# COUPLING BETWEEN WALL VIBRATIONS AND THE AIR COLUMN IN BRASS WIND INSTRUMENTS: A COMPARISON BETWEEN THEORETICAL PREDICTIONS AND EXPERIMENTAL RESULTS

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## ABSTRACT

It has been shown that the bell vibrations of brass wind instruments can significantly affect the sound produced by the instrument, and over the past decade several theories have been proposed in attempts to explain how this is possible. All of the proposed theories can explain many of the observed effects, however, two aspects have been difficult to accurately predict: the broad-band response and the frequency dependence. Recently, Kausel, et al. [J. Acoust. Soc. Am. **137**, 3149 (2015)] have proposed a mechanism that may explain how the acoustic field inside the instrument can couple with the wall vibrations. We present the results of experimental investigations and compare them to predictions of this theory. The agreement between the predictions and the experimental results indicates that the proposed coupling mechanism can account for the observed phenomena.

## 1. INTRODUCTION

The question of whether the bell vibrations affect the sound of brass wind instruments has been a topic of discussion for at least a century. For most of that time musicians universally believed that bell vibrations affect the sound produced during play, but lacking experimental evidence scientists were not convinced. However, experiments performed a decade ago using artificial lips to play a trumpet conclusively determined that the sound produced by the instrument is affected by the vibrations of the bell, and this effect is significant enough to be perceived by the audience.[2] A thorough review of the subject can be found in Ref. 3.

It was proposed in the original work that showed the existence of such effects that the vibrations in the instrument feedback to the lips, changing lip motion and producing an altered sound.[2] While this may indeed happen, the characteristics of the effects attributable to bell vibrations indicate that there are other processes at work as well. Furthermore, these unidentified processes may be the dominant cause of the perceived differences in sound attributable to bell vibrations. Indeed, the effects of bell vibrations have been shown to be measurable when the air column is excited by a speaker attached to the mouthpiece, which eliminates any effects attributable to lip motion.[3]

Beyond the lack of the necessity of lip motion, two other important aspects of the effects of bell vibrations provide clues to the origin of the effects: the broad-band nature of the effects and the fact that the bell vibrations may enhance or decrease the sound level produced by the instrument depending upon the frequency of air column oscillations.[3] A successful theory must simultaneously explain the lack of necessity for lip motion, the broad-band nature of the effects, and the frequency dependence.

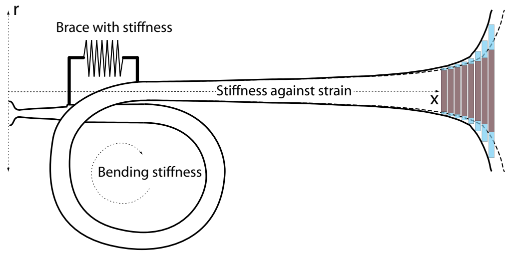


Figure 1: Diagram of a brass wind instrument and how axial vibrations can cause changes in the bore diameter. (After Ref. 1)

Recently, Kausel et al. have proposed an explanation for the origin of the effects of bell vibrations on the sound produced by brass wind instruments.[1] The theory posits that vibrations along the bell axis are responsible for these effects and it predicts both the broad-band nature of the effects and the fact that the sound power at some frequencies are enhanced while it is decreased at others. The work reported here was designed to test this theory.

## 2. PROPOSED THEORY

The proposed theory is presented in detail in Ref. 1, but for the present purposes it is sufficient to understand that the theory posits the existence of axial motion of the instrument. This axial motion, which can excite a series of axial resonances, results in changes in the cross sectional area of the of the bore within the bell region. The mechanism that translates axial motion to a change in bore area is illustrated in Fig. 1. As the bore oscillates in the axial direction, the motion causes the length of the instrument to change. Although the changes are small in comparison to the length of the instrument, and therefore the effect on the air column resonances will be minuscule, in the flaring region of the bell the axial motion translates into a change in the area of the bore. The theory posits that origin of the effects attributable to bell vibrations is this variation in the bore, which oscillates at the frequency of the resonating air column.

As presented in Ref. 1, the theory posits that the axial vibrations can be excited by the internal pressure in the mouthpiece, eliminating the need for considering lip vibrations. However, as noted above, for the theory to encompass the experimental evidence it must account for two other important observations: the broad-band nature and the changes in the sign of the effect as the frequency changes. Both of these characteristics are evident

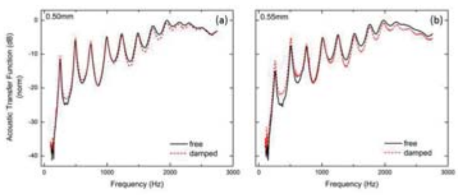


Figure 2: Acoustic transfer function of two straight bells with mouthpieces for the case of the bell freely vibrating (solid) and with the bell heavily damped with bags of sand (dashed).

when the acoustic transmission function (ATF) of a trumpet is measured under conditions where the bell is free to vibrate compared to when the bell vibrations are heavily damped by bags of sand. The results of this type of experiment were reported in Ref. 3 and they show a change in the ATF up to 3 dB over a bandwidth of approximately 2 kHz. Furthermore, the difference between the ATF measured for the two cases changes sign twice within this range, changing from the vibrations reducing the magnitude of the acoustic transfer function to increasing it and back to decreasing it. The frequency at which the sign of the effect changes is termed the *crossover frequency*. Similar effects are seen in measurements of the input impedance, and the theory developed in Ref. 1 predicts both of these effects.

Because the axial extension will be a maximum when the exciting frequency is near the frequency of an axial resonance, the bandwidth of the effects are predicted to be related to the bandwidth of the resonances. Since the effect on the radiated sound are typically broad-band, the theory demands that the axial resonances be similarly broad. Likewise, because the phase of the axial oscillations will experience a shift around the resonance frequency, the theory predicts that the effect on the air column will change sign at this frequency. Thus the theory can be tested by identifying the axial resonance frequencies, comparing the bandwidth of the resonances to the frequency range of the effects on the sound, and then identifying the crossover frequency as being the frequency of an axial resonance.

In what follows we describe experiments that measure the first axial resonance of two straight trumpet bells with an attached mouthpiece. The resonance frequencies and bandwidths are compared to the measured ATFs and it is found that the crossover frequency coincides with the axial resonance frequency. Similarly, the bandwidth of the resonance is shown to be broad enough to encompass the frequency range over which effects attributable to bell vibrations are observed.

## 3. EXPERIMENTS

### 3.1. Measurement of the acoustic transfer function

To test the predictions of the theory, two trumpet bells were manufactured by the Swiss instrument maker *Musik Spiri*. The bells were manufactured without bends and were both approximately 65 cm long. 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. Each bell was fitted with a 7C trumpet mouthpiece and the acoustic transfer function was measured with the bell heavily damped with sandbags and again with it left free to vibrate.

To measure the ATF of the bells, a horn driver with a titanium diaphragm was attached to the mouthpiece. The adapter used to connect the speaker to the mouthpiece was modified to mount a microphone between the driver and the mouthpiece, and a matched microphone was placed approximately 1 m from the bell. The bell was braced with a 2.5 cm wide clamp centered approximately 37 cm from the driver. It is known that the bell of a trumpet radiates in all directions and that changes to the area near the rim can result in changes to the input impedance. Therefore, 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 to ensure that the bell was free to vibrate. Measurements were made with sound absorbing foam surrounding the entire apparatus. 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.

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 - 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 measured power in the driving frequency was then used to determine the 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 for both bells are shown in Fig. 2. In Fig. 2 the solid line denotes the ATF measured when the bell is free to vibrate and the dashed line indicates that the bell vibrations were heavily damped. Note that the two bells behave similarly, with the magnitude of the ATF enhanced at low frequencies and depressed at higher frequencies. The difference between the two transfer functions for the thicker bell is shown in the top graph in Fig. 3, where it can be seen that the crossover frequency occurs at approximately 860 Hz.

The difference in the ATF calculated using the model described in Ref. 1 is shown in the middle graph in Fig. 3, which demonstrates that the predicted crossover frequency agrees with the experimental result. But while the agreement between the experimental determination of the crossover frequency and the prediction of the model is quite good, comparing the measured and calculated differences indicates that the overall form of the predicted change in the ATF is not similar to the measured change. This disagreement was found to be attributable to the 2 mm gap between the rim of the bell and the baffle. The gap between the baffle and the bell allowed the bell to freely vibrate while still ensuring that the presence of the sandbags used to damp the vibrations did not affect the acoustical arrangement. Unfortunately, the gap was sealed by the bags of sand when the bell vibrations were damped but open when it was left free to vibrate. It was found that the presence of this gap produced a small but measurable change in the ATF.

The bottom graph in Fig. 3 shows the calculated difference between the ATF of the bell with the gap and without it. In this case the wall vibrations were not included in the model, so one would predict that the measured ATF could be approximated by a weighted superposition of the two lower graphs in Fig. 3. The measurement, shown in the upper graph, does indeed have this

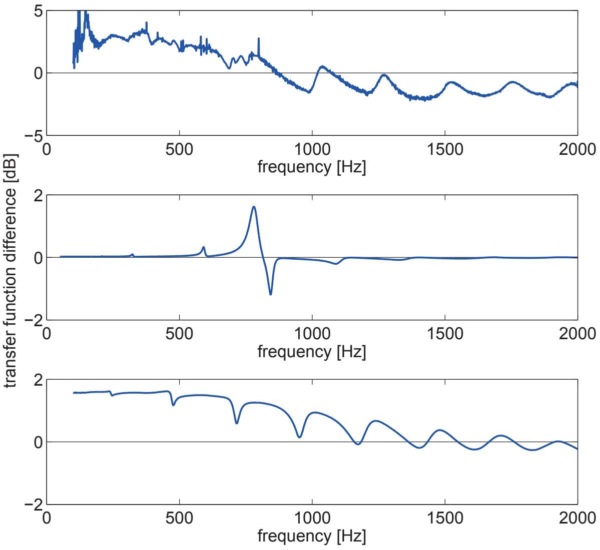


Figure 3: (Top) Difference in the acoustic transfer functions shown in Fig. 2b. The crossover frequency occurs at approximately 860 Hz. (Middle) Calculated difference in the ATF using the model described in Ref. [1]. (Bottom) Calculated difference in the ATF including the gap between the bell and baffle. Details are given in the text.

form.

The effects of the gap between the bell and the baffle complicate the interpretation of the measurement of the ATF, however, it does not appear to significantly affect the measurement of the crossover frequency. The crossover occurs at the frequency predicted by the model when the gap is not included, and as will be shown below, it also occurs at the frequency of an axial resonance.

### 3.2. Identification of axial mode frequencies

To compare the crossover frequencies with the axial resonance frequencies it is necessary to unambiguously identify the axial resonances. However, determining the frequencies of the axial resonances is more difficult than measuring the ATF. This difficulty stems primarily from the fact that there are numerous structural resonances of a trumpet bell, resulting in a variety of symmetric deflection shapes.[4] The majority of these resonances are attributable to elliptical mode shapes, which are characterized by radial vibrations that have one or more radial nodes and one or more nodal circles. These resonances typically have quality factors of 100 or more and only minimally affect the area of the bore because the contiguous antinodes are $\pi$ out of phase.[3] Therefore, while it is highly unlikely that elliptical modes have a significant affect on the sound produced by an instrument, they make it difficult to determine which resonances can be attributed to purely axial motion.

Two methods were devised to distinguish between the axial modes and the elliptical modes so that the frequencies of the axial resonances could be unambiguously determined. Both methods involved measuring the mechanical transfer function (MTF) of axial vibrations from the mouthpiece to the end of the bell, averaged over the cross section of the bell. Although the measurements were made 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, Florida, USA

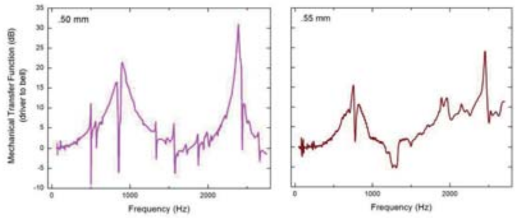


Figure 4: Axial MTF from mouthpiece to bell of the two trumpet bells. The transfer function for the 0.50 mm thick bell was measured using accelerometers and the measurements of the 0.55 mm thick bell were made using a laser Doppler vibrometer.

the vibrations of the straight bell with a nominal thickness of 0.55 mm 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 bell motion. 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 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, Austria, however, in these experiments eight accelerometers were attached to the bell and mouthpiece rather than using LDVs to measure the vibrations.

Results from both experiments are shown in Fig. 4, where the magnitude of the MTF is plotted as a function of driving frequency for both bells. The slight variations in the frequencies of the resonances can be attributed to the differing thicknesses of the metal and the added mass of 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, which 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.

The measurements shown in Fig. 4 reveal 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 and at slightly lower frequencies in the thinner bell. 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. This 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 inte-

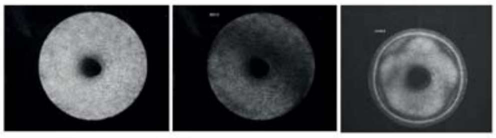

Figure 5: Decorrelated electronic speckle pattern interferograms of the bell with (a) no excitation, (b) oscillating at the first axial resonance frequency (883 Hz) and (c) oscillating at the second axial resonance freqeuncy (2451 Hz).

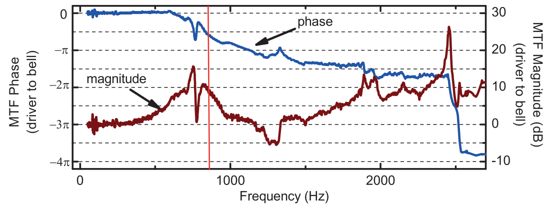


Figure 6: The phase and amplitude of the MTF of the 0.55 mm thick bell. The vertical line indicates the crossover frequency of the ATF seen in Fig. 3.

grated effects along the entire bell axis, resulting in a significant asymmetry in the axial direction.

To characterize the mode shapes of 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.[5] 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. 5, where Fig. 5a is an image of the static bell, Fig. 5b is an image of the bell vibrating at the lower resonance frequency (883 Hz), and Fig. 5c 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 can be attributed to small changes in the mounting arrangement.

Nodes are represented as white in the interferograms and dark fringes indicate contours of equal displacement. The image in Fig. 5b 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 with a slight asymmetry in the deflection, which results in a single diagonal fringe. The interferogram shown in Fig. 5c exhibits an obvious nodal line close to the rim. Both of these mode shapes agree with those predicted in Section II of Ref. 1.

## 4. CONCLUSIONS

As noted above, the model posited in Ref. 1 predicts that crossover frequencies occur whenever there is an axial resonance. As can be seen in Fig. 3, the crossover frequency for the 0.55 mm thick bell occurs at approximately 860 Hz. The MTF shown in Fig. 4 indicates that for this bell there is an axial resonance near that frequency. To determine the frequency of the resonance more precisely it is useful to plot the phase of the MTF, since the phase will experience a shift of $\pi/2$ as it passes through resonance. This is shown in Fig. 6, from which it can be determined that the axial resonance occurs within $3\%$ of the crossover frequency. This small difference can be attributed to slight changes in the mounting between measurements.

The second experimental observation for which the theory of Ref. 1 must account is the broad-band nature of the affects of bell vibrations. As can be seen in Fig. 2, although the sign of the effect changes at the crossover frequency, the effects can be seen to span several hundred hertz. The MTF shown in Fig. 6 clearly indicates that the axial resonance has a bandwidth that extends over a similar range.

These measurements lend significant credence to the model presented in Ref. 1. Axial vibrations have been shown to exist in a trumpet bell and the difference in the ATF that is measured when the bell is free to vibrate compared to when the vibrations are damped is consistent with predictions. As predicted by the model, the bell vibrations can enhance or diminish the magnitude of the acoustic transfer function. Which manifestation of the effect is observed depends on the relative phase between the air column and the axial bell motion. Similarly, the broad-band nature of the effects of bell vibrations on the sound are explained by the fact that the axial resonances are similarly broad.

How important the mechanical vibrations of the lips are to the process has yet to be determined. There is no reason to expect that the vibrations of the lips transmitted to the mouthpiece will have a consistent phase relationship with the motion of the bell. Indeed, one may expect that the relative phase changes as a function of frequency and playing style. The role the lips play in the excitation of axial vibrations, the importance of vibratory feedback to the lips and the relationship between the phase of the lip motion and the phase of wall vibrations excited by the air column are suitable subjects for future research.

## 5. ACKNOWLEDGEMENTS

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