Bell Vibrations and How They Affect the Sound of the Modern Trumpet

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Within the last decade several experiments have verified that bell vibrations can affect the sound produced by brass wind instruments. Measurements on trumpets have indicated that the bell vibrations can either increase or decrease the acoustic transfer function, that the sign of the change is frequency dependent, and that these observed effects cannot be attributed to direct radiation from the vibrating bell. Kausel, et al. have proposed that these effects can be explained by an expansion and contraction of the walls enclosing the air column that is induced by the internal standing wave. Since the sign of the effect changes at specific frequencies, if the coupling between the internal air pressure and the vibrating wall is indeed responsible for the effects there must be structural resonances that occur at these frequencies that results in a change in the phase relationship between the air column and the wall vibrations. Furthermore, the mode shapes at these resonances must have no nodal diameters or the mean volume change will be close to zero. The work reported here demonstrates the presence of these structural resonances. The mechanical and acoustic transfer functions between the mouthpiece and the bell of a trumpet were measured and it was found that there are indeed body resonances with frequencies that match the frequencies at which the bell vibrations change from reducing the acoustic transfer function to enhancing it. However, computer modeling indicates this coupling may not explain all of the experimental observations.

1 Introduction

There has been an ongoing debate for years concerning the effects that bell vibrations may or may not have on the sound of brass wind instruments. Lawson reported that the material used to make a French horn bell affects the sound produced.[1] While Smith stated that the material of a trombone bell does not affect the sound perceived by the audience.[2] Pyle supported the hypothesis that bell vibrations do affect the sound of brass instruments by showing that lacquering the bell of a French horn affects the sound.[3] However, in all of these experiments a human played the instrument, resulting in some uncertainty in the results.

In 2005 Moore, et al. demonstrated conclusively that the vibrations of a trumpet bell have an audible and measurable effect on the sound.[4] To demonstrate this, the acoustic power spectrum was measured both when the bell was free to vibrate and when the bell vibrations were heavily damped with sandbags; artificial lips were used to eliminate any uncertainty related to the use of humans. Kausel, et al. performed a similar experiment using a French horn, which yielded similar results.[5]

With these experimental results clearly showing that wall vibrations have an effect on the sound of brass wind instruments, we are now interested in the cause of this effect. In 2010 Kausel, et al. compared the acoustic transfer function of a trumpet when the bell was damped to one measured with the bell left free to vibrate.[6] Instead of using artificial lips, a speaker driver was used to excite the air column of the trumpet over a range of frequencies.

It was found that at low frequencies, the acoustic transfer function measured when the vibrations were damped was greater than that of the undamped bell. As the frequency increases, the acoustic transfer function measured when the vibrations were damped becomes less than that of the undamped bell. Here we refer to the frequency at which the effects of the bell vibrations on the radiated sound change as the crossover frequency. This frequency dependence provides some insight into the process by which bell vibrations can affect the sound of brass wind instruments.

2 Theory

The presence of a crossover frequency may be indicative of a coupling of a mechanical resonance to the air column.

We posit that these effects occur because the internal air pressure at the antinodes increases the volume enclosed by the walls. Assuming adiabatic and isothermal conditions, this increase in volume reduces the internal air pressure. Because the internal pressure of the air column is always normal to the wall, and it is much easier for the metal of the bell to bend than for the radius of the metal tubing to increase, the expansion of the tubing is minimal and insignificant. The bending of the bell, however, causes a significant change in the air column. This explains the observation that damping vibrations anywhere on the instrument except the bell results in no measurable effect. Because the bell vibrations affect the internal air column, it is possible that the crossover frequency is attributable to a mechanical resonance of the bell.

There are two types of structural resonances in the trumpet bell. The first type of resonance results in a modal shape with radial nodes, an example of which is shown in the electronic speckle pattern interferogram shown in Fig. 1(a). These mode shapes are radially symmetric and have narrow band-widths. The sequential antinodes of this type of mode shape are out of phase with one another, therefore, they do not significantly affect the air column because the average change in volume around the bell is approximately zero.[6] Here we refer to these as elliptical modes.

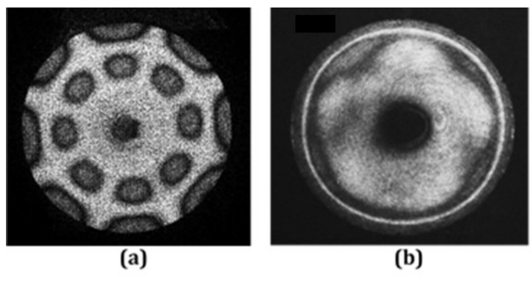

Figure 1: Interferograms of the two types of mechanical modes in the trumpet bell. (a) The trumpet bell vibrating at an elliptical mode. (b) The trumpet bell vibrating at an axial mode.

The second type of resonance results in a modal shape that is axially symmetric but contains no radial nodes. An electronic speckle pattern interferogram of this type of mode shape is shown in Fig. 1(b).[6] We refer to these as axial modes. In this type of resonance, the wall displacement is always in the same direction because there are no radial nodes. We posit that these axial resonances are broad-band and are responsible for the audible effects of bell vibrations on the trumpet sound. Because there are no radial nodes, at any axial point the motion of the bell wall is entirely in phase or out of phase with the air column. As frequency changes from below resonance to above an axial resonance, the phase relationship between the bell and the air column changes by π. This explanation implies that there is an axial mechanical resonance at the same frequencies as the crossover frequencies seen in the acoustic transfer function.

The change in the phase relationship between the bell and the internal air column is consistent with that reported in ref. 6. Damping the bell increased the sound power radiated at low frequencies, but at frequencies above resonance damping decreases the radiated sound because the motion of the bell and air column are out of phase. This is only true provided a mechanical resonance occurs at the crossover frequencies. To demonstrate this, we measured the frequencies of axial mechanical resonances and compared them to the crossover frequencies.

3 Experiment

To determine if the axial resonant frequency and the crossover frequency of the acoustic transfer function coincide, we measured both the acoustic and mechanical transfer functions of a trumpet bell. Rather than using a fully assembled trumpet, a simplified straight bell was manufactured by Spiri Corporation to facilitate the modeling effort of the system. This straight bell consists of straight tubing with one end flaring into the shape of a trumpet bell. For this experiment, we attached a speaker driver to the mouthpiece end of the straight bell and the bell was inserted into a baffle. The baffle was sealed using silicon sealant to fill the gap between the rim of the bell and the baffle. The presence of the silicone reduced the possibility of acoustic short circuiting around the bell. Measurements of the acoustic transfer function of this bell with the vibrations damped and with the bell free to vibrate were then made. The difference between the two acoustic transfer functions is shown in Fig
2.

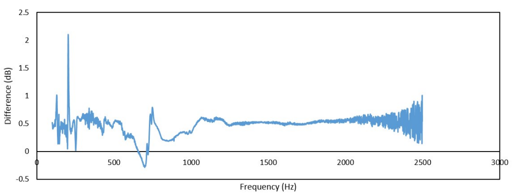

Figure 2: Difference between the acoustic transfer function of the damped bell and the undamped bell versus driving frequency.

As is evident in Fig. 2, the crossover frequencies occur mainly between 500 and 800 Hz. If axial vibrations are responsible for the effects on the sound of the trumpet, the crossover frequency must coincide with an axial resonance. To determine if this is correct, we measured the mechanical transfer function of the straight bell and compared it to the acoustic transfer function.

To measure the mechanical transfer function, the same experimental arrangement was used to measure the mechanical transfer function as was used to measure the acoustical transfer function. However, instead of recording the acoustic signal, the amplitude of the motion of the bell and the mouthpiece was measured using a laser Doppler vibrometer, and the mechanical transfer function was calculated from the quotient of the two measurements. To differentiate between axial and elliptical modes, the motion of bell was recorded at twelve symmetric points around the edge of the bell and the measurements were averaged in the complex plane. In so doing, the motion of the radially symmetric antinodes of the elliptical modes averaged to zero, while that of the axial modes did not. The magnitude of the mechanical transfer function for the straight bell is shown in Fig. 3. There are two broad-banded mechanical resonances between 500 and 800 Hz that coincide with the crossover frequencies of the acoustic transfer function.

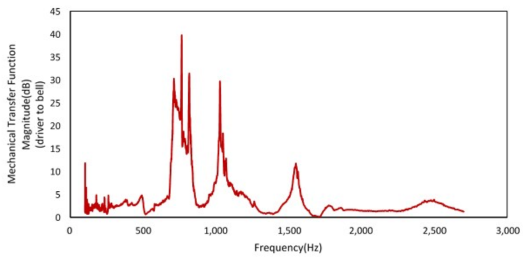

Figure 3: The magnitude of the mechanical transfer function versus driving frequency of the straight bell.

4 Conclusion

The work reported here suggests that the air column of a trumpet is affected by broad-band mechanical resonances that occur naturally. Both the acoustic and mechanical transfer functions of a straight bell were measured and compared. Resonance frequencies of the mechanical transfer function occur at approximately the same frequencies as the crossover frequencies of the acoustic transfer function. This supports the theory that the vibrations associated with an axial resonance couple with the internal air column. The effects of this coupling are such that they change at the resonance frequency, due to the phase shift between the wall vibration and the air column that occurs at the mechanical resonance frequency. It is likely that this phenomenon occurs in all brass wind instruments. It is also likely that such coupling is just one of several effects that affect the sound of such instruments. Future work will concentrate on quantifying the magnitude of this effect and determining its importance in relation to other interactions.

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