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Axial vibrations of brass wind instrument bells and their acoustical influence: Experiments

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It has recently been proposed that the effects of structural vibrations on the radiated sound of brass wind instruments may be attributable to axial modes of vibration with mode shapes that contain no radial nodes [Kausel, Chatziioannou, Moore, Gorman, and Rokni, J. Acoust. Soc. Am. **137**, 3149–3162 (2015)]. Results of experiments are reported that support this theory. Mechanical measurements of a trumpet bell demonstrate that these axial modes do exist in brass wind instruments. The quality factor of the mechanical resonances can be on the order of 10 or less, making them broad enough to encompass the frequency range of previously reported effects attributed to bell vibrations. Measurements of the input impedance show that damping bell vibrations can result in impedance changes of up to 5%, in agreement with theory. Measurements of the acoustic transfer function demonstrate that the axial vibrations couple to the internal sound field as proposed, resulting in changes in the transfer function of approximately 1 dB. In agreement with theory, a change in the sign of the effect is observed at the frequency of the structural resonance.
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I. INTRODUCTION

It is widely believed by experienced players of brass wind instruments that bell vibrations significantly affect the sound produced by the instrument. Whether this is indeed true has been a subject of debate for over a century. Throughout the nineteenth century several studies attempted to determine whether wall vibrations affect the sound of wind instruments, with an emphasis primarily on organ pipes. Late in the century, Helmholtz noted that the tubing of wind instruments must be strong enough to "resist" the internal forces of the air column or there will be a reduction in sound power.[1] Shortly after the turn of the twentieth century, Miller constructed a double-walled flue pipe that could be filled with water to reduce wall vibrations and concluded that the wall vibrations had an effect on the sound.[2] However, 30 years later, Boner and Newman performed experiments on flue pipes of several different materials and concluded that the material "has very little effect on the steady-state spectrum of the pipe."[3] In the 1960s, Backus and Hundley concluded that wall vibrations in cylindrical pipes had "negligible influence on the steady pipe tone," however, they opined that there may be non-negligible effects if the pipe is not cylindrical.[4] By the 1970s the research emphasis had shifted to brass wind instruments and Wogram[5] and Smith[6] both reported that bell vibrations could have small effects on the sound of trombones. In the next decade, experiments with French horns led Lawson,[7] Pyle,[8] and Lawson and Lawson[9] to claim that the bell vibrations had a noticeable effect on the sound.

By the 1980s results of a number of experiments provided evidence that the vibrations of the metal may affect the sound of brass instruments, but theoretical work by Watkinson and Bowsher indicated that this may not be the case.[10] Similarly, both Wogram[11] and Smith[12] eventually concluded that the effects of the vibrations are probably the result of the player adapting to the sensation of the vibrating metal. Their conclusions highlighted the most significant problem associated with the results of previous experiments, i.e., the necessity of using humans to play the instrument. Indeed, it was the use of humans in the experiments that led many to be skeptical of all of the reported experimental results. In 2005, Moore *et al*. removed the human element by performing experiments using artificial lips to play a trumpet and showed that the vibrations of the bell affected the spectrum of the radiated sound in a statistically significant manner.[13] These results were soon confirmed by Kausel *et al*. who measured changes in the acoustic transfer function when the vibrations of the bell of a French horn were damped.[14,15] A more complete history of the subject can be found in Refs. 16 and 17, but suffice it to say, by 2008 it was generally believed that wall vibrations, and specifically bell vibrations, measurably affect the sound of brass wind instruments.

Once it was established that wall vibrations do affect the sound produced by brass wind instruments, efforts turned to explaining the origin of the effects. It was proposed in Ref. 13 that feedback of vibrations to the lips was responsible, but the experiments reported by Kausel *et al*. indicated that this is unlikely because effects were measured when the air column was driven only by a speaker.[15] In 2008 Nief *et al*. demonstrated that there is coupling between the internal sound field and the vibrations of elliptical modes in the walls

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of a simplified wind instrument, but they concluded that the effects are probably negligible in brass wind instruments.[18] In 2010 Kausel *et al.* proposed a coupling mechanism that relied on the presence of axi-symmetric displacements without radial nodes in the bell. These axisymmetric modes were predicted in trumpet bells, and it was shown that these displacements can be of sufficient magnitude to change the radiated sound field. Although these mechanical resonances were not verified experimentally in an actual trumpet, the observed effects on the input impedance and acoustic transfer function of the air column of a trumpet were shown to exhibit the predicted effects.[16]

The work reported in Ref. 16 has recently been extended by Kausel *et al.,* who demonstrated theoretically how the whole-body motion of brass wind instruments can couple to the internal sound field and how this coupling can explain many of the observed effects on the radiated sound of the instrument under normal playing conditions.[19] Their results of computer modeling of a simplified trumpet indicate that this coupling is broad-band and frequency dependent, in agreement with previous experimental results. Furthermore, the results predict that whole-body motion can either increase or decrease the amplitude of the acoustic transfer function (ATF), which is defined as the ratio of the acoustic pressure in the open air in front of the bell to that in the mouthpiece. The frequency at which the effect on the amplitude of the ATF changes in sign, from increasing the magnitude to decreasing it or vice versa, is referred to as the *crossover frequency*. The modeling indicated that the crossover frequencies coincide with the mechanical resonance frequencies of the structure, and that the change in sign of the effect on the ATF is due to the phase shift that occurs between the structural vibrations and the oscillating internal acoustic pressure as the system passes through a mechanical resonance.

In what follows, we present experimental evidence of the interaction between the vibrating walls and the internal air column of a trumpet bell similar to that predicted in Ref. 19. In Sec. II A, measurements of the mechanical transfer function (MTF) of the bell are presented, where the MTF is defined as the ratio of the axial displacement of the bell to that of the mouthpiece as a function of driving frequency. From these measurements the frequency of the first axial resonance is determined. These results are also compared to the results of simulations using the model presented in Ref. 19. In Sec. II B measurements of the acoustic input impedance and the ATF are reported, and the first crossover frequency is identified. These results are also compared to the results of simulations presented in Ref. 19. Finally, the crossover frequency determined from the ATF is shown to occur at the same frequency as the mechanical resonance identified in the MTF. Taken together these results validate many aspects of the theory.

II. EXPERIMENTAL EVIDENCE OF THE ACOUSTIC INTERACTION WITH AXI-SYMMETRIC MECHANICAL VIBRATIONS

To conclusively demonstrate the presence of axi-symmetric modes and verify their effect on the sound of the instrument, two trumpet bells were manufactured by the Swiss instrument maker *Musik Spiri*. The bells were manufactured without bends and were 645 ± 1 mm in length. Both bells were manufactured identically, with the only difference being that the brass used in one bell had a thickness of 0.50 mm and the other was 0.55 mm thick. (Trumpet bells normally range in thickness from 0.4 to 0.7 mm.) The input diameter of the bell was 11.25 ± 0.05 mm and the diameter of the bell at the output was 122.5 ± 0.1 mm. The bells were fitted with a 7 C trumpet mouthpiece and the measurements of the bore profiles of these bells were used to construct the model described in Ref. 19. With one exception, which is noted in Sec. II A, all of the experiments described below were performed on the 0.55 mm thick bell. The bell was braced with a 25 mm wide clamp centered approximately 350 mm from the small end of the horn. The clamp consisted of two semicircular rubber coated pieces that were screwed together to apply light pressure, leaving a gap of approximately 8 mm on each side. While the positioning of the clamp may have affected the axial vibrations, changing the pressure applied by the clamp did not noticeably change the sound produced by striking the bell; however, the range of pressures applied was limited to avoid damaging the bell.

To validate the model, the MTF of each bell was measured and compared with the predictions. From the MTF, the frequencies of the two lowest whole-body resonances were determined and the deflection shapes of the bell oscillating at each of the resonance frequencies were imaged using electronic speckle pattern interferometry (ESPI). These resonance frequencies and deflection shapes are shown to agree with the predictions of the model. To demonstrate that the effects attributable to wall vibrations are indeed attributable to the axial resonances, the ATF of the bell was measured with the bell vibrations damped and with the bell left free to vibrate and the crossover frequencies were identified. The observed crossover frequencies were then compared to the axial resonance frequencies determined from the MTF.

A. Structural measurements

Previous work has shown that the primary acoustical effects attributable to the wall vibrations of brass instruments are due almost entirely to the motion of the bell section. It was proposed in Ref. 16 that this is because the flaring walls bend in reaction to the force from the internal standing wave, whereas expansion of the bore in the cylindrical portion is negligible. Throughout the instrument the internal pressure wave is always perpendicular to the wall, but in the cylindrical portion of the bore the forces on the wall are radial and the cross-sectional area can only change if the diameter of the pipe increases. In the bell section the force of the internal pressure wave has a component in the axial direction, which increases with increasing flare angle. The stress required to deform the metal by bending it is significantly less than that required to expand the pipe diameter, and therefore the magnitude of the change in the air column is much larger in the bell section than in the cylindrical part. In Ref. 19 it was further posited that the axial motion of the bell results in changes in the cross-sectional diameter at

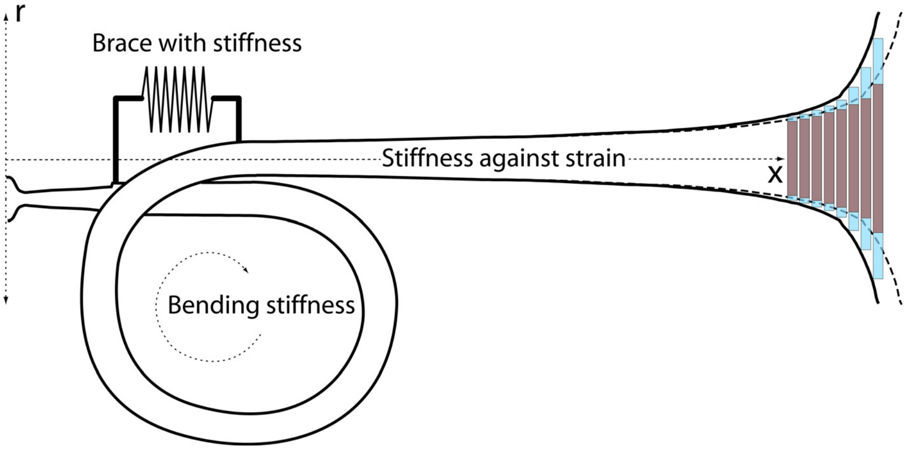

FIG. 1. (Color online) Brass wind instrument showing how axial vibrations can translate into variations in the bore diameter. Reproduced from Ref. 19.

every point in the bell region due to the bell flare, as shown in Fig. 1. Therefore, the MTF that is of most interest is between the input of the instrument and the bell. However, in measuring the MTF it is necessary to separate the elliptical modes, which are characterized by narrow-band resonances and mode shapes with radial nodes, from the axial modes that are broad-band and have shapes that do not have radial nodes.

To discriminate between the two types of modes, the MTF between the mouthpiece and bell, averaged over the cross section of the bell, was measured for both of the straight bells. The measurements were accomplished using two different experimental techniques, at two different laboratories, with two different bells. The results of the two experiments are similar.

In experiments conducted at Rollins College, the MTF of the straight bell with a nominal thickness of 0.55 mm was measured. Vibrations were induced at the small end using a piezoelectric transducer that scanned the frequency spectrum from 100 Hz to 2.5 kHz. The frequency was scanned in a logarithmic sweep using BIAS software. The amplitude and phase of the motion of the driver were measured using a laser Doppler vibrometer (LDV), and similar measurements were made of the axial motion of the bell. To ensure that the whole-body motion was detected and the effects of the elliptical modes were diminished, measurements of the bell motion were made approximately 1 cm from the rim at 12 equally spaced radial locations. These measurements were then averaged in the complex plane so that the displacement attributable to the symmetric antinodes canceled due to their complementary phases. This process ensured that only the displacement due to whole-body motion was recorded. Similar experiments were conducted with the 0.50 mm thick bell at the Institute of Music Acoustics (Wiener Klangstil) in Vienna, however, in these experiments accelerometers were attached to the bell and mouthpiece rather than using a LDV to measure the vibrations. The accelerometers each had a mass of 0.2 g and four were attached to the bell in a radially symmetric pattern. After the measurement the accelerometers were rotated on the bell by 45° to provide eight symmetric measurements, which were averaged in the complex plane. The cables attached to the accelerometers had a linear density of 9.5 g/m, and while they provided some damping of the vibrations, there was no noticeable effect on the narrow-band elliptical modes so it is likely that the effect on the axial modes was negligible.

Results from both experiments are shown in Fig. 2, where the magnitude of the MTF is plotted as a function of driving frequency for both bells. Note that the transfer functions are qualitatively similar, with slight variations in the frequencies of the resonances that can be attributed to the differing thicknesses of the metal and the added mass of

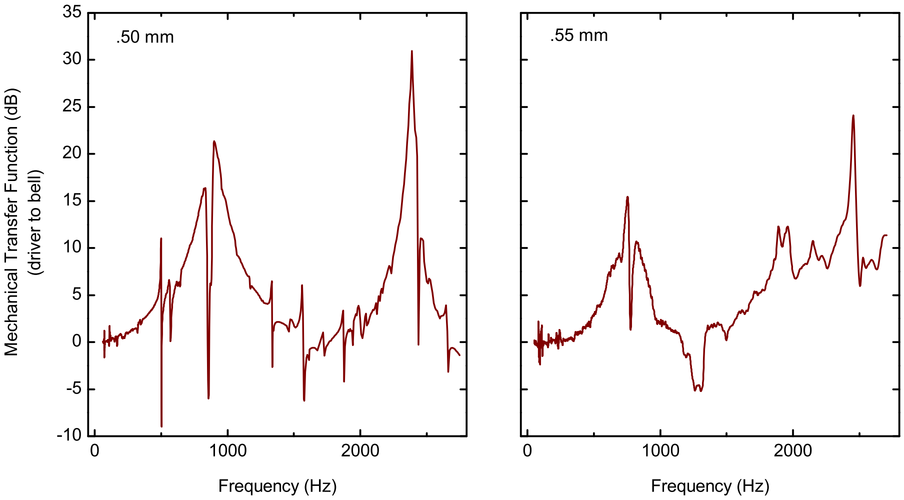

FIG. 2. (Color online) Average MTF from mouthpiece to bell of the two straight bells described in the text. The transfer function for the 0.50 mm thick bell was measured using accelerometers and the measurements of the 0.55 mm thick bell were made using laser Doppler vibrometers. Details are given in the text.

the accelerometers in one case. The measurements of the 0.50 mm thick bell also show evidence of the elliptical modes, which are identifiable by their narrow-bandwidth; these can be explained by the fact that the placement of the accelerometers on the bell induced a slight asymmetry. This asymmetry caused the amplitudes of the antinodes to not completely cancel during the averaging process. Laser Doppler vibrometry is a non-contact measurement, therefore the effects of these elliptical modes are greatly reduced in the measurements of the 0.55 mm thick bell.

An inspection of Fig. 2 reveals that there are two significant whole-body resonances that may be responsible for the observed acoustical effects. These resonances occur at approximately 835 Hz and 2.5 kHz in the 0.55 mm thick bell (measured using LDV) and at slightly lower frequencies in the thinner bell (measured using accelerometers). Both resonances exhibit apparent mode splitting that can be attributed to asymmetries of the structure. The most significant asymmetry is probably the seam in the metal that extends along the length of the bell. The seam may have minimal effects on the local deflection shapes that characterize elliptical modes, but the whole-body resonance of the bell is attributable to the integrated effects along the entire bell axis. Therefore, the asymmetry probably has a much larger effect on the axial modes than it does on the elliptical modes. The clamp used to mount the bell may also contribute to the asymmetry.

To characterize the deflection shapes associated with the two identified resonances and ensure that they do indeed represent whole-body motion, the thicker bell was driven at the two resonance frequencies using a piezoelectric transducer attached to the small end while the large end was imaged using decorrelated electronic speckle pattern interferometry.[20] To ensure that the interferograms were not biased by possible resonances of the driver, and to eliminate the effects attributable to common motion of the bell and driver, the reference beam of the interferometer was reflected from a mirror attached to the driving mechanism. In this way, only motion of the bell that differed in some manner from the driving motion was visible in the interferogram.

The interferograms are shown in Fig. 3, where nodes are represented as white and the dark lines represent contours of equal displacement. Figure 3(a) is an image of the static bell, Fig. 3(b) is an image of the bell vibrating at the lower resonance frequency (883 Hz), and Fig. 3(c) is an image of the bell vibrating at the higher resonance frequency (2451 Hz). The slight shift in the frequencies of the resonances from those observed in the measurement of the transfer functions may be attributable to small changes in the mounting arrangement. Specifically, the position of the clamp may have varied by as much as 2 mm between experiments. Also, while the pressure applied by the clamp was similar in every case, no measurement was made to ensure a level of precision. Shifts in the resonance frequencies of up to 5% were commonly observed when moving the apparatus and changing the driving mechanisms.

The image in Fig. 3(b) shows no evidence of the normal ring structure associated with circular nodes because the entire bell was moving in phase. The dark image indicates whole body motion that is not in phase with the driver, with no evidence of a nodal line. This interferogram is consistent with whole-body motion similar to that depicted in Fig. 1 with a slight asymmetry in the deflection, which results in a single diagonal fringe.

The interferogram shown in Fig. 3(c) exhibits an obvious nodal line close to the rim. It is a circular node and indicates that the rim motion is out of phase with the motion of the rest of the bell. A slight asymmetry of this deflection shape is also apparent, as one would expect. Both of these deflection shapes agree with those predicted in Sec. II in Ref. 19.

Figure 3(c) can be compared directly to bell motion depicted in Fig. 4, which is reproduced from Ref. 19. A comparison between the predictions of the model and the measured MTF of the bell is shown in Fig. 5, indicating that the model can accurately predict the axial resonance frequencies of a symmetric bell.

B. Air column measurements

If the predictions of the model are correct, eliminating the vibrations of the walls of an instrument under test will result in a change in the input impedance measured at the mouthpiece. This change can be predicted by calculating the input impedance both with the bell free to vibrate and again with the vibrations completely damped. The difference in input impedance can be determined experimentally by measuring the input impedance with the bell heavily damped with bags of sand and again with it left free to vibrate.

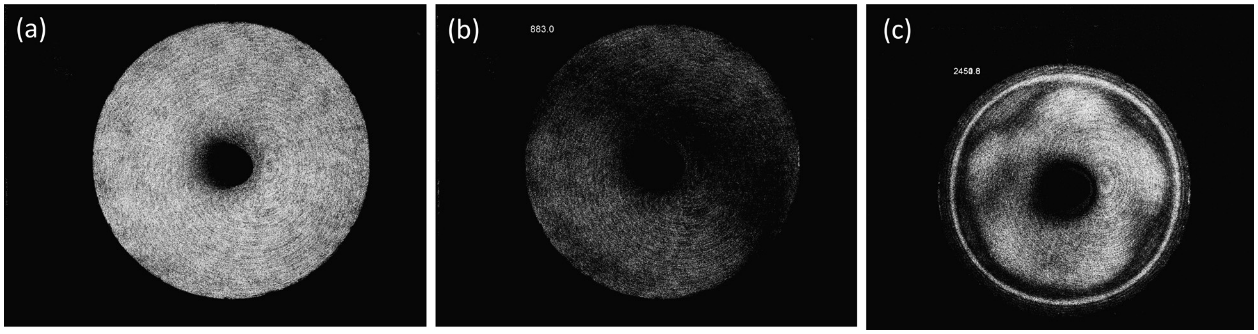

FIG. 3. Decorrelated electronic speckle pattern interferograms of the bell with (a) no excitation, (b) oscillating at the first axial resonance frequency (883 Hz), and (c) oscillating at the second axial resonance frequency (2451 Hz).

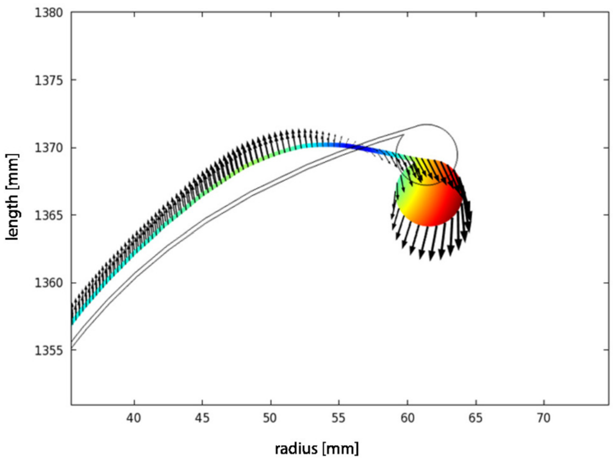

FIG. 4. (Color online) Deformation of the bell at the second axial resonance scaled by a factor of 3000. Reproduced from Ref. 19.

It is known that the bell of a trumpet radiates in all directions and therefore changes to the environment around and immediately behind the bell may result in changes to the input impedance.[21,22] Because the bell does not radiate into an infinite half-plane, placing sandbags around the back of the bell, which extend up to but not in front of the rim, can possibly change the experimental environment. To ensure that the measurement was not affected by a change in the environment near the bell, a wooden baffle was placed around the bell with approximately 2 mm of clearance at the rim so that the bell was left free to vibrate. Measurements were made using the BIAS system in an anechoic room with sound absorbing foam tiles on the floor, ceiling and walls. These precautions ensured that any change in the input impedance was attributable to changes in the internal air column and not due to placing the bags of sand near the bell rim. The results of both the experiments and model are shown in Fig. 6.

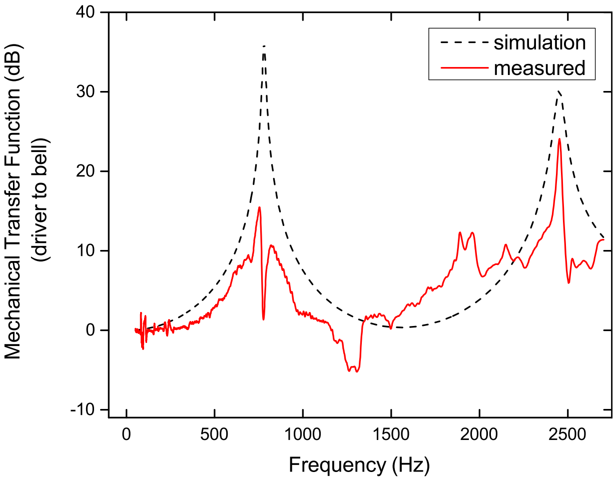

FIG. 5. (Color online) Comparison of the measured MTF of the bell (solid line) with that predicted by the model described in Ref. 19 (dashed line).

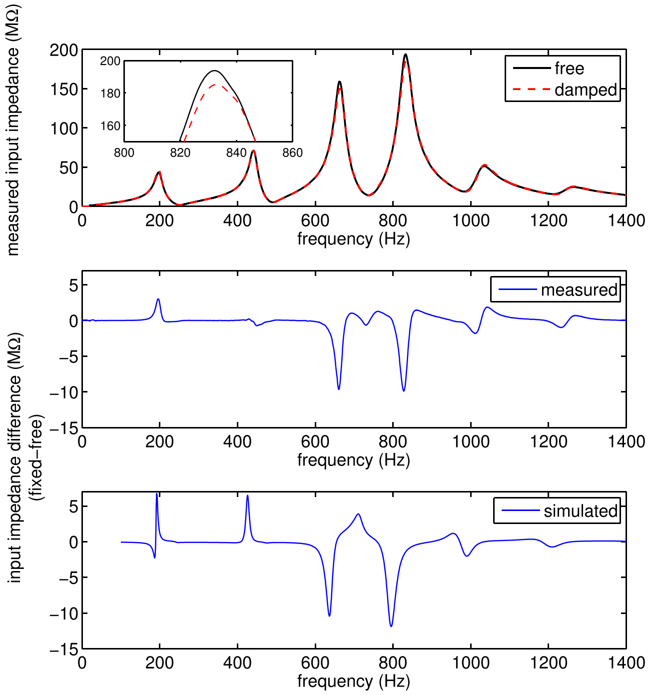

FIG. 6. (Color online) The measured input impedance of the bell with vibrations damped and with it free to vibrate (top). The difference between the two cases (center), and the predicted difference calculated numerically (bottom). The inset in the top graph is an enlargement of one of the impedance peaks that exhibits a measurable difference in the impedance.

The measured input impedance with the bell vibrations damped and with the bell left free to vibrate are plotted in the top portion of Fig. 6. The center graph in Fig. 6 shows the difference between the two cases, while the predictions of the model are shown in the lower graph. The primary difference between the predictions of the model and the measured impedance occurs at the minimum between the two highest impedances. For reasons not currently understood, the errors in the impedance calculation in regions of low impedance are much larger than those at the frequencies of air column resonances. Similarly, the lack of a large change at the second resonance near 400 Hz indicates that some aspect of the experiment is not accounted for in the model. However, the similarity between the two curves serves both to confirm many of the predictions of the model as well as to verify again that the bell vibrations result in a measurable change in input impedance.

To unambiguously identify the acoustic effects attributable to wall vibrations of the bell, and to identify the crossover frequencies, the ATF of the bell was also measured with the bell free to vibrate and again with the bell heavily damped with bags of sand. The measurements were accomplished by replacing the BIAS head that was attached to the mouthpiece with a horn driver containing a titanium diaphragm. The horn driver had a maximum input power of 75 W with a mass of 2.3 kg and was secured to a steel optical table. The adapter that connected the speaker to the mouthpiece had an internal diameter of 27 mm, with a gap of 12 mm between the diaphragm and the mouthpiece. A microphone was mounted in the gap between the driver and the mouthpiece, and another microphone was placed approximately 30 cm from the bell.

To minimize any effects attributable to sound from the driver that was not confined to the air column of the instrument, as well as any other acoustic effects not effectively

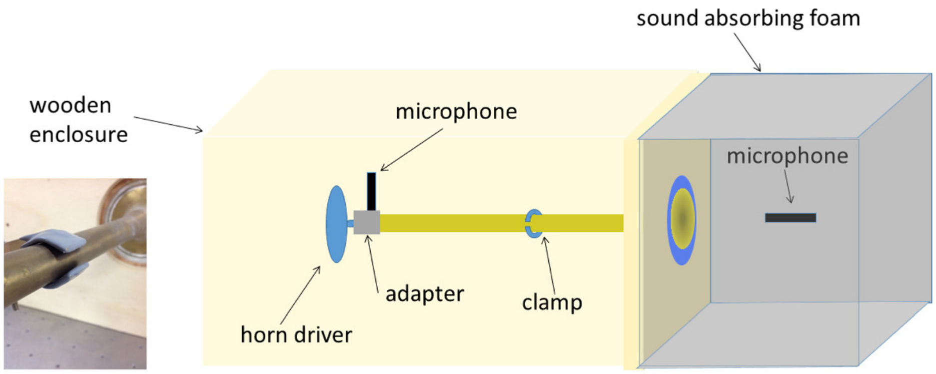

FIG. 7. (Color online) Experimental arrangement for the measurement of the acoustic transfer function. The inset shows the clamp used to support the bell.

eliminated by the baffle, the entire bell and acoustic driver were enclosed in a box made of plywood approximately 18 mm thick. The wall of the box through which the bell was inserted was further reinforced to be approximately 31 mm thick. The end of the bell was arranged so that it was flush with the outside of the box and the gap between the bell and the baffle was filled with silicone sealant. Although the apparatus was not mounted inside an anechoic chamber, the area between the bell and the microphone used to record the transmitted signal was surrounded by sound absorbing foam. The experimental arrangement is shown schematically in Fig. 7. Care was taken to ensure that there were minimal changes to the experimental geometry when the sandbags were placed on the bell, so any effects attributable to the external environment affected all measurements similarly.

To ensure a precise measurement of the ATF, a sinusoidal signal lasting 1 s was used to drive the horn driver at each frequency of interest. The frequency of the signal was varied from 100 Hz to 3 kHz in increments of 1 Hz. A 1 s delay was inserted before changing the driving frequency to provide time for any bell vibrations to decay before driving the air column at the next frequency. The signals from the input and output microphones were recorded at each driving frequency and the power spectra were calculated in real time. The power in the driving frequency measured at the bell was divided by the power measured at the mouthpiece to determine the magnitude of the acoustic transfer function before changing the frequency of the driving signal. The long sample time allowed for precise measurements as well as ensuring that the bell vibrations had adequate time to reach steady-state at each frequency.

The results of these measurements, and the difference between them, are shown in Fig. 8. The predictions of the model are also plotted in Fig. 8. The experimental results agree well with the model, with the exception of a large maximum at approximately 1 kHz. This artifact is probably not associated with the bell vibrations but rather with the box surrounding the bell; the justification for this assumption is discussed in Sec. II C.

C. Analysis of the experimental results

The measurements described in Sec. II A indicate that whole-body resonances do exist as was postulated in Refs. 16 and 19. However, if these resonances are responsible for the changes in the ATF when the wall vibrations are damped, the crossover frequency must coincide with the frequency of a mechanical resonance. The MTF of the bell is shown in Fig. 5 and agrees well with the predictions of the model, however, because the bell was attached to the baffle when the ATF was measured the structural resonances were modified. The MTF measured while the bell was attached to the baffle is shown in Fig. 9, where both the magnitude and phase of the MTF are plotted. The resonance frequencies can be identified unambiguously by the phase shift in the MTF that occurs at resonance.

Connecting the bell to the baffle shifted the frequency of the lowest mechanical resonance only slightly to approximately 850 Hz, but the second resonance was lowered by almost 500 Hz. The large shift of the second resonance is not surprising given the deflection shape depicted in Fig. 4. The coupling of the bell to the baffle increased the effective mass of this portion of the bell significantly due to the rotation about the node very close to the rim. However, the lower resonance is characterized by whole body motion, which is damped somewhat by attaching the bell to the baffle, but the axial motion is largely unchanged.

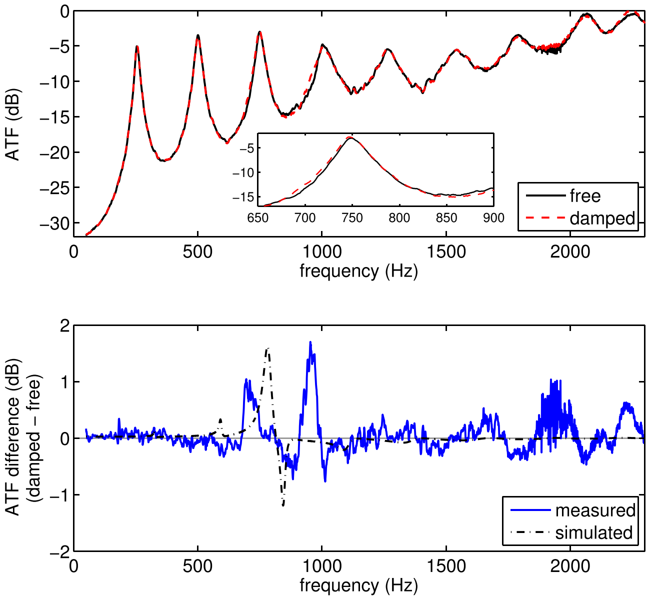

FIG. 8. (Color online) (Upper) The acoustic transfer functions of a straight bell with the vibrations damped and with the bell free to vibrate, normalized to the maximum transmission. (Lower) The difference between the two measurements plotted with the predictions of the model. The inset in the top graph is an enlargement of the range that includes the crossover frequency.

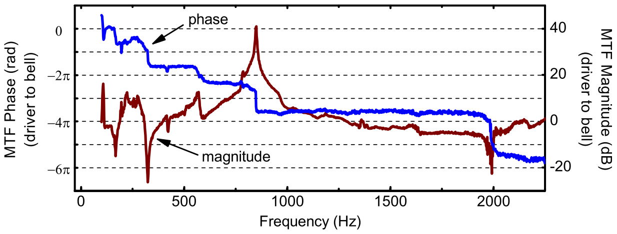

FIG. 9. (Color online) The phase and amplitude of the MTF of the bell with the gap between the baffle and the bell sealed with silicone sealant.

It is clear from Figs. 8 and 9 that the sign of the effect on the ATF does indeed change at the lower resonance frequency as predicted. The frequency of the lower mechanical resonance varies from the crossover frequency by less than 5% (850 vs 812 Hz), which is within the range attributable to changes in the apparatus between measurements. It appears that there is a similar effect at the higher resonance frequency, and indeed there may be some small effect. The presence of a mechanical resonance near 2 kHz is clear, however, at this frequency the ATF does not provide sufficient resolution to unambiguously assert that the crossover frequency is coincident with the frequency of the axial resonance. As noted in Ref. 19, the motion of the bell at this resonance, depicted in Fig. 4, should have only a small effect on the ATF due to the nodal line near the rim.

This lack of an expected effect at the second mechanical resonance can be explained by observing the deflection shape, which can be determined from the inteferogram shown in Fig. 3(c). The interferogram shows the closely spaced contours of equal displacement associated with an antinode and the circular nature of the deflection indicates that this is a whole-body resonance. (The closely spaced contour lines can be made clearly visible by magnifying the image in the digital version of this article.) However, the antinode with the largest displacement occurs only at the rim. There is a node close to the bell rim, and behind this node there is much smaller displacement. Furthermore, since there is a node between the rim and the rest of the bell, what motion there is behind the node is out of phase with the motion of the rim. Unlike the mode shape associated with the resonance at the lower frequency, which has no nodes in the bell region, the nodal line associated with the higher-frequency resonance results in the motion of the two regions of the bell moving out of phase with each other. Therefore, it is not surprising that the effects of coupling this resonance to the air column are reduced. There is little motion except near the bell rim, and what motion there is includes two out of phase components. In contrast, the lack of a nodal line at the lower resonance indicates that the entire bell moves in phase, maximizing the effect on the air column.

As expected the MTF shown in Fig. 9 has no indication of an axial resonance at 1 kHz, indicating that the artifact at this frequency seen in Fig. 8 is indeed due to a resonance of the box surrounding the apparatus. Measurements of the ATF made without the baffle do not provide a precise measurement of the transfer function due to acoustic effects from the driver that are not transmitted through the bell section, however, measurements made without the box show no noticeable features in the ATF near 1 or 2 kHz. Therefore it is likely that these artifacts can be ignored in the context of this investigation.

III. CONCLUSIONS

The experimental results presented here agree with many of the predictions of the model described in Ref. 19. The measured changes in the input impedance attributable to the vibrations of a trumpet bell are similar to the predictions of the model. The frequencies of the axial mechanical resonances of the bell are also in agreement. Many of the details of the MTF of the bell are not predicted by the model, however, much of the disagreement can be attributed to axial mode splitting. Radial asymmetries are not included in the axi-symmetric model, so this splitting is not predicted. Most significantly, the crossover frequency observed in the ATF is coincident with the axial resonance frequency, indicating that there is coupling between the air column and the axial motion of the bell.

The experimental evidence demonstrates that the interaction between the axial modes and the internal air column is responsible for some of the effects that bell vibrations have on the sound of brass wind instruments. The correlation between the whole-body resonance frequency and the crossover frequency of the ATF indicates that the theory presented in Ref. 19 is indeed valid. The lack of an effect attributable to the narrow-band elliptical resonances indicates that the elliptical modes are not important in determining the acoustical properties of the instrument, which is in agreement with the results of previous research.

The crossover frequencies in the ATF determine which overtones are enhanced and which are diminished by the presence of bell vibrations, and therefore they are the most significant parameter in determining the effect of these vibrations on the final sound of the instrument. Since the axial resonances are affected by the details of the construction of each instrument, it is unlikely that an appropriate generalization exists concerning the value of these crossover frequencies and it is likely that the crossover frequencies are unique to each instrument. The variability of the crossover frequencies within a single class of brass wind instruments and the importance of mechanical feedback of vibrations to the lips are suitable subjects for future research.

ACKNOWLEDGMENTS

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