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Session 4pMU: Measurements, Modeling, and Simulations of Brass Instruments

4pMU4. Influence of the bell profile of the trombone on sound reflection and radiation.

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One of the most striking external features of a modern trombone is its wide and rapidly flaring bell. The bore profile of this final section of the instrument influences its musical behaviour in a number of different ways, since it determines both the strength of the acoustical feedback from the instrument to the lips of the player and the nature of the radiated sound field. These effects have been explored in an experimental study in which a number of trombones have been progressively modified by the removal of annular sections of the bells. Measurements of input impedance, transfer function and directivity of radiated sound are presented, and the implications for the timbre and playability of the instruments are discussed.

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INTRODUCTION

The flaring bell section of a modern orchestral trombone is one of its most striking visual features. A typical tenor trombone has a total tube length of around 2700 mm, but in the last 500 mm the bore diameter expands from around 20 mm to over 200 mm. The detailed form of this bore expansion influences the musical behavior of the instrument in various ways. The generation of sound occurs by the modulation of air flow through the vibrating lips of the player, and this process is strongly influenced by the internal reflection of sound energy from the bell to the lips. The radiation of sound from the instrument also depends on the size and shape of the bell.

Five centuries ago, trombones (known then in English as “sackbuts”) had bells considerably smaller than those of modern instruments, and reproduction of these early instruments are now made for historically informed performance of music of the time. The project described in this paper is an attempt to clarify the significance of changes in the last few centimeters of the trombone bell. For this purpose two twentieth century trombones were progressively modified by the removal of annular sections from the bells. The resultant changes in the reflection of sound were monitored by measurements of the input impedance of the instruments at each stage. To examine the change in the nature of the radiated sound field the pressure transfer functions between the input of the instrument and several points in the radiation field were measured.

EXPERIMENTAL PROCEDURE

The trombone under test was mounted in an anechoic chamber. The instrument did not have its normal mouthpiece; instead, the mouthpiece receiver was inserted directly into a small cylindrical coupler fitted to the throat of a JBL 2446 horn loudspeaker driver. A Labview program was used to generate a swept sine wave, which was fed through a National Instruments interface and an audio amplifier to the horn driver. A PCB 106B microphone in the coupler recorded the input pressure signal. A similar setup has been used to investigate effects of nonlinear wave propagation in brass instruments [1]. In the experiments described here, the amplitude of the driving signal was restricted to a level at which such nonlinear effects were not significant.

The radiated sound was recorded using a Bruel and Kjaer 1” microphone. Measurements were taken 50 cm from the bell centre, defined as the point at which the bell axis intersects the exit plane, and at angles of 0°, 30°, 60°, 90° and 120° relative to the bell axis.

After each pressure transfer function measurement session, the input impedance of the instrument was measured using the BIAS system [2]. This measurement was done with the cylindrical coupler in place of the normal mouthpiece to facilitate direct comparison between input impedance and transfer function.

BOOSEY AND HAWKES IMPERIAL TROMBONE

One of the instruments studied was a Boosey and Hawkes Imperial tenor trombone made in 1970. All measurements were done with the slide in first position (fully retracted). In its unaltered state the total tube length was 2701 mm, the internal diameter of the slide sections was 12.35 mm and the bell exit diameter was 190 mm. This state is described as “uncut”. After the first set of measurements, the final 12 mm section of the bell was removed by a professional brass instrument repairer, reducing the exit diameter to 145 mm; the resulting state is described as “semicut”. Subsequently a further 21 mm section was removed from the bell, reducing the exit diameter to 100 mm; this state is described as “fully cut”. Figure 1 shows the instrument in its fully cut state, together with the sections removed. In this state the bell diameter is similar to that typical of tenor trombones of the sixteenth century; some trombonists use modern instruments modified in this way to perform renaissance and early baroque music.



FIGURE 1: Boosey and Hawkes medium bored trombone (AM1229), showing fully cut state with two previously removed annular bell sections.

Input Impedance Measurements

Figure 2 shows the measured input impedance curves for the uncut and fully cut states of the Boosey and Hawkes instrument. The input impedance is defined as

$$Z(f) = \frac{p_i(f)}{u_i(f)}, \quad (1)$$

where p_i is the acoustic pressure at the input and u_i is the acoustic volume velocity into the instrument for a sine wave input at frequency f . The input impedance peaks are close to the frequencies of the played notes on the instrument, although the peak frequencies would be slightly shifted if the normal mouthpiece were used.

The input impedance is closely linked to the way in which the player's lips interact with the instrument. Two features of Figure 2 are interesting in this respect. The removal of the final 33 mm reduces the length of the instrument by 2%, but it has a much smaller effect on the frequencies of the impedance peaks. The fourth peak, for example, has moved from 226.2 Hz to 226.8 Hz, a change of 0.3%; this corresponds to a pitch rise of only 5 cents, which is musically insignificant. A more important change can be seen in the heights of the impedance peaks above 500 Hz: the peak heights diminish much more rapidly with increasing frequency for the uncut instrument than for the fully cut instrument.

Pressure Transfer Measurements

Figure 3 illustrates the way that the pressure transfer function between the input and the radiated sound field depends on frequency. To show the global trends of the data, the mean square pressures were averaged over frequency bands with width 500 Hz and centre frequencies 300 Hz, 800 Hz, 1300 Hz, 1800 Hz, 2300 Hz, 2800 Hz, 3300 Hz, 3800 Hz and 4300 Hz. P_i and P_o are the square roots of the mean square input and output pressures respectively.

It is evident from Figure 3 that the on-axis transfer function is reduced significantly by cutting the bell for all but the highest frequencies measured. The change is much less noticeable for the off-axis measurements. The directional behavior of the radiation is more clearly seen in Figure 4, in which data from a selection of energy bands is plotted against angle. For the uncut trombone, the radiation is almost isotropic for the 300 Hz band, but becomes increasingly directed along the axis for higher frequencies. For the fully cut instrument, the radiation in the 800 Hz band is still almost isotropic, with a strong directivity along the axis evident only above the 1300 Hz band.

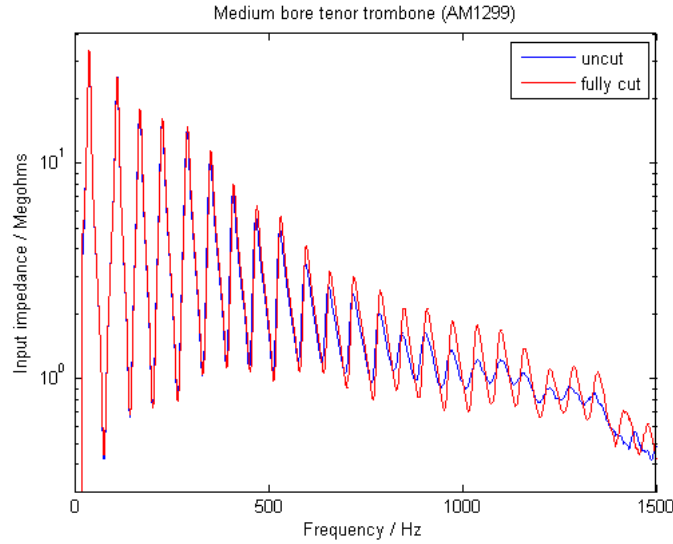


FIGURE 2: Input impedance magnitude for Boosey and Hawkes medium bored trombone (AM1229) with coupler.

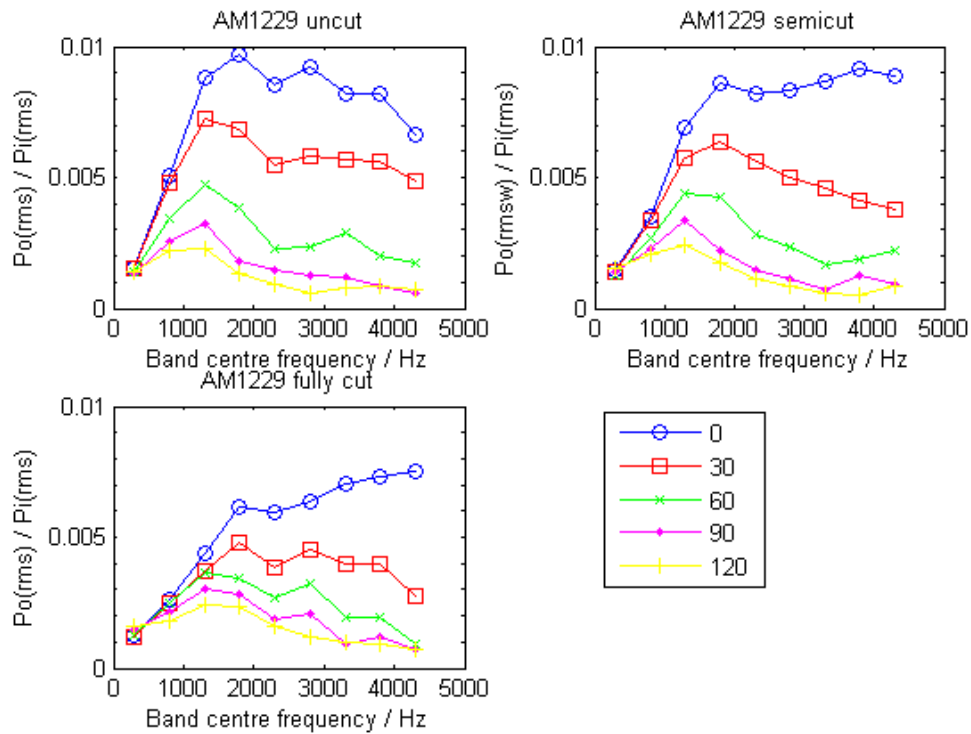


FIGURE 3: Pressure transfer function between the instrument input coupler and a point (r, θ) from the midpoint of the bell plane. $r = 50$ cm; parameter = θ (degrees). Boosey and Hawkes medium bored trombone (AM1229)

Radiated Power

One of the principal reasons for the increase in trombone bell diameters during the nineteenth and twentieth centuries was the desire for greater radiated power for moderate input pressures. To obtain an approximate estimate of the overall radiated sound power, the radiation field was divided into six sectors. The first sector included radiation angles from 0° to 15° ; it was assumed that P_o in this sector was equal to

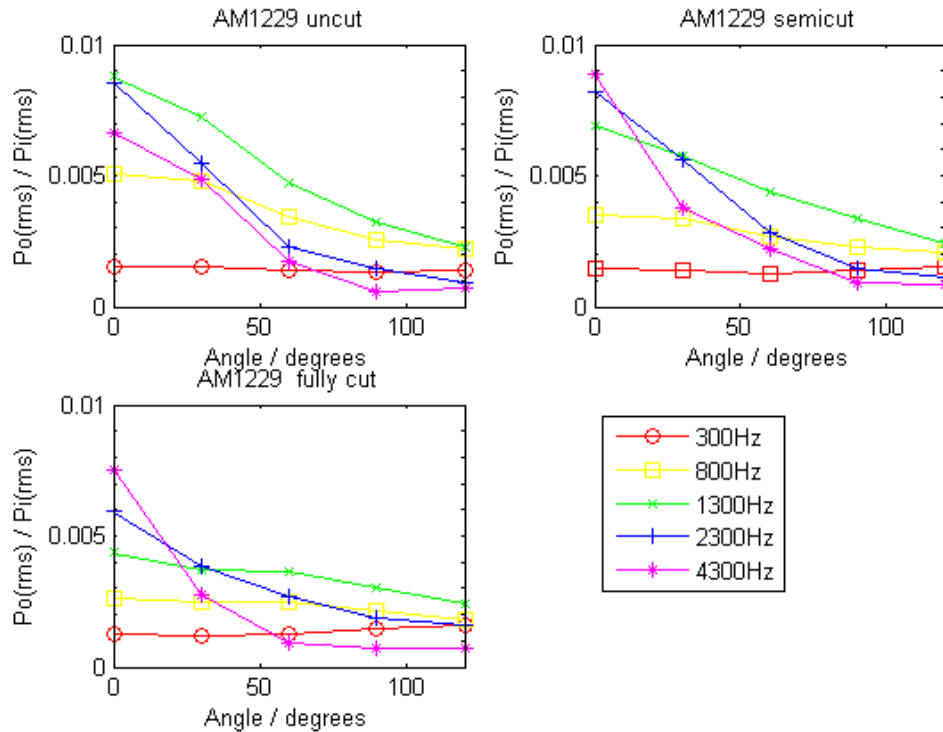


FIGURE 4: Pressure transfer function between the instrument input coupler and a point (r, θ) from the midpoint of the bell plane. $r = 50$ cm; parameter = centre frequency of 500 Hz frequency band. Boosey and Hawkes medium bored trombone (AM1229)

$P_o(0^\circ)$. The second sector included angles from 15° to 45° , and was assigned a uniform $P_o = P_o(30^\circ)$. The third, fourth and fifth sectors included angles from 45° to 75° , 75° to 105° , and 105° to 135° ; these were assigned P_o values $P_o(60^\circ)$, $P_o(90^\circ)$ and $P_o(120^\circ)$ respectively. It was assumed that radiation at angles greater than 135° did not contribute significantly to the total radiated sound power.

The relationship between radiated power and bell diameter is strikingly illustrated in Figure 5. For the uncut instrument the maximum estimated sound power for a 100 Pa input is 1.3 mW in the 1300 Hz band; for the fully cut instrument the maximum power is 0.7 mW in the 1800 Hz band.

ALEXANDER TROMBONE

The second trombone studied had a bell section by Alexander (AM0900), dating from the first half of the twentieth century. The original slide section was missing, and was replaced for the purposes of these measurements by the slide section of a Besson medium bore tenor trombone (EU3752). The Alexander bell had an exit diameter of 218 mm, significantly larger than the Boosey and Hawkes Imperial. It was reduced in three stages. A 15 mm section was removed, giving a bell exit diameter of 163 mm (“semicut”); then a 29 mm section was removed to reduce the diameter to 100 mm (“fully cut”). Finally, a 75 mm section was removed, taking the diameter down to 55 mm (“overcut”).

Pressure Transfer Measurements

Figures 6 and 7 illustrate the pressure transfer functions measured for the trombone with the Alexander bell. These curves show the same general features as those for the Boosey and Hawkes instrument. The on-axis transfer function for frequencies below 2000 Hz decreases as the bell diameter is progressively reduced, but (apart from the overcut case) the reduction is much less significant for off-axis radiation. For the uncut instrument with its large diameter bell, only radiation in the 300 Hz band is approximately isotropic,

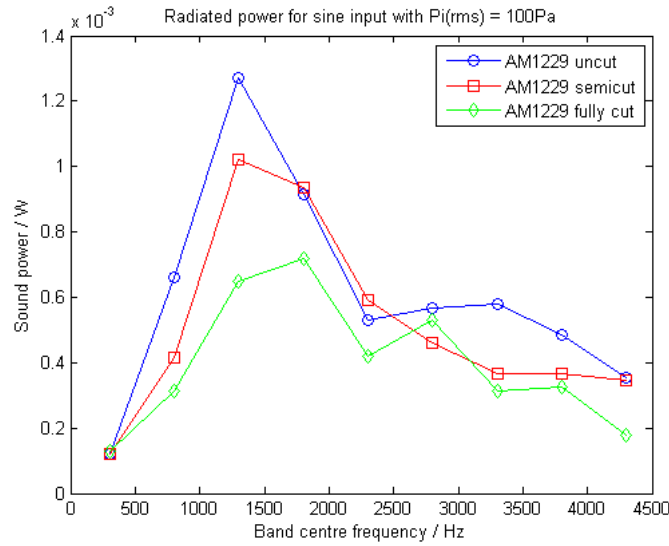


FIGURE 5: Radiated power for a sine wave input with rms pressure 100 Pa. Boosey and Hawkes medium bored trombone (AM1229)

but the concentration of radiation in the forward direction becomes progressively less marked as the bell diameter is reduced. For the overcut case, only the 4300 Hz band shows a marked directivity.

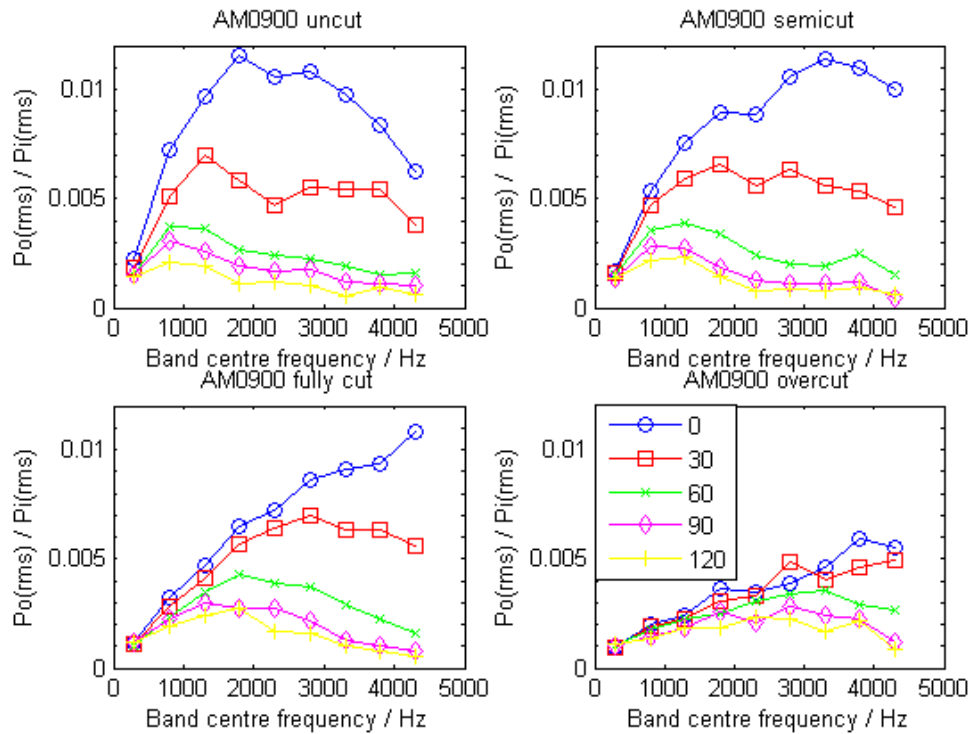


FIGURE 6: Pressure transfer function between the instrument input coupler and a point (r, θ) from the midpoint of the bell plane. $r = 50\text{ cm}$; parameter = θ (degrees). Alexander trombone (AM0900)

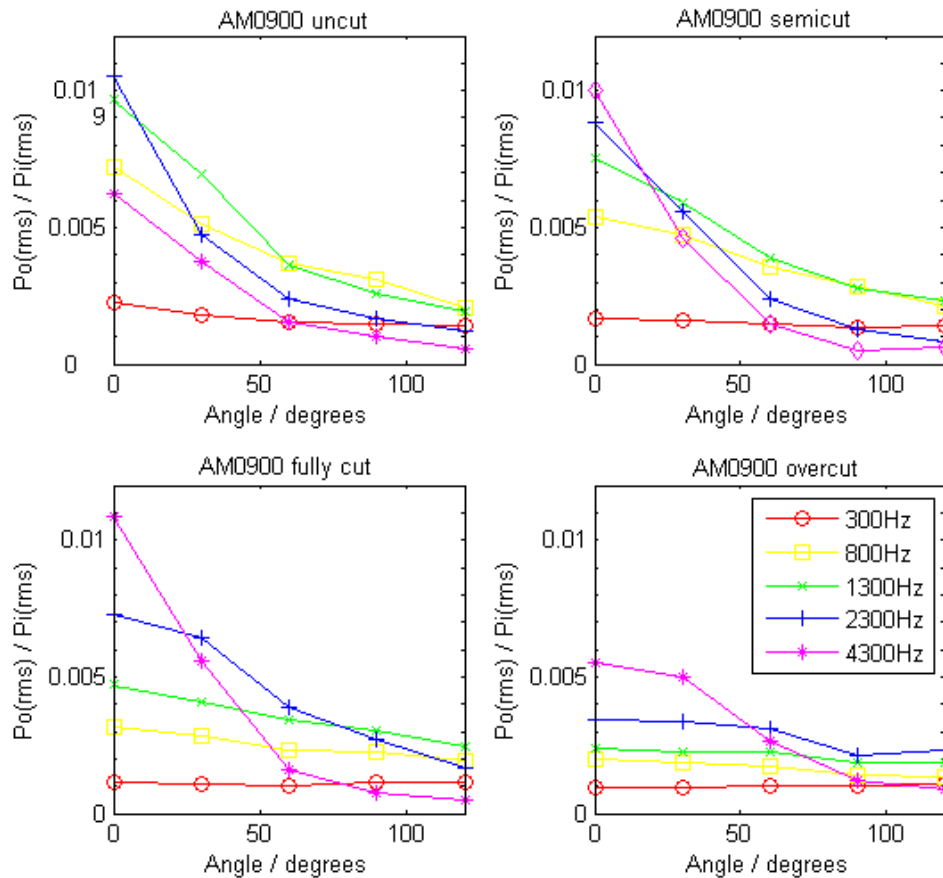


FIGURE 7: Pressure transfer function between the instrument input coupler and a point (r, θ) from the midpoint of the bell plane. $r = 50$ cm; parameter = centre frequency of 500 Hz frequency band. Alexander trombone (AM0900)

Radiated Power

The radiated power estimation for the Alexander bell resembles that for the Boosey and Hawkes instrument for the first three frequency bands, showing a progressive decrease in power as the bell diameter is reduced. There is, however, an interesting difference for higher frequencies. The reduction in the bell diameter has the effect of increasing the strength of off-axis radiation in the upper frequency bands. As a consequence, the sound power radiated by the fully cut bell in the 2800 Hz band is almost equal to that radiated by the uncut bell in the 1300 Hz band with an equal input pressure amplitude, although the fully cut bell area is only 21% of the uncut bell.

CONCLUSION

The exit diameters of the trombones measured in this study had very little influence on the frequencies of the input impedance peaks, but a reduction in bell diameter increased the heights of the peaks, most significantly in the frequency region above 700 Hz. This effect is related to an increase in the bell cutoff frequency with reducing diameter. An important musical implication is that the more prominent high frequency peaks in instruments with small bells make it easier to sound very high pitched notes with security of intonation.

The reduction in bell diameter resulted in a decrease in the pressure transfer function at low frequencies, although this could be accompanied by an increase in the pressure transfer function at high frequencies.

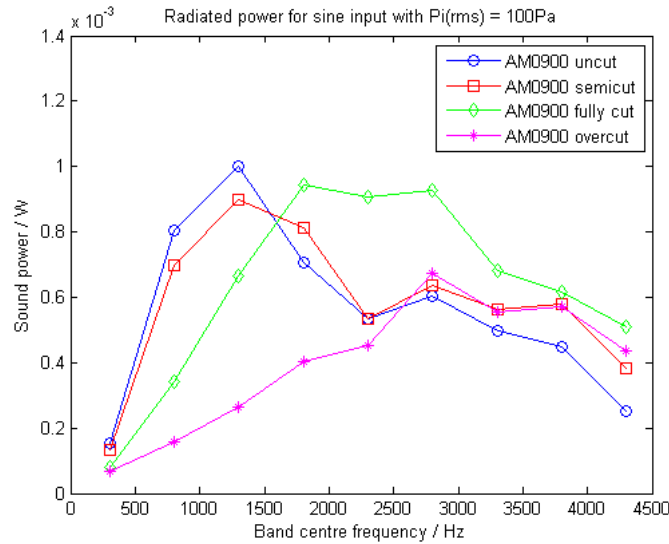


FIGURE 8: Radiated power for a sine wave input with rms pressure 100 Pa. Alexander trombone (AM0900)

Thus a large bell modern trombone is likely to have a more powerful but less bright sound than a small-belled instrument with otherwise similar bore profile.

For all the bells studied, the radiation at frequencies below 500 Hz was effectively isotropic. As the frequency was increased, the radiation was more and more directed along the bell axis, although for bells of diameter 100 mm this directivity was only pronounced for frequencies above 1000 Hz. These observations are consistent with a rule of thumb that the radiation can be considered approximately isotropic when the condition $ka \leq 1$ is satisfied, k being the wave number and a the bell radius.

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