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4pMU9. Axial vibrations of brass wind instruments

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It has been proposed that axial vibrations of the bells of brass wind instruments can lead to audible effects in the sound. (Kausel, et al., 2010) Using both laser Doppler vibrometry and a novel implementation of electronic speckle pattern interferometry we have demonstrated that these vibrations exist, and that the magnitude is of the order predicted. (Work supported in part by a grant from the National Science Foundation)

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INTRODUCTION

The effect that the vibrations of the walls of the air column may or may not have on the sound produced by wind instruments has been under discussion for many years. Reports of experiments within the context of organ pipes date back over a century and reports of experiments on lip reed instruments date back over 40 years. The arguments for or against the presence of these effects have been both prolific and at times confusing. An extensive review of the history of the subject can be found in ref. [1] and will not be repeated here. However, it is important to note that in 2005 an unambiguous demonstration that wall vibrations affect the sound of a trumpet was reported.[2] Since that time the emphasis has turned to explaining the origin of the effect rather than verifying that there is one.

In ref. [2] it was shown that damping the vibrations of the bell of a trumpet changes the distribution of sound power in a significant way. In general it can be stated that the presence of wall vibrations decreases the power in the fundamental and first overtone, while increasing the power in the higher harmonics. The result is that vibrations of the bell produce what is normally characterized as a brighter timbre, and the authors posited two possible mechanisms by which this may occur: a change in the thickness of the viscous boundary layer due to wall vibrations, and mechanical feedback to the lips through the metal structure. The authors opined that the most likely cause was the latter. Similar results were reported by Kausel, et al. a few years later using a French horn.[3, 4]

In 2010, Kausel et al. demonstrated that damping the vibrations of the bell of a trumpet resulted in a measurable change in the input impedance even with low levels of acoustic excitation.[1] This unambiguously showed that mechanical feedback to the lips was not the primary cause of any effect since the reported experiments were completely passive and involved no lip excitation, either artificial or human. This does not completely rule out an effect attributable to mechanical feedback to the lips, but the results reported in ref. [1] show that this type of feedback is not necessary for the effects of wall vibrations to impact the sound produced by a brass wind instrument.

In addition to experiments demonstrating that wall vibrations can affect the input impedance of a brass wind instrument, it was posited in ref. [1] that these effects can be attributed to coupling between the wall vibrations driven by the internal pressure and the air column producing that pressure. However, simulations indicate that the wall vibrations causing the effect are not the elliptical normal modes of a column or bell structure such as those shown in ref. [2]. Indeed, experiments have shown that these vibrations do not appear to have a significant affect on the sound of most musical instruments.[5] Rather, it appears that circular expansion and contraction of the walls resulting in a change in radius (not shape) are necessary. These changes in radius are due to the circularly symmetric pressure of the standing wave in the air column. The effect is most noticeable due to vibrations of the bell rather than the internal tubing because the internal pressure wave is always orthogonal to the wall structure. Therefore, the pressure causes expansion and contraction of the walls in the cylindrical tubing but in the bell region such pressure variations lead to bending of the metal rather than expansion. It requires much less force to bend the metal near the bell rim than it does to expand the radius of a metal tube and therefore the effect is more pronounced.

In both refs. [1] and [2] it was shown that the effects of the bell vibrations are frequency-dependent. That is, below a certain frequency the effects of the vibrations are to diminish the sound power, while above this frequency the sound power is increased by the presence of wall vibrations. The most likely explanation for this is that there is a structural resonance that occurs between the frequencies where the power is enhanced and those where the power is diminished. These structural resonances cannot be due to modes having a sinusoidal angular dependence that have been noted elsewhere and result in interesting modal patterns.[6, 7] Instead, the vibrational patterns of these resonances must be circular, with no nodes that bisect the axis of the bell.

Here we present new data that indicates the presence of these modes of vibration in the bell of a brass wind instrument. The deflection patterns of these modes are circular, not elliptical or having some other complex symmetric shape, as is required if the theory posited in ref. [1] is valid. Furthermore, they are induced solely by axial stimulation of the bell. In what follows we demonstrate the presence of these vibrational mode structures using two techniques: laser Doppler vibrometry (LDV) and a new method of electronic speckle pattern interferometry (ESPI) that is not sensitive to overall motion of the body caused by the driving mechanism, termed common-mode rejection ESPI (CRESPI).

EXPERIMENTS

The experiments reported here were performed on a trumpet bell section that contained no bends and was not mounted onto an instrument. The wall thickness of the brass tubing used to create the bell section was 0.50 mm. The bell section was approximately 64.5 cm long with an approximately 12.0 cm diameter bell. The end opposite the bell (i.e., the end normally attached to the valve section of a trumpet) had a diameter of approximately 1.1 cm and was cemented to
FIGURE 1. Relative displacement of the rim of the bell with respect to the displacement of the driver.

a 1.9 cm wide piece of aluminum that was securely mounted to a 7.6 x 10.2 cm translation stage. The motion of the translation stage was driven by a piezoelectric stack that was controlled by either a computer or manually using a function generator producing a sinusoidal waveform. The translation stage was secured directly to a 1.2 x 1.8 m optical table that was actively isolated from ambient vibrations by a pneumatic system.

Measurements of bell motion by laser Doppler vibrometry

Detection of the presence of circular deflection shapes during vibration of the bell section was accomplished using a single-point laser Doppler vibrometer. The vibrometer was oriented such that only motion of the bell parallel to the central axis was detected. The piezoelectric stack was driven by a sinusoidal signal generated by a computer using the Brass Instrument Analysis System. This program was used for both generation of the driving signal and for procuring and analyzing the resulting signal from the LDV. The input signal was swept from 50 Hz to 5 kHz over a period of 180 sec and the resulting signal was then integrated to determine the displacement as a function of frequency. The displacement of the driver was then subtracted from the displacement of the bell rim, yielding a measurement of the displacement without whole-body motion induced by the driver.

The modal patterns of interest are circular and are superimposed on the non-circular, but circularly symmetric, modes showing a sinusoidal angular dependence. Therefore, to detect the circular modes unambiguously the displacement of the bell rim was measured at 12 points around the rim of the bell, with each measurement representing an angular change of 30°. By averaging all 12 of the measurements in the complex domain and subtracting the displacement of the driver, the effects of the modes with a sinusoidal angular dependence were reduced significantly and the motion attributable to the circular modes was enhanced. (Note that had the measurements been exactly spaced by 30° the effects of modes with a sinusoidal dependence would have been completely eliminated; however, a small uncer-
The results of these measurements are shown in Fig 1, where it is clear that there are at least two broad resonances in the frequency range where one would expect them to occur given the results of impedance measurements performed on the same bell section and reported elsewhere.[9] At this time it is unclear whether the narrow-band resonances are artifacts of elliptical modes or are actually the signature of circular modal structures.

Measurements of deflection shapes by electronic speckle pattern interferometry

Electronic Speckle Pattern Interferometry (ESPI) was also used to demonstrate the existence of circular deflection shapes. ESPI is an optical process that produces contours of equal displacement superimposed on the image of the object under investigation. It has been used successfully in the past to investigate the motion of trumpet bells.[7] An explanation of the process of ESPI is beyond the scope of this work, but the details can be found elsewhere in the literature.[10, 11, 12] The most important aspect of ESPI for this investigation is the ability of the process to detect out of plane motion. This is accomplished by interfering light reflected from the vibrating bell with a reference beam having a phase that is uncorrelated with the motion of the object.

While ESPI provides valuable information about the relative motion of parts of the object under investigation, whole body motion of the object results in a uniform background intensity that is difficult to distinguish from the contours. To study the motion of the bell described above, the interferometer was changed in such a way as to make the phase of the reference beam correlated with the motion of the driver. This was accomplished by placing a mirror on the platform used to drive the motion of the bell and reflecting the reference beam from it. In this way, the effects of whole body motion were eliminated from the interferogram. We have termed this method of interferometry common-mode rejection electronic speckle pattern interferometry (CRESPI). By eliminating the effects of whole body motion, CRESPI produces an interferogram that renders nodal areas as black and antinodal areas with contours of equal displacement.

Results of CRESPI analysis of the bell described above are shown in Fig. 2. In this interferogram the normally observed modes with a sinusoidal dependence are visible, but the nodes of these deflection shapes are not black, as they should be if indeed the only motion was in phase with the driver and having an similar amplitude. Although much more work must be accomplished before a complete comparison can be made with a finite element model, these preliminary results clearly show that there is some motion of the bell that is not due to whole-body motion, but has contours of equal displacement that are circular at and near the rim of the bell. This is exactly the type of motion that will result in the effects reported in references [1] and [2]. Note also, that in the absence of whole-body motion...
FIGURE 3. CRESPI image of the trumpet bell showing significant deflection at the bell rim.

the antinodes would all appear identical in the interferogram. It is clear that they are not in Fig. 2. More convincing evidence for the presence of circular mode shapes is shown in the CRESPI image reproduced in Fig. 3. It is obvious from the contours visible in this interferogram that there is significant motion around the rim of the bell.

CONCLUSIONS

The work reported here demonstrates that there are circular mode shapes with antinodes at and near the rim of the bell of a trumpet in addition to those with a sinusoidal angular dependence that are normally discussed in the literature. The presence of these modes was predicted in ref. [1], where it was posited that they are the cause of a change in the input impedance when the bell vibrations are damped. Similarly, the acoustic effects that occur when bell vibrations are damped, which were originally reported in ref. [2], can be traced to presence of these mode shapes.

The results reported above are preliminary in nature, and significant work remains before there is a complete understanding of how bell vibrations affect the sound of the modern trumpet. However, these results clearly demonstrate the existence of such motion and that it can be excited by axial motion. It is anticipated that future work will show that these resonances occur at frequencies between those where the power is enhanced by bell vibrations and frequencies where it is diminished.

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REFERENCES