EFFECTS OF NON-LINEAR PROPAGATION ON TIMBRE OF BRASS INSTRUMENTS

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1 INTRODUCTION

One characteristic feature of the orchestral brass instruments is the distinct change in timbre that occurs at the loudest dynamic levels. This noticeably 'brassy' sound is a result of an increase in energy levels of the higher harmonics. Musicians make use of this feature as an added form of musical expression, and listeners often describe the sound as 'bright'.

Sound production in brass instruments arises from a forced oscillation of the lips of the player. The lips act as a valve and modulate the flow of air through the mouthpiece and into the instrument. If the tube is of the correct length and bore profile then the oscillation becomes self-sustaining and is developed at one of the resonant modes of the instrument. Some of the energy from this resonance is transmitted to the atmosphere via the bell.

The behaviour of the lip-reed is highly non-linear because of the complicated relationship between the time-varying impedance of the lip-opening and the input impedance of the instrument[1,2] This can result in a significantly non-sinusoidal pressure waveform within the mouthpiece of the instrument. A more detailed explanation of the motion of the lip-reed is given by Campbell[3].

It is generally acknowledged that the reason for the onset of the brassy regime is a result of the non-linear progression of the acoustic wavefront along the bore of the instrument, as demonstrated by Hirschberg *et al*[4]. When high amplitude pressure oscillations are generated in the mouthpiece, the leading edge of the pressure wave steepens as the wave progresses. If the amplitude of the wave is large and the rise abrupt enough then the pressure rise may become near instantaneous for instruments with a sufficiently long air column. These 'shock-waves' give rise to an increase in the higher frequency components present within the sound. However, it is also predicted that an increase in the rate of change of pressure rise in the mouthpiece waveform will lead to increased brassiness of the instrument.

Recent work has attempted to correlate the brassiness of an instrument with the shape of its bore profile[5] and earlier work by this author investigated the motion of the lip-reed during 'brassy' playing[6].

2 EXPERIMENTAL PROCEDURE

Three instruments were investigated; two horns and a tenor trombone. Players (amateurs with extensive playing experience) were asked to sound pairs of notes at the same pitch but at two different dynamic levels: one clearly 'brassy' to the ear of the player, and the other 'non-brassy'. The radiated sound was recorded using a PCB microphone at a distance of one bell radius. A second PCB microphone with probe attachment was inserted into the mouthpiece of the instrument in order to capture the pressure waveform at the input to the instrument.

Two horns were chosen for the study in order to probe the effect of different instrument lengths. The first horn was a 1.7m F-alto horn, and the second a Bb horn with valves one and three depressed (giving a 3.6m F horn). The same pitch was played on both instruments. The tenor trombone was played in the first position.

Once the recordings were completed, they were transferred to computer and analysed using MATLAB. For each recording, frequency spectrum and spectral centroid were both calculated.

2.1 SPECTRAL CENTROID ANALYSIS

For a harmonic sound with harmonic components F_n each with pressure amplitude P_n we may define the spectral centroid of the sound as:

$$Spectral\,Centroid\,(Hz) = \frac{\sum_n F_n \times P_n}{\sum_n P_n}$$ **(EQUATION 1)**

The spectral centroid is measured in Hz and may be thought of as being analogous to the centre of mass; it is a measure of power distribution over frequency. Psychoacoustic testing has shown that the spectral centroid is strongly correlated with the brightness of the sound as perceived by a listener[7].

3 RESULTS

Figures 1 and 2 show typical recordings of both the mouthpiece pressure and the radiated sound of the note D4 on the tenor trombone for both 'brassy' and 'non-brassy' playing. For the mouthpiece pressure, the difference between 'brassy' and 'non-brassy' is subtle; the 'brassy' recording has a far higher amplitude, and a larger rate of change of pressure amplitude, but otherwise is not dissimilar to the 'non-brassy' recording. For the radiated sounds, it is clear that the 'brassy' notes are far less sinusoidal than their 'non-brassy' counterparts: one can easily identify the near instantaneous rises in pressure consistent with the idea of shock-waves forming within the bore of the instrument. This indicates that the majority of the timbral change occurs as the wave propagates through the instrument.

Figures 3 and 4 show the frequency spectra for these notes. Here, the differences between 'brassy' and 'non-brassy' mouthpiece pressures is more obvious; the second and third harmonic are more prominent in the 'brassy' case. For the radiated sounds, the differences between 'brassy' and 'non-brassy' playing are again startlingly clear. The 'non-brassy' recordings display a rapid decease in the intensity of the higher frequency harmonic components, with no significant peaks above 5kHz. The 'brassy' recordings, however, show only a 20dB drop-off over the same range, with significant harmonic peaks as high as 15kHz.

Figures 5 and 6 show pressure waveforms for both mouthpiece and radiated sound for the note F4 as played on the 1.7m F-alto horn in the case of both 'brassy' and 'non-brassy' playing. Figure 7 shows the radiated waveforms for the same pitch as played on the Bb horn (with valves one and three depressed). The 'brassy' mouthpiece pressure for the 1.7m horn demonstrates similar behaviour to that of the tenor trombone; the amplitude is increased and there appears to be a steepening of the pressure rise as compared to the 'non-brassy' case. Examination of the radiated sounds again shows a clear development of shock-waves within the bore of the instrument.

Frequency spectra of the note F4 as recorded on the two different horns are shown in figures 8 and 9. In the case of 'brassy' playing, there are clearly still significant harmonic peaks as high as 15kHz, whereas in the 'non-brassy' examples there are almost no harmonics present with frequencies greater than 2.5kHz.

It is interesting to compare the frequency spectra for 'brassy' playing of the same note as played on the french horn with two different lengths of tubing. The higher frequency harmonics drop off far quicker for the shorter instrument, with a difference of at least 10dB by 5kHz. This implies that the longer instrument will sound 'brassier' to the listener and is in agreement with the theory of shock-waves forming as the wave propagates through the instrument.

Spectral centroids for both mouthpiece pressures and radiated sound were calculated for all the recordings made and are shown in table 1. In all cases, the 'brassy' sounds have a higher spectral centroid than the 'non-brassy' recordings. The largest difference in centroids for both 'brassy' and 'non-brassy' playing is found in the radiated sounds; differences between mouthpiece centroids are several times smaller. This suggests that whilst the main source of the higher frequency components lies in the bore of the instrument, there are also more subtle effects that occur within the mouthpiece itself.

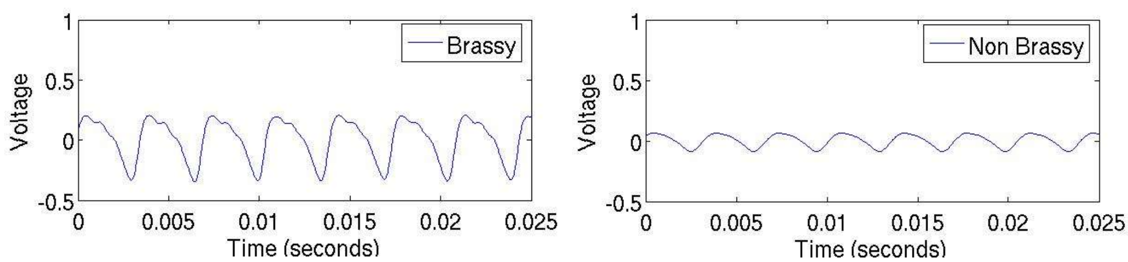

FIGURE 1: *Mouthpiece pressure waveforms for both brassy and non brassy sounds. Note D4, tenor trombone*

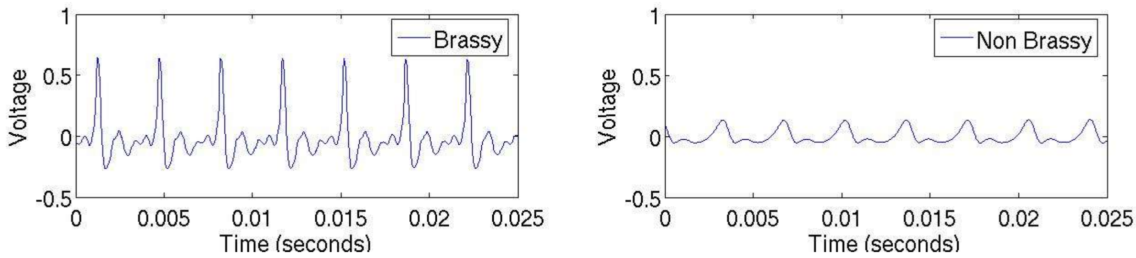

FIGURE 2: *Radiated sounds for both brassy and non brassy sounds. Note D4, tenor trombone*

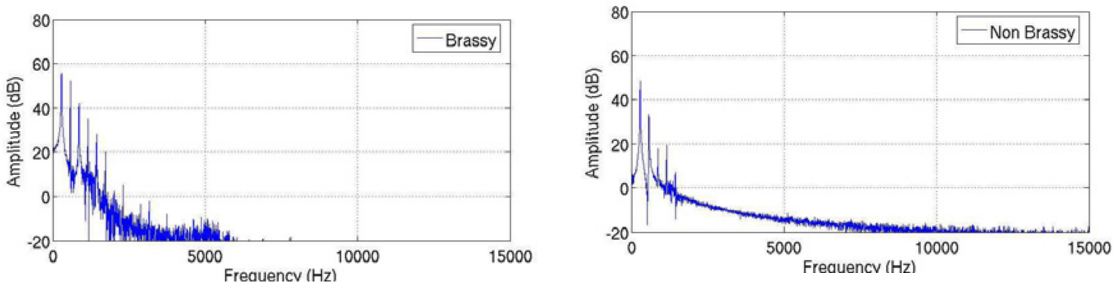

FIGURE 3: *Mouthpiece fourier spectra for both brassy and non-brassy sounds. Note D4, tenor trombone.*

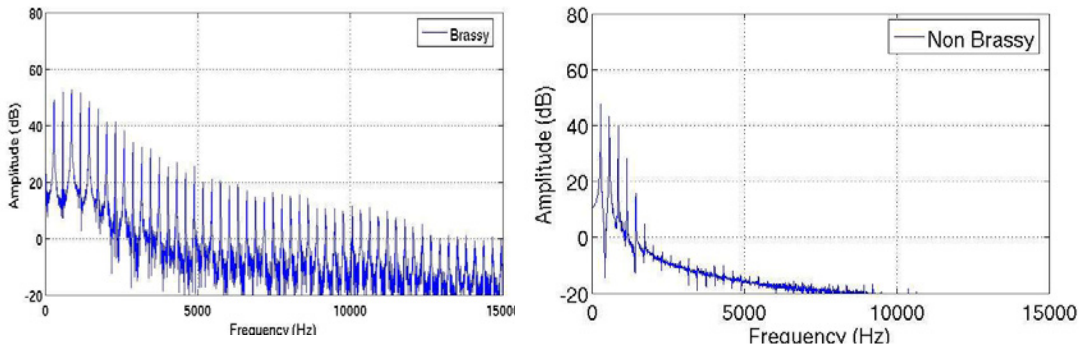

FIGURE 4: *Frequency spectra of radiated sound for brassy and non brassy playing. Note D4, tenor trombone.*

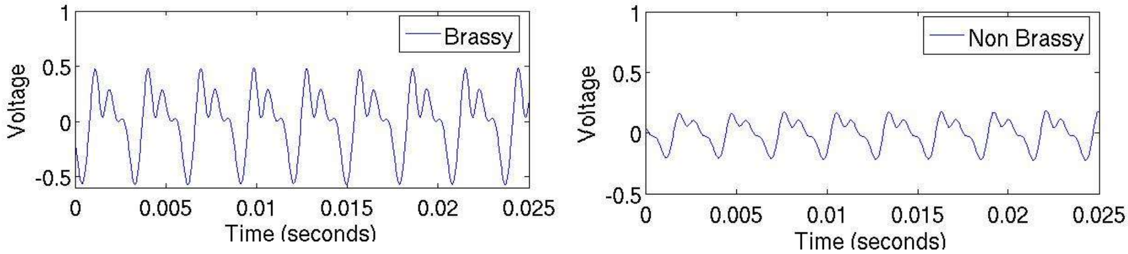

FIGURE 5: *Mouthpiece pressure waveforms for both brassy and non brassy sounds. Note F4, 1.7m F-alto horn*

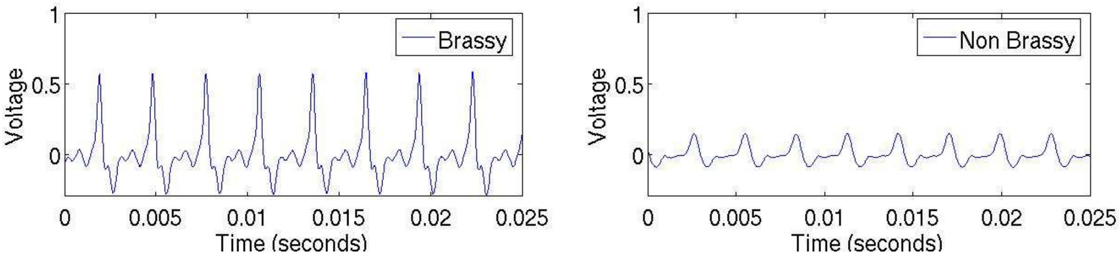

FIGURE 6: *Radiated sounds for both brassy and non brassy sounds. Note F4, 1.7m F-alto horn*

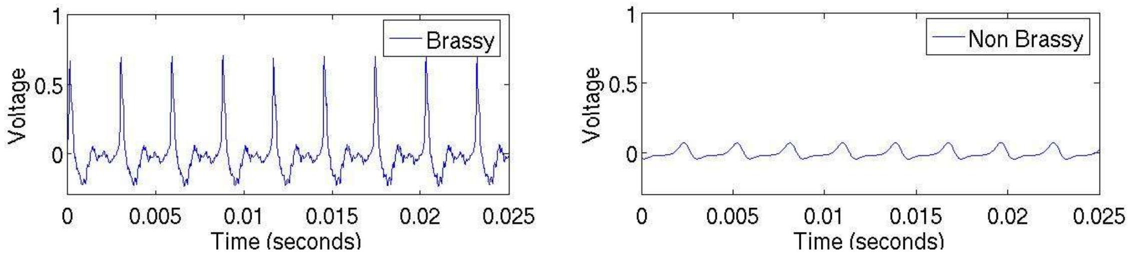

FIGURE 7: *Radiated sounds for both brassy and non brassy sounds. Note F4, Bb horn with valves 1+3 (3.6m F horn)*

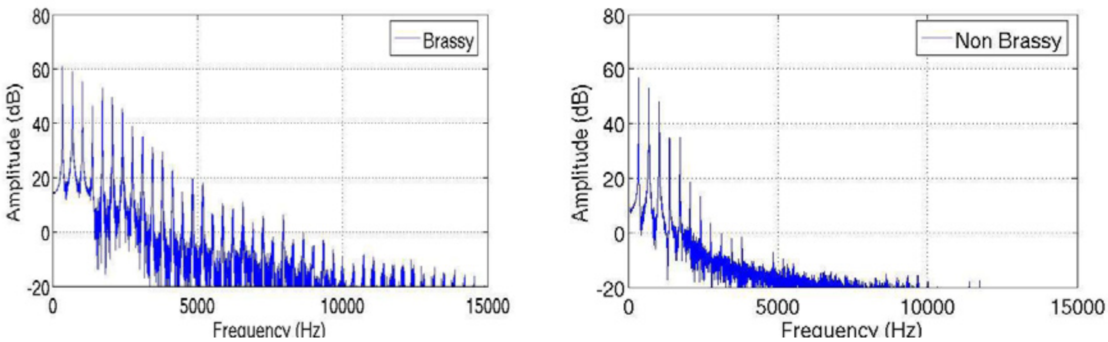

FIGURE 8: *Frequency spectra of radiated sound for brassy and non brassy playing. Note F4, 1.7m F-alto horn*

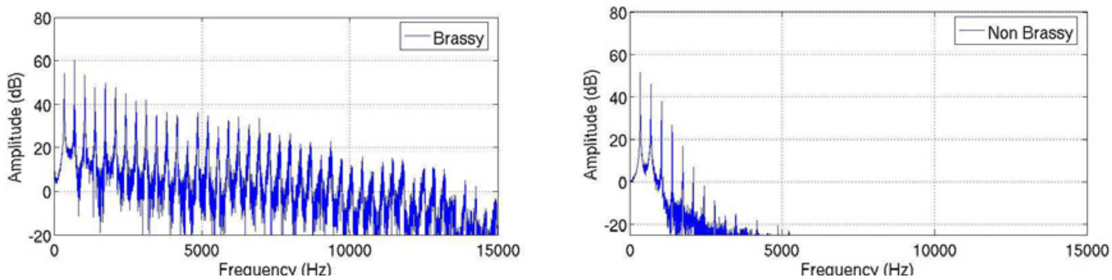

FIGURE 9: *Frequency spectra of radiated sound for brassy and non brassy playing. Note F4, Bb horn with valves 1+3 (3.6m F horn)*

	Spectral centroid: Brassy	*Spectral centroid: Non Brassy*
tenor trombone, note D4 (radiated)	1720 Hz	523 Hz
tenor trombone, note D4 (mouthpiece))	485 Hz	373 Hz
Bb horn 1+3 (3.6m F horn), Note F4 (radiated)	2461 Hz	593 Hz
Bb horn 1+3 (3.6m F horn), Note F4 (mouthpiece)	746 Hz	520 Hz
1.7m F-alto horn, note F4 (radiated)	1352 Hz	703 Hz
1.7m F-alto horn, note F4 (mouthpiece)	714 Hz	624 Hz

TABLE 1: *Spectral centroids calculated for both radiated and mouthpiece brassy and non-brassy sounds as recorded on different instruments.*

4 CONCLUSION

There are considerable differences in the sounds produced by orchestral brass instruments at different dynamic levels. The results obtained are consistent with the idea of non-linear propagation leading to development of shock-waves within the bore of the instrument. However, subtle differences in the form of the pressure in the mouthpiece for both 'brassy' and 'non-brassy' playing suggest that the characteristic timbre of brass instruments at extreme playing level also has a dependence on the form of the pressure input to the bore of the instrument.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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