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Characterisation of brass instruments with mutes through experimental means and finite-element simulations

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Abstract

A number of mutes have traditionally been used to modify the timbre and volume of the sound of brass instruments. In the present work, the effects of adding straight, cup, and Harmon mutes to trumpets and trombones are analysed and discussed initially through the measurement of input acoustic impedance and frequency response. The input impedance was obtained in a frequency range between 50 and 3000 Hz, and the frequency response was measured between 50 and 6400 Hz. These results were then compared with finite-element simulations of acoustic propagation in the complete instrument with and without mutes. These comparisons allow for validation of the numerical method, and make numerical experimentation possible with mutes with a wide variety of geometries, potentially helping to save time and reduce costs during the design process. X-ray images of the mutes and instruments were used to define their contour by means of a CT Nikon Metrology XT H225ST system.

Keywords: Input acoustic impedance, finite-element simulations, brass instruments, mutes.

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1 Introduction

The input acoustic impedance has long provided the standard means for the characterisation of brass instruments. Once obtained, the input impedance spectrum is typically used to determine the intonation and response of the instruments [6]. It may also be used to provide a primary diagnostic for ill-behaved instruments, and to establish how modifications to instruments affect their performance [3]. The most common way to alter the response of trumpets and trombones without modifying their geometry has been through the use of mutes, some of which reduce the sound output and change the quality of sound increasing the brightness of the instrument [2, 4]. Ancell [1] proposed a model where trumpet mutes acted simply as Helmholtz resonators, while Backus [2] described their effect in terms of an equivalent circuit, obtaining their resonance frequencies, and comparing with measurements in the case of trumpet mutes.

Sound propagation in both the trombone and the trumpet, with and without mutes, can be modelled in the linear regime though the use of finite-element methods. The numerical results obtained in this manner may be validated by comparison with measurements of the input acoustic impedance of both instruments. Once this is achieved, is would be possible in principle both to study the changes in radiated sound due to the use of all kinds of existing mutes, including mutes for which we did not measure the input impedance, and to observe the effects of mutes with arbitrary geometries, saving time and reducing costs during the design process.

2 Methods

2.1 Measurement of input acoustic impedance

A brass impedance head was built, based on the two-cavity model proposed by LeRoux and Dalmont [5]. A variety of custom-made adapters allow us to measure the input acoustic impedance of both a trombone and a trumpet. To test the effects of introducing different mutes, we have selected the straight, cup and Harmon mutes, which are all available for both instruments.

The input impedance was calculated in a frequency range between 50 and 3000 Hz, measured in three separate intervals, from 50 to 500 Hz, from 500 to 1500 Hz, and from 1500 to 3000 Hz. The system has a reliable response up to 5 kHz. The impedance head has been calibrated using an infinite impedance termination, a short closed pipe, and a radiation impedance, by means of an open cavity[8]. The excitation signal used was a chirp of 2-second duration which exhibited a flat frequency spectrum with a resolution of 0.5 Hz. For each combination of instrument and mute, five measurements were obtained, dismounting and mounting the system before each measurement, and in the end all five measurement were averaged. The temperature was constant for all measurements (19^oC), which were held in the anechoic chamber at the acoustics laboratory at CCADET, UNAM.

2.2 Finite-element simulations

COMSOL Multiphysics was used for all finite-element simulations. In order to make the simulations more manageable, both the trumpet and the trombone are modelled as straight pipes with circular cross-sections of varying surface. We further assume that all instruments and mutes can be obtained from a two-dimensional profile by rotating this curve around the central axis of the instrument or object. The profiles of all instruments and mutes were obtained by X-Ray imaging, using a Nikon Metrology CT XTH225ST system. This system was used to project the contours of instruments and mutes onto a plane image, which was then used to correlate the pixel size with real dimensions. The parameters used to find contrasted images were 200 KV and 100 μA. The resolution of the panel used was 2000$\times$2000 pixels.

In all cases the sound pressure field inside the instruments was modelled using the same frequency range and spatial resolution. We have used a linear elastic model with attenuation, as included in the COMSOL "Pressure Acoustics" module, where we use a standard form of the attenuation coefficient in this context, given by $\alpha = 3.378e^{-5}\sqrt{f}/a$, where f is frequency and a is the radius of the instrument [7]. For both brass instruments, the input boundary condition was given in the form of plane wave radiation with amplitude 1.1 Pa (94.8 dB), which is to say firmly in the linear regime. In order to obtain the input acoustic impedance, the pressure and the velocity are integrated in the input mouthpiece boundary. At the other end, a "Perfectly Matched Layer" (PML) simulates an anechoic termination that prevents the formation of reflected waves. During simulations, the trombone is placed in the middle of a sphere with radius 1.33 m, with 34 cm of PML spherical domain; the trumpet is surrounded by a sphere with a radius of 1.13 m, with 28 cm of PML spherical domain. The mesh size is variable, with a finer mesh employed near the bell boundaries as well as for the mutes, as more spatial detail is needed to discretise these geometries properly. The sound pressure field simulated in this manner for a trumpet both with and without a mute is portrayed in Figure 1. In this figure a general attenuation due to the presence of the mute is clearly observed, as are minor differences in the directivity pattern between the two cases, as expected.

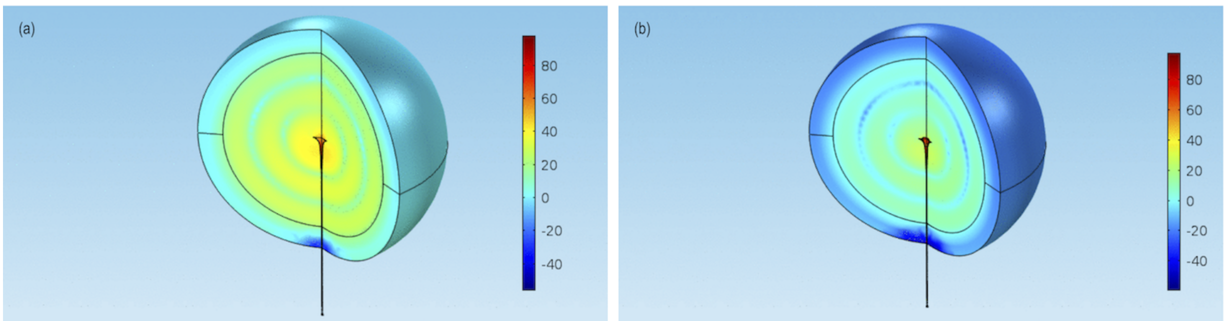

Figure 1: **Sound pressure field associated with a trombone (a) without a mute, and (b) with a straight mute inserted, both at 402.5 Hz.**

3 Results

The input impedance as a function of frequency was calculated from measurements and from finite-element simulations for both the trombone and the trumpet, without mutes and with each of the available mutes. Both measurements and simulations are of trombones and trumpets with their respective mouthpieces. Agreement between measurements and simulations was generally very good, with differences between measured and simulated impedance peaks of at most 10 Hz. It was also observed in all cases that the effects of attenuation are more marked in the high-frequency range for simulations than they are for measurements. Below, we plot the measured impedance of the trombone with and without mutes in order to illustrate the effect of each of the available mutes. We also use the trumpet and a cup mute to both show how closely the finite-element simulation agrees with measurements, and to discuss the general effect of inserting a mute.

3.1 Trombone

As Backus [2] reports, all mutes introduce a pronounced formant into the acoustic impedance of the trombone, as we see in Figure 2. As expected, the insertion of mutes results in a slight upward shift in frequency of the impedance peaks, due to the shortening of the instrument resonator. This effect is more pronounced, however, for the straight mute. Apart from this, the straight mute does not seem to induce formants as pronounced as the other two types of mutes, except for the appearance of a small impedance peak at around 140 Hz. The cup mute preserves the tuning of the instrument much better than either the straight or Harmon mutes, and the amplitude of any impedance peaks above a frequency of 800 Hz is greatly diminished. Perhaps the most radical effect on the general shape of the impedance curve is produced, not surprisingly, by the Harmon mute, which produces a very noticeable increase in the amplitude of the impedance peaks between 600 and 1000 Hz.

3.2 Trumpet

We may consider the trumpet and any mute to be elements of a system to be connected in series so that the impedance of the complete system is simply the sum of the individual impedances. In Figure 3 we see that the effect of the cup mute is barely noticeable, as the impedance peaks of the cup mute lie at frequencies greater than the trumpet's cutoff frequency, although there is a distinct rise in the impedance curve of the trumpet with a cup mute inserted at around 1200 Hz, which is the location of the first impedance peak of the cup mute. We also confirm that the fit between measured and simulated impedance curves is quite good, even if, as we have mentioned before, the effect of attenuation is exaggerated by the simulation for frequencies above 600 Hz. Further, this result is very much in line with that obtained by Backus [2], for the same type of mute.

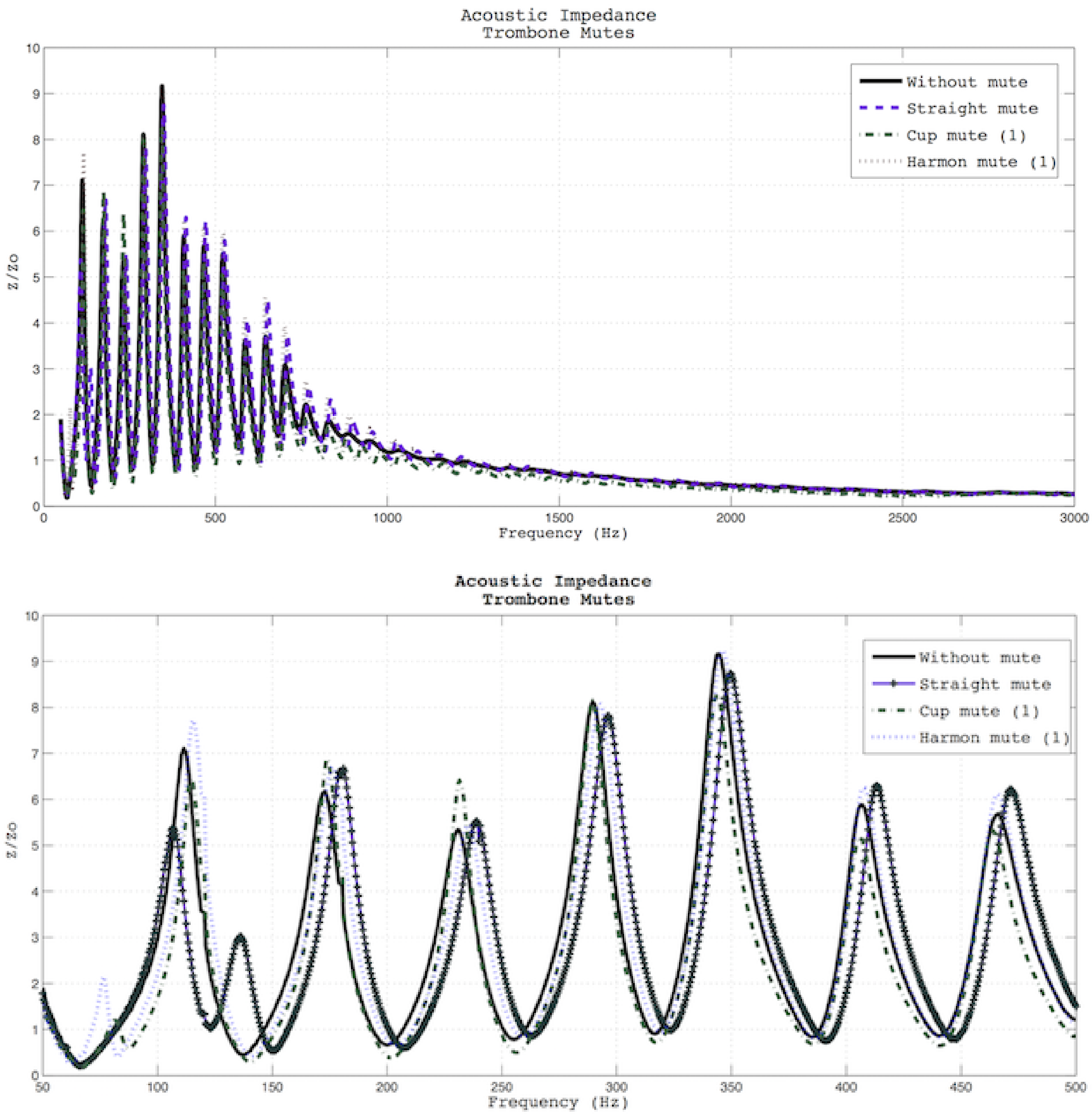

Figure 2: **Measured input acoustic impedance of a trombone with and without mutes. A zoomed image focusing on the frequencies between 50 and 500 Hz is shown below the plot of the complete frequency domain.**

4 Conclusions

Inserting a mute in trombones and trumpets reduces the radiation from the bell, and thus typically enhances the high resonance peaks. However, one of the main effects of a mute is to change the quality of the sound by increasing the radiation of high frequencies relative to that of low frequencies. The manner in which the introduction of a mute affects the shape of the input impedance curve depends very subtly on the geometrical features of the mute. It is also expected that the pitch of the instrument will suffer a slight shift upwards with the introduction of a mute, as, in general, the length of the resonator is shortened. We have observed that for both the trumpet and trombone, the Harmon mute has the greatest effect on the sound, and the cup mute the least. The results obtained through finite-element simulations in COMSOL are very similar to those obtained through direct measurements, and the fit can very probably be improved by using a more appropriate model for attenuation at high-frequencies. This will be the subject of future work. With the simulation validated, it will, in principle, be possible to realise numerical experiments involving mutes with a very wide variety of geometries, possibly providing a useful aid for their design.

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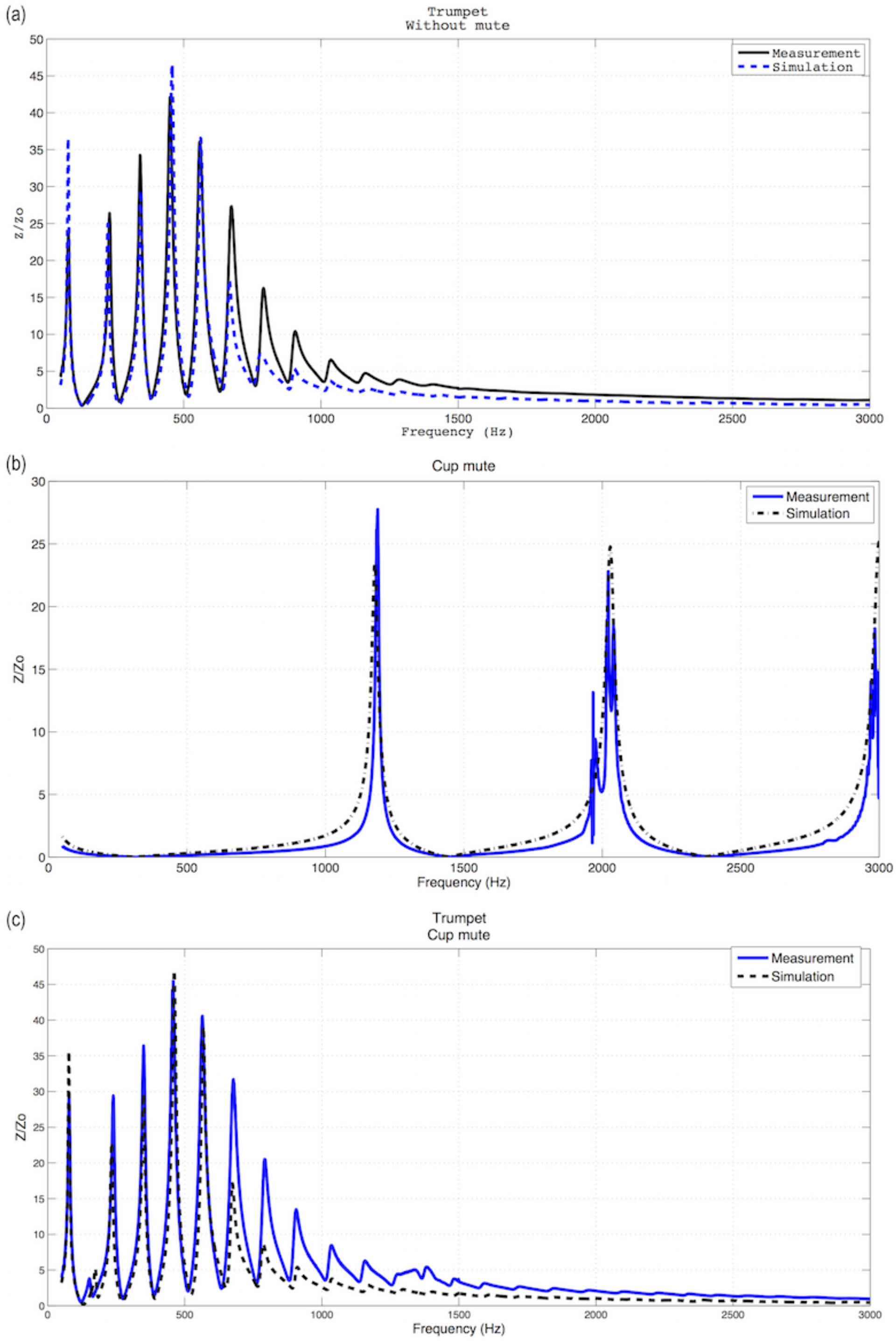

Figure 3: **Measured and simulated input acoustic impedance for (a) a trumpet, (b) a trumpet cup mute, and (c) a trumpet with a cup mute inserted.**