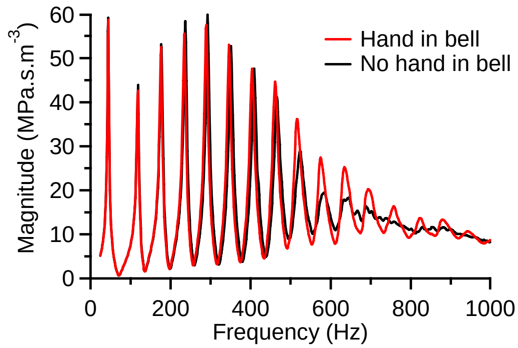

Figure 5. Impedance spectra for the open Bb horn with and without hand in bell.

When the same setup (horn, mouthpiece, and replica hand) was measured in independent trials, the rms difference in the amplitude and frequency of the impedance peaks 1 to 20 was 0.1 dB and 0.4 Hz, respectively. The different replica hands (with the same horn and mouthpiece) showed reproducible, measurable changes in *Z*, with an rms difference in the amplitude and frequency of the impedance peaks 1 to 20 of up to 0.6 dB and 1.3 Hz, respectively. Differences in amplitudes of resonance peaks for the open Bb horn and the three different hands (Figure 6) are apparent above the third resonance (175 Hz) and are greater above the eighth resonance (460 Hz).

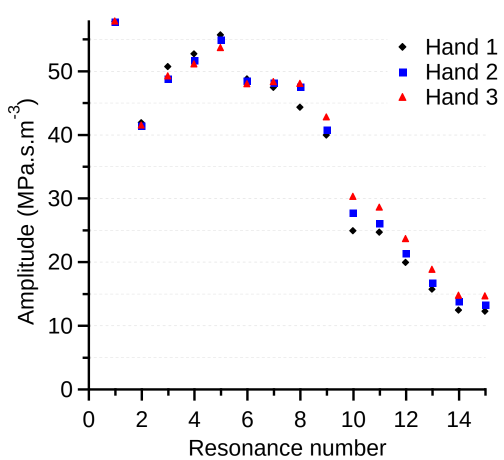

Figure 6. Amplitudes of resonance peaks for an open Bb horn with three different hands in the bell. (Error bars typically within size of symbol).

Although there was great variation among players' subjective responses to the intonation when playing with the three different hands (Figure 7), there is a general trend in the data. The intonation of the horn with hand 3 is considered by most players to be flatter than with hand 1 or hand 2.

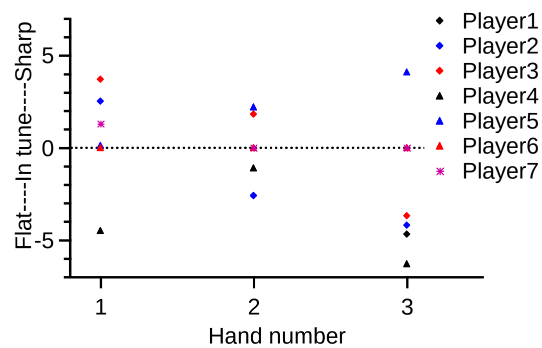

Figure 7. Players' responses to the intonation of playing the horn with three different hands in the bell.

The notes shown in Figure 8 (written C4, F4, C5, F5, G5, A5, and C6 which sound F3, Bb3, F4, Bb4, C5, D5, and F5 when played on the horn) are all generally played on the open Bb horn (no valves down) and figured prominently in the excerpt played by the horn players. Figure 8 shows that the frequency of the corresponding resonance peaks lie at frequencies below the nominal equal temperament frequencies for these notes. The data show that, for all the hands, the resonance peaks are flat relative to the equal temperament frequency for C5 and above. This is not surprising: firstly, the impedance curves were measured at room temperature in dry air while the players filled the bore with warm, humid air; secondly, the playing frequency does not coincide exactly with the impedance peak. We note that hand 3 shows peaks in *Z* that are flatter than those of either hand 1 or hand 2. This correlates well with players' judgements that when playing with hand 3, the intonation was flatter than with the other two hands. Player 2 confirms the results of the data with the comment, "[hand 3 is] lower in pitch, especially on open high notes e.g. 'G' and 'A'" (written G5 and A5).

Thus the effects of different hand shapes and playing position on the amplitudes and frequencies of the impedance spectra of the horn correlate well with intonation.

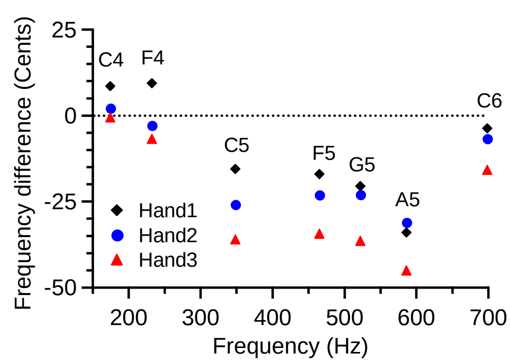

Figure 8. Variation in frequency of resonance peaks from nominal equal temperament frequencies for written C4, F4, C5, F5, G5, A5 and C6 (sounding F3, Bb3, F4, Bb4, C5, D5 and F5) for three different hands in open Bb horn.

Practice Mutes

As mentioned above, an ideal practice mute would simply reduce radiation from the bell of the horn without changing playing properties. This would require a low transmission coefficient with a reflection coefficient that was unchanged across all frequencies. As Figure 9 shows, the shape of the impedance spectrum changes when the hand is replaced with a practice mute. The amplitudes of low frequency resonances are lowered and the amplitudes of high frequency resonances are raised. There is also a measurable frequency shift which decreases the harmonicity of the resonance peaks.

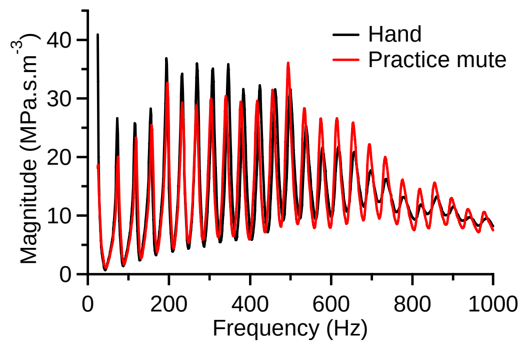

Figure 9. Impedance spectra for valve 1, F horn with hand in bell and practice mute in bell.

The relative amplitudes of the resonance peaks for the practice mutes were measurably different to those for a hand (Figure 10) and also differed markedly among practice mutes.

The frequencies of resonance peaks also differed between the hand and practice mutes (Figure 11). Although the first resonance has a very large variation, this is of little musical significance as it is not used, except for exotic effects. Figure 11 shows that practice mute 1 is closest to the hand in its harmonicity and practice mute 2 is the least harmonic, with resonances 2 and 3 sharper than for the other mutes and resonances 6 to 17 flatter than for the other mutes. This correlates well with players' judgements of intonation for each of the mutes, as four out of the five players (who answered this question) rated practice mute 1 as 'in tune' whilst practice mute 2 was considered flat by three players and sharp by the other two players.

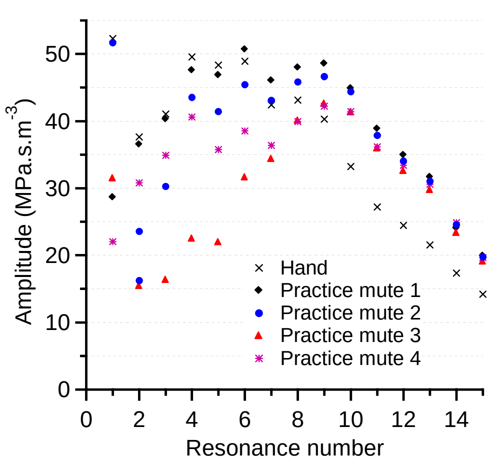

Figure 10. Amplitude of resonance peaks for valve 1, Bb horn with hand in bell and four different practice mutes in bell. (Error bars typically within size of symbol).

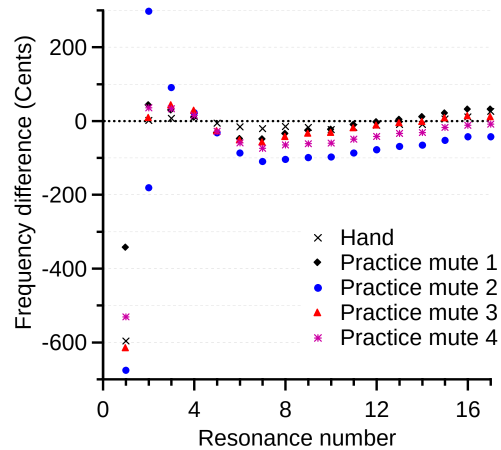

Figure 11. Variation in frequency of resonance peaks from harmonicity for valve 1, Bb horn with hand in bell and four different practice mutes in bell. (Error bars within size of symbol).

Results from *Z* measurements quantify the change in response of the horn when a practice mute is substituted for a hand. Further, each different practice mute measured affected the amplitudes and frequencies of the resonance peaks to a greater or lesser extent. For horn players who use practice mutes often, this could potentially impact the way they play because of the intonation changes, and because of the way they change the response in the high range.

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