WHY DO BRASS INSTRUMENTS SOUND BRASSY?

DM Campbell University of Edinburgh, Edinburgh, UK

1 INTRODUCTION

Orchestral wind instruments are categorized by musicians as belonging to two main families: woodwinds and brasses. These names suggest that the classification is made on the basis of the material of manufacture, but this is not the case. Flutes and saxophones, members of the woodwind family, are commonly made from metal rather than wood, and trombones made from plastic are now being successfully marketed. From the acoustical standpoint, the distinguishing feature of a “brass” instrument is not the wall material of its tubing but the fact that the sound generation mechanism is based on the vibration of the player's lips[1].

Although acousticians may prefer to describe trumpets, trombones and horns as “lip-excited wind instruments”, many players are convinced that the sound of these instruments is intimately related to the nature of the metal (usually brass) which forms the tubing and bell of the instrument. In particular, the characteristically bright timbre of a fortissimo note is often described as “brassy”. This paper reviews the acoustical factors which determine the sound quality and performance characteristics of lip-excited wind instruments. It is now understood that the physics of brass instrument behaviour depends critically on the nonlinear dynamics of the sound generation mechanism and the nonlinear nature of sound propagation in the bore of the instrument. Nevertheless, the bell of a brass instrument does vibrate when the instrument is blown, and recent work suggests that under some circumstances wall vibrations may result in a small but detectable contribution to the timbre.

2 TIMBRAL CHARACTERISTICS OF BRASS INSTRUMENTS

Although the members of the brass instrument family have many different shapes and musical functions, there are some common sonic features which can be identified as characteristic of the class. One of the most important is the way in which the timbre of a note played on a lip-excited instrument changes as the loudness of the note is increased. Figure 1 shows the spectrogram of the note F4 played on a tenor trombone. The duration of the note is around 4 seconds. At the start it is played quietly (musical dynamic *p*), and only the first three or four harmonics contribute significantly to the frequency spectrum. As the loudness is increased higher harmonics enter one by one. This spectral enrichment accelerates dramatically as the loudness approaches its maximum level (musical dynamic *ff)* which corresponds to the onset of the “brassy” timbre. At this level the harmonic content remains strong well beyond the 10kHz upper limit of the spectrogram shown in Figure 1.

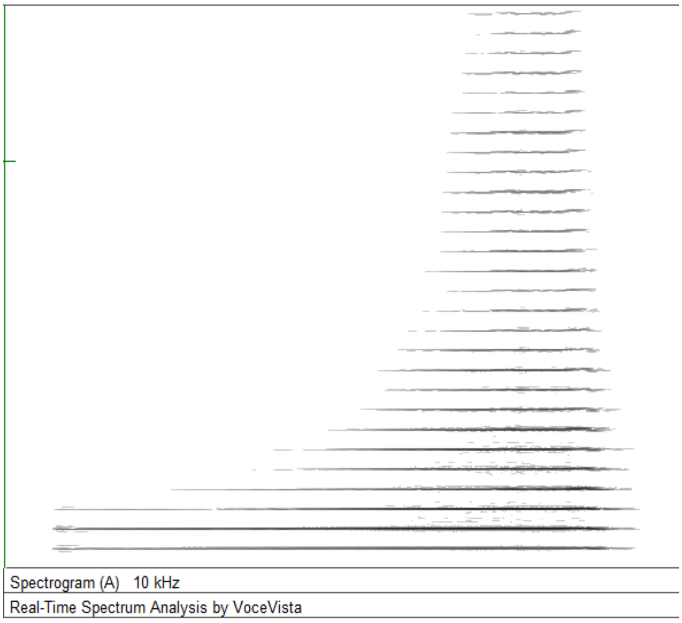

Figure 1: Spectrogram of a trombone playing a crescendo on the note F4.

While the gradual increase of spectral content with increasing loudness is a common feature of all brass instruments, the extent to which the timbre hardens into “brassiness” at the fortissimo level depends on the nature of the bore profile. For instruments with substantial lengths of cylindrical tubing, including trumpets and trombones, very loud playing is always “brassy”; however, instruments with predominantly conical bore, such as saxhorns and tubas, can reach their maximum dynamic level without displaying the dramatic increase of upper harmonic content associated with “brassy” timbre.

3 THE NONLINEAR LIP VALVE

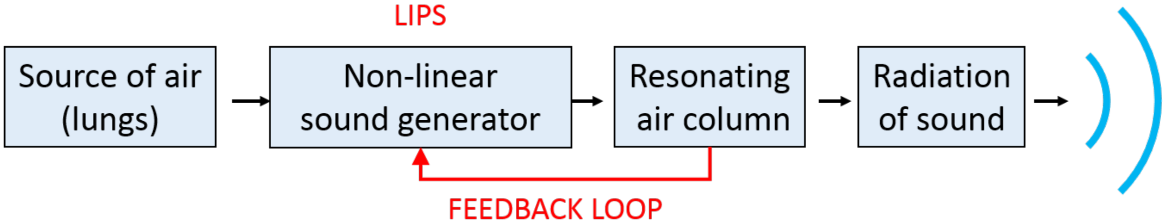

Figure 2: Schematic diagram of a lip-excited wind instrument.

Figure 2 illustrates schematically the acoustical functioning of a lip-excited wind instrument. The player's lips are pressed against a cup-shaped mouthpiece at the entrance to the tubing of the instrument. To a first approximation the lips can be modelled as a mass-spring system, with a characteristic lip resonance frequency determined by the muscles around the mouth. The player generates a pressure higher than atmospheric in the mouth, and allows air to flow through a small gap between the lips. When the mouth overpressure reaches a critical threshold level the lips start to oscillate, and the resulting variation of the open area modulates the flow of air into the instrument. If the lip resonance frequency is chosen to be close to one of the acoustic resonances of the instrument a standing wave builds up in the air column, with a pressure antinode in the mouthpiece.

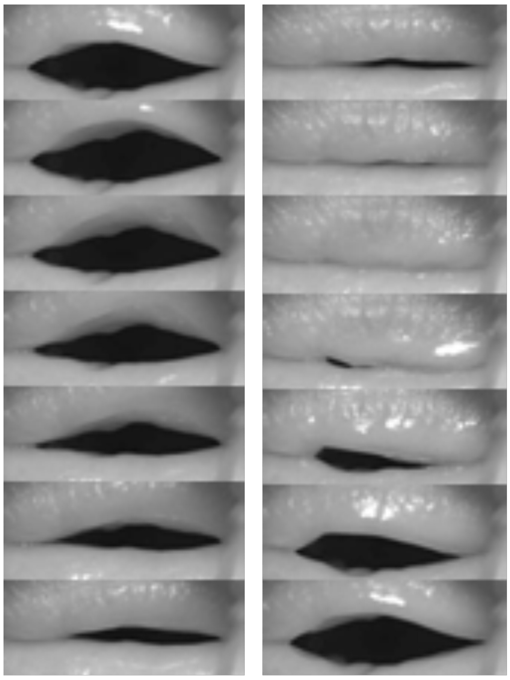

Figure 3: 14 stages in one complete cycle of closure and opening of a trombonist's lips[2]. Stages 1-7 from top to bottom, left column; stages 8-14 from top to bottom, right column.

At one time it was believed that the generation of harmonic content in the sound of a brass instrument was due to the complex waveform shape of the variation of open lip area with time. However experimental measurements using a transparent mouthpiece and high speed camera, such as those illustrated in Figure 3, have shown that the open area function is almost sinusoidal, and does not change significantly as the loudness of the played note increases[3].

The evolution of harmonics in the sound spectrum at low to medium dynamic levels is in fact a consequence of the nonlinear nature of the lip valve pressure-flow characteristic. For the simple lip model with only one degree of freedom the air flow u into the mouthpiece is given by the equation

$$u = F(p) = wh\left(1 - \frac{p_m - p}{h\mu_r\omega_r^2}\right)\left(\frac{2}{p}\right)^{1/2}(p_m - p)^{1/2}$$

where w and h are the width and height respectively of the lip opening, p_m the pressure in the player's mouth, p the pressure in the instrument mouthpiece, μ_r the effective lip mass per unit area and ω_r the lip angular resonance frequency. The strongly nonlinear nature of this equation has the consequence that, although the variation of open area $A = wh$ is approximately sinusoidal, the air flow into the instrument can have a rich harmonic spectrum. A full treatment of the nonlinear dynamics of the coupled system of lips and air column[4] shows that the harmonic content is expected to increase steadily with blowing pressure, in agreement with the behaviour shown on the left hand side of Figure 1.

4 NONLINEAR SOUND PROPAGATION

While the nonlinear pressure-flow relationship explains the spectral enrichment which occurs in brass instruments at low dynamic levels, it does not predict the dramatic rise in upper harmonic content which occurs in “brassy” playing. This is due to distortion of the wavefront of the sound propagating from the mouthpiece towards the bell of the instrument. When a brass instrument is played fortissimo the pressure amplitude in the mouthpiece can be of the order of 10kPa; at this dynamic level linear acoustics is inadequate to describe sound propagation. The local sound velocity increases with pressure, which means that the crest of an acoustic wave travels faster than the trough. The rising part of the pressure wave gradually steepens as the wave travels (Figure 4), and over a sufficiently long propagation distance the almost instantaneous pressure jump characteristic of a shock wave can appear.

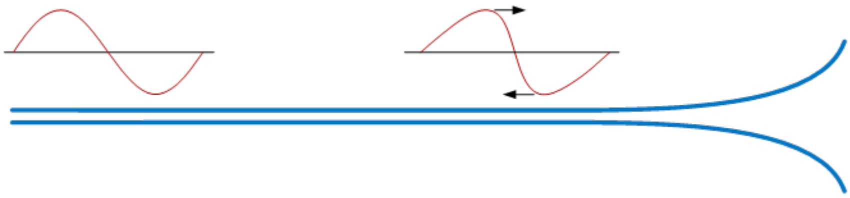

Figure 4: Illustration of the distortion of an initially sinusoidal pressure wave of high amplitude propagating from left to right in the bore of a straight trumpet.

The formation of shock waves in a trombone was demonstrated by Hirschberg et al. in 1996[5]. Below 1kHz the radiation efficiency of the bell of a trombone increases with increasing frequency; as a consequence, the pressure jump is effectively differentiated as it passes through the bell, introducing a sharp spike in the waveform of the radiated sound. The appearance of this spike is associated with the extended train of high harmonics perceived as a “brassy” timbre. A shock wave radiating from the bell of a trumpet is illustrated in Figure 5.

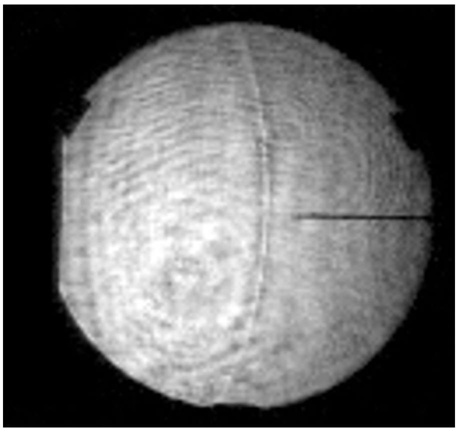

Figure 5: Image of a shock wave radiated from a trumpet bell (at left of picture). The trumpet was excited by a 700Hz sine wave, and the image obtained using Schlieren optics and high speed digital photography by Pablo Rendon of UNAM, Mexico.

5 CLASSIFYING BRASS INSTRUMENTS BY TIMBRE

Although the generation of shock waves is the most spectacular musical consequence of nonlinear sound propagation, it has become clear in recent years that more modest levels of distortion at dynamic levels well below fortissimo still play a significant role in determining the overall timbral characteristics of different types of instrument. It has been proposed that the relative rate at which nonlinear distortion develops in a given instrument could be used as a quantitative timbral parameter[6]. Almost all brass instruments start with a narrow entrance tube and gradually widen, ending often in a rapidly flaring bell. The rate at which nonlinear distortion develops in the initial part of the tube depends on the maximum rate of change of pressure with time at the input. If the tube remains cylindrical, the pressure amplitude will remain approximately constant as the wave travels along the tube, apart from losses due to viscothermal effects at the inner tube walls. The rate at which distortion develops will also remain high. In a section of tubing in which the diameter expands, however, the increase in the wavefront area will result in a reduction in the pressure amplitude, and the nonlinear distortion will develop more slowly. A cylindrical tube is thus expected to show more spectral enrichment than any realistic brass instrument of the same length with some degree of flare, and an instrument with a large fraction of cylindrical tubing will develop a "brassy" timbre at a much lower dynamic level than an instrument with a wide conical bore.

The effect of the bore profile on spectral enrichment has been quantified in terms of a "brassiness potential parameter" *B,* which depends only on geometrical measurements of the bore profile:

$$B = \frac{1}{L_{ecl}} \int_0^L \frac{D_0}{D(x)} dx$$

where D_0 is the entrance diameter, $D(x)$ is the diameter at a distance x from the entrance plane, and L_{ecl} is the equivalent cone length, a normalizing length based on the nominal playing pitch of the instrument.

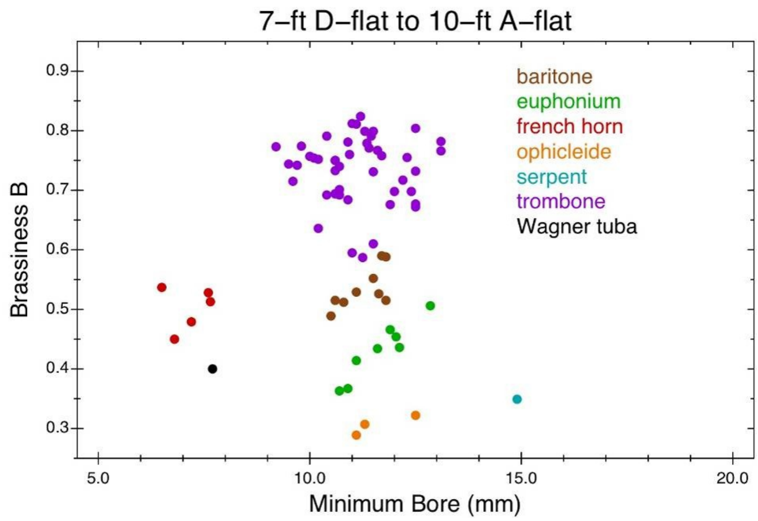

Figure 6: Different members of the brass instrument family plotted on a graph of brassiness potential parameter *B* against minimum bore diameter D_0. From Myers et al.[6]

The usefulness of the brassiness potential parameter in grouping the various members of the brass instrument family into sub-classes is illustrated in Figure 6. All of the instruments plotted have nominal playing lengths between 2m and 3m. The trombones are the highest group on this plot, reflecting the substantial lengths of cylindrical tubing in the slide sections of these instruments. The lowest instruments on the plot are the ophicleides, brass instruments from the first half of the nineteenth century with almost perfectly conical bores.

The parameter *B* is not entirely successful in predicting the relative degree of spectral enrichment. For example, the french horns are shown as having a slightly lower value of *B* in Figure 6 than the baritones (members of the saxhorn class), but in musical performance the french horn often achieves a very “brassy” sound while the baritone rarely does. One reason for this is that the french horn has a much smaller entrance diameter than the baritone: as a consequence, to generate a sound with the same radiated energy the player must generate a larger mouthpiece pressure amplitude in the french horn than in the baritone. Although the brassiness parameter values for the two instruments are similar, when a note of the same musical dynamic level is played on each the pressure wave starts with greater pressure amplitude in the french horn, and therefore the nonlinear distortion develops more rapidly.

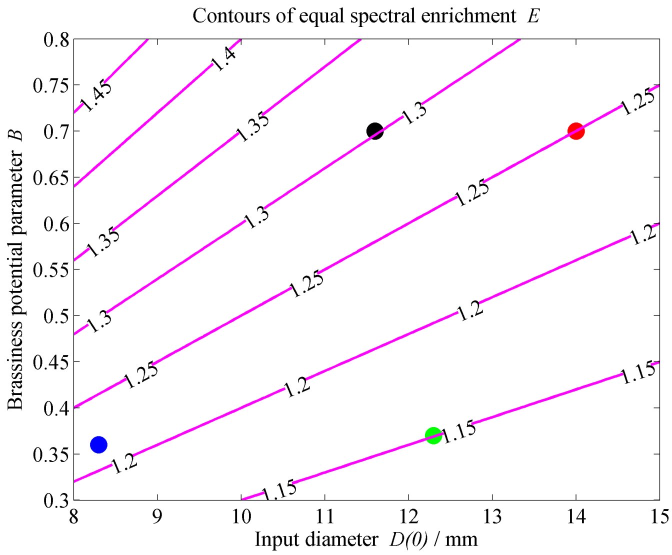

Figure 7: Plot of brassiness potential parameter against input diameter for four contrasting brass instruments: a narrow bore tenor trombone (black), a large bore bass trombone (red), a narrow bore Wagner tuba (blue) and a wide bore Kaiserbaryton tuba (green). Magenta lines are contours of equal spectral enrichment parameter.

A semi-empirical spectral enrichment parameter has recently been proposed[7] which estimates the rate of spectral enrichment taking into account both the relative bore profile and the absolute radial scale of the instrument. This parameter is defined by the equation

$$E(B, D(0)) = 1 + 5B/D(0).$$

In Figure 7 four instruments with very different types of bore are shown on a plot of *B* versus *D(0)*. Also shown on this graph are contours of equal spectral enrichment *E*. It can be seen that an instrument with a given value of *B* but a small input diameter is correctly predicted to have a higher rate of spectral enrichment due to nonlinear propagation than an instrument with the same value of B but a larger input diameter.

6 INFLUENCE OF WALL MATERIAL ON BRASS INSTRUMENT TIMBRE

The research reviewed in the previous sections has shown that the major characteristic timbral properties of brass instruments can be explained by the nonlinear nature of the pressure-flow relationship in the sound generating mechanism and by the nonlinear nature of sound propagation in the air column of the resonating tube. Although the large metallic bell on a trombone has a superficial resemblance to a loudspeaker cone, the “brassiness” in a trombone fortissimo is not caused by radiation from structural vibrations of the bell. Nevertheless, many musicians remain convinced that the type of metal used and the thickness of the wall in the bell of a brass instrument significantly influence the timbral character of the instrument.

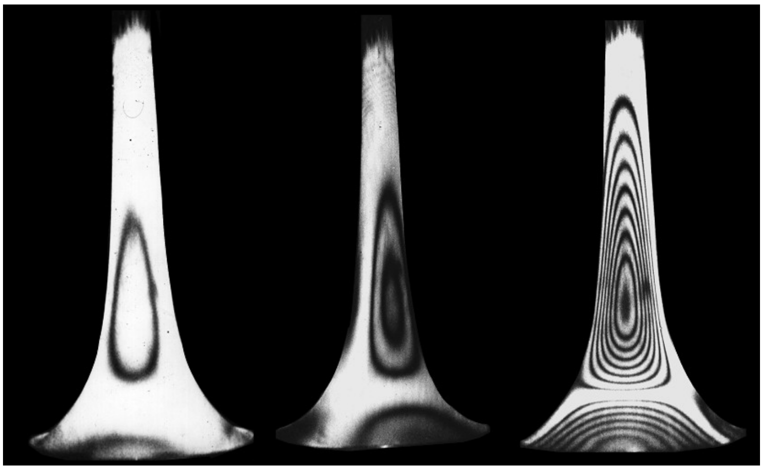

Figure 8: Holographic interferometry images of structural vibration modes of three trombone bells with the same bore profile and wall material but different wall thicknesses: 0.5mm (left), 0.4mm (centre), 0.3mm (right). From Smith (1986)[8].

Figure 8 reproduces holographic images of wall vibrations of artificially excited trombone bells obtained by Richard Smith in a classic experiment three decades ago[8]. These images provide graphic evidence that structural modes of brass instrument bells can be excited through coupling with the acoustic field in the air column, and that the amplitude of these modes (inversely proportional to the contour spacing) increases as the wall thickness diminishes. However this type of excitation can occur only if there is a near coincidence between an acoustic mode and a structural mode, so it is unlikely to have a global influence on the timbre of the instrument.

Recent work by Wilfried Kausel, Thomas Moore and colleagues[9] has explored a different type of structural mode, corresponding to a periodic expansion and contraction along the axis of the instrument. Finite element modelling has shown that this mode is capable of coupling to acoustic modes over a relatively wide frequency range[10]. Experiments have been carried out using instruments excited by an artificial mouth to examine the influence of wall material vibration on the radiated sound. Figure 9 shows the experimental arrangement used to selectively damp the wall vibrations of a french horn. The instrument is embedded in a large box inside an anechoic chamber, with the bell free to radiate through a circular hole in one wall of the box. When the box is filled with sand the wall vibrations of the bell are damped, and changes of the order of 2dB are observed in several of the frequency components of the radiated sound.

Experiments with an artificial mouth, a sand box and an anechoic chamber are of course a long way from the conditions in which brass instruments are normally performed, and further studies are required to investigate the extent to which wall vibrations influence the sound quality perceived by players and listeners in more realistic musical situations. A cautionary note is provided by the work of Richard Smith referred to in the discussion of Figure 8. Smith carried out a series of tests in which a number of professional trombonists compared the playing behaviour of trombones which differed only in the wall thickness of the bells. The players were blindfolded, and the instruments equally weighted to suppress tactile cues. Although variations of several dB were recorded in some radiated spectra, the musicians were unable to reliably distinguish between the instruments. After thirty years, the perceptual significance of wall vibrations in brass instruments is still a hot topic!

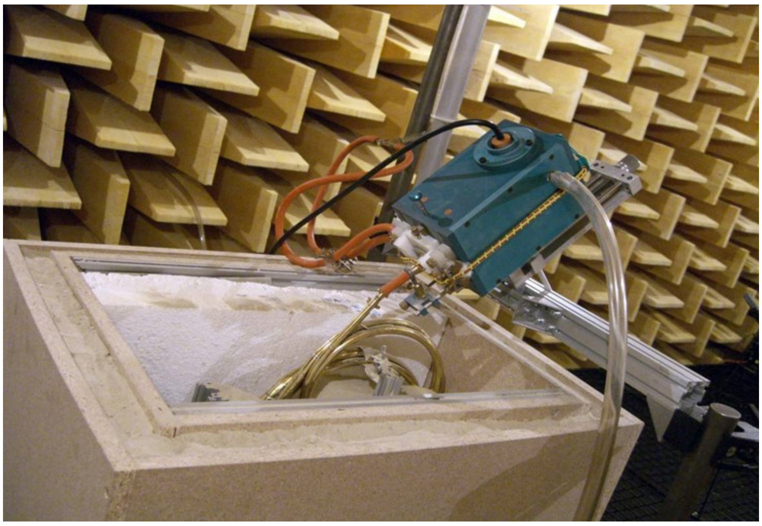

Figure 9: Experimental arrangement for damping wall vibrations in an artificially excited french horn. Picture courtesy of Wilfried Kausel, Musical Acoustics Laboratory, University for Music and Performance Studies, Vienna.

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