WHAT'S THE DIFFERENCE? PREDICTING AND CHARACTERISING TIMBRAL DISTINCTIONS BETWEEN FAMILIES OF BRASS INSTRUMENTS

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1 INTRODUCTION

The common instruments of Western music can be broadly classified as either strings, woodwinds, brass, or percussion. This paper is concerned with the third of these classes. Although the description "brass" reflects the fact that most of the members of this class are manufactured from brass or some similar alloy, the distinguishing feature of a brass instrument is that the sound is generated by the vibration of the player's lips pressed against an entrance hole or mouthpiece. The word "labrosone" (literally "lip-sound") has been coined as a more scientifically based generic name for a brass instrument.

The labrosone class incorporates many families of instruments, each with characteristic distinguishing properties. From the musical point of view, the timbre or tone quality of an instrument is one of its most important features, and timbral differences play a vital role in distinguishing between different families of brass instrument. One particular aspect of timbre – the increase in the brightness of the sound which occurs during a crescendo – is so characteristic of brass instruments that the sound of a very loud and bright note is often described as "brassy".

In Section 2 of the paper the generation of brassy timbre by nonlinear sound propagation inside the instrument is described. A brassiness potential parameter, which can be calculated from knowledge of the bore profile, is defined, and its usefulness in characterising the different timbres of different brass families is illustrated. In Section 3 the influence of the absolute radial scale of the instrument is discussed, and several approaches to a more general spectral enrichment parameter are reviewed.

2 "BRASSINESS" OF BRASS INSTRUMENTS

2.1 Timbral Distinctions Between Brass Families

Figure 1 illustrates frequency spectra measured 50cm from the bell of a trombone on which the note B♭3 was being played. In the upper graph the dynamic level was pianissimo *(*very quiet): the first harmonic is the strongest frequency component, and only the first few harmonics contribute sigificantly to the sound. A dramatic contrast is provided by the lower graph, in which the dynamic level was fortissimo (very loud): the strongest component is now the fourth harmonic, and a significant retinue of harmonic components continues up to (and beyond) 20kHz.

The increase in the relative amplitude of high frequency components as the dynamic level rises, described as spectral enrichment, is characteristic of all brass instruments. The degree of spectral enrichment varies among the different families of labrosones, and is in fact one of the main factors which distinguishes one family from another. French horns, for example, display a high level of spectral enrichment, while the saxhorns which are important components of a traditional brass band have relatively low spectral enrichment.

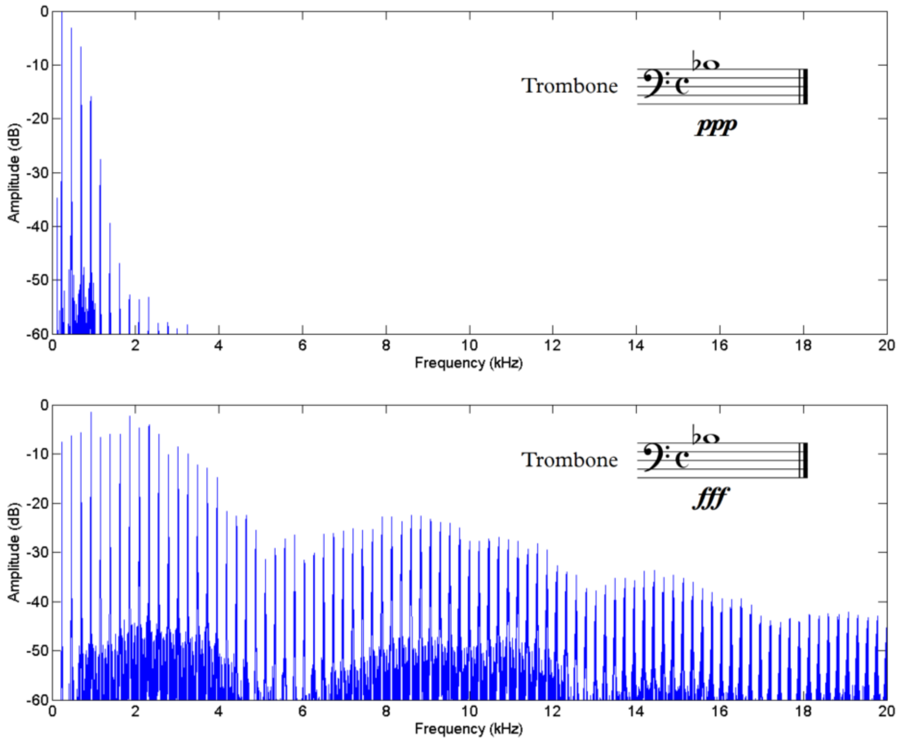


Figure 1: Spectra of a trombone note played very quietly (upper graph) and very loudly (lower graph), illustrating increase in spectral enrichment with increased loudness.

2.2 Nonlinear Propagation and Brassiness

A major factor in determining the rate of spectral enrichment in brass instruments is the nonlinear nature of sound propagation in the tubing of the instrument.[1,2] The sound pressure level generated in the mouthpiece of a loudly played brass instrument can exceed 10kPa, which is 10% of atmospheric pressure. At such high levels the linear approximation to the acoustic wave equation is inadequate, and the local speed of propagation is not independent of the acoustic particle velocity. As illustrated in Figure 2, the crest of an initially sinusoidal wave travels faster than the trough, resulting in a gradual increase in the time rate of change of the rising pressure.

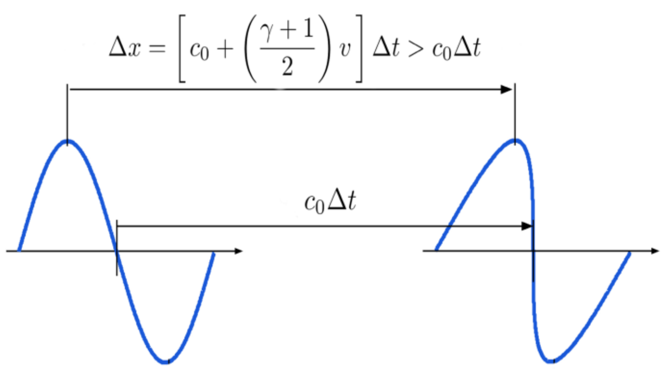


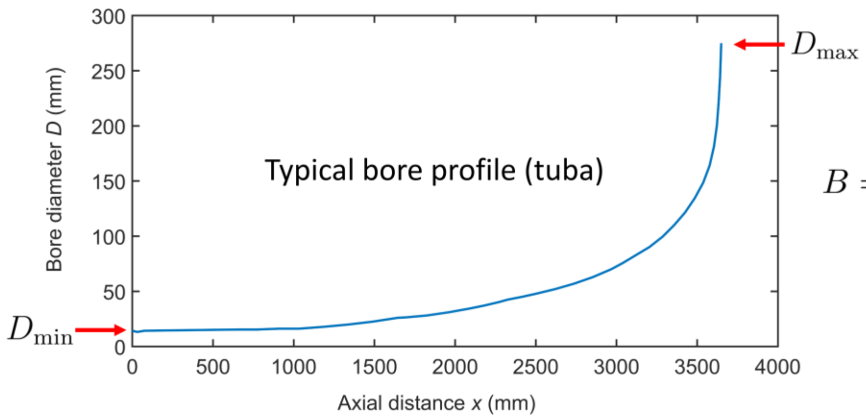
Figure 2: Illustrating nonlinear distortion of a high amplitude sine wave propagating from left to right. c_0 = linear speed of sound. v = acoustic particle velocity. Δx = distance travelled by a point on the wave in time Δt. γ = specific heat ratio.

If propagation continues for a distance described as the shock length, the rate of pressure rise approaches infinity, and a shock wave is generated inside the instrument tube. This wave has a characteristic N shape in the time domain. When it reaches the bell of the instrument, the transformation from internal to external sound fields has a filtering effect similar to time differentiation, and the resulting sound resembles that of a train of very narrow pulses. This is the hard, bright sound described as “brassy”.

2.3 Effect of Bore Profile on Spectral Enrichment

In a cylindrical tube, the pressure amplitude remains constant as the wave propagates (neglecting losses). The rate of wave steepening is therefore also constant. In a tube which flares outwards, like a trumpet bell, the pressure amplitude diminishes as the wave progresses, and the rate of distortion also falls.

The brassiness potential parameter *B*, defined in Figure 3, provides a quantitative measure of the extent to which the nonlinear wave steepening in a tube with length *L* and bore profile *D*(*x*) is reduced in comparison with a cylinder of the same effective length.[3]



$$B = \frac{1}{L_{\mathrm{ecN}}} \int_0^L \frac{D_{\mathrm{min}}}{D(x)} dx$$

Figure 3: The brassiness potential parameter *B* compares the nonlinear distortion of a sine wave in a tube of total length *L* and minimum bore diameter D_{min} with the distortion in a cylindrical tube of the same effective length L_{ecN} and constant diameter D_{min}.

2.4 Bright and Mellow Brass Instruments

Within the broad class of brass instruments, a distinction is often drawn on timbral grounds between two sub-classes: the “bright” instruments, such as the trumpet and trombone, and the “mellow instruments”, such as the flugelhorn and the euphonium. The brassiness potential parameter *B*, which can be calculated straightforwardly from measurements of the bore profile, helps to understand the different characters of these two sub-classes. The plot in Figure 4 shows the result of measurements on a large number of trumpets and flugelhorns. These instruments have similar tube lengths (around 1.5m), and broadly equivalent playing registers.

Figure 4 is a scatter plot, with the horizontal axis representing the minimum diameter of the instrument and the vertical axis representing its brassiness potential parameter. The two families of instruments occupy distinct areas in the plot. As expected, the “bright” trumpets have higher *B* values than the “mellow” flugelhorns. There is, however, a large range of values of *B* values within each family. There is also evidence of a correlation between the *B* and D_{min} values, particularly among the trumpets. This suggests that the timbral characteristic which defines a trumpet musically may depend not only on the relative bore profile (which determines *B*), but also on the absolute radial scale (related to D_{min}). The role of radial scale will be discussed in Section 3.

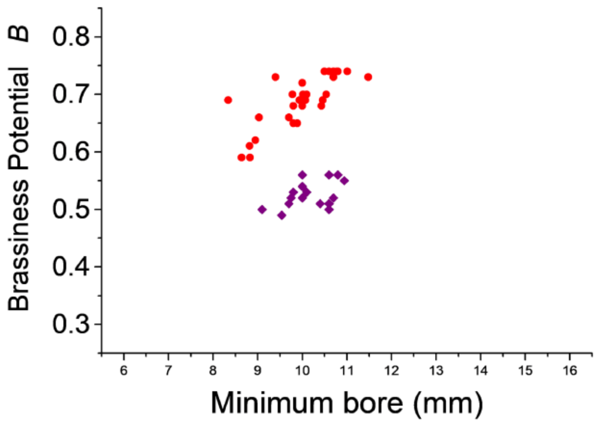


Figure 4: Scatter plot of brassiness potential parameter *B* against minimum bore diameter D_{min} for typical trumpets (orange circles) and flugelhorns (magenta diamonds).[2]

3. EFFECT OF RADIAL SCALE ON SPECTRAL ENRICHMENT

3.1 Narrow Bore and Wide Bore Instruments

The brassiness potential parameter *B* is determined by the rate at which the tube diameter expands from the input to the output. Instruments which flare outwards at the same rate, but from different input diameters, will have the same value of *B.* It is not true, however, that the rate of spectral enrichment is independent of radial scale.[4] Musical experience shows that narrow bored instruments develop a brassy timbre at a lower dynamic playing level than wide bored instruments with a similar bore profile. A particularly striking example is provided by a comparison of the narrow bored orchestral trombones used by British and French orchestras in the early twentieth century and the wide bored instruments now in use. The narrow bored trombone, affectionally known as the "peashooter", is capable of developing a bright, brassy edge to the sound which can only be achieved on a wide bored modern trombone at a much higher dynamic level.

3.2 A Single Spectral Enrichment Parameter?

Is it possible to combine the effects of the relative flaring and the absolute radial scale of the bore into a single parameter, calculated from bore profile measurements, which can predict the degree of spectral enrichment in the sound of the instrument? In a semi-empirical approach to this goal, simulations of nonlinear propagation have been carried out using bore profile data measured on a very large corpus of brass instruments, many of which are in major musical instrument museums. To avoid complications arising from internal reflections within the instrument, the simulations used sinusoidal excitation with a frequency higher than the bell cutoff frequency of the instrument in question. The degree of spectral enrichment is defined as the spectral centroid of the output sound at a defined dynamic level. The aim is to find a parameter *E* which correctly predicts the degree of spectral enrichment from knowledge of *B* and a characteristic radial scale length D_c.

A first attempt at a suitable formula[5] is illustrated in Figure 5. The characteristic radial scale length is taken to be the minumum diameter D_{min}. Figure 5 shows a scatter plot for a large number of instruments with tube lengths around 3m.[6] Contour lines of equal predicted spectral enrichment E_1 do appear to capture the expected timbral musical distinctions. “Bright” trombones are clearly separated from “mellow” euphoniums on the scatter plot. French horns and trombones have similar values of predicted spectral enrichment, even though the brassiness potential parameter values for the french horns are much lower than those for the trombones. However the fit between simulated and predicted values of spectral centroid was not acceptable for all the instruments studied.

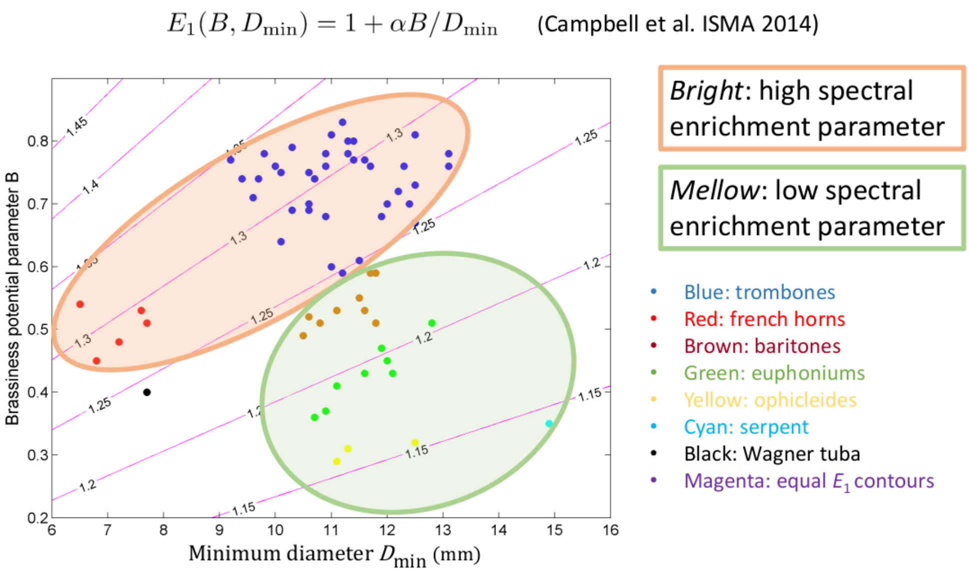


Figure 5: Scatter plot of brassiness potential parameter *B* against minimum bore diameter D_{min} for trombones and instruments of similar effective length. Magenta lines show contours of equal spectral enrichment parameter E_1

3.3 Theoretical Explanation for Radial Scale Effect

A trombone player controls the pressure amplitude p_{in} at the input to the instrument in order to create an output pressure p_{out} in the radiation field corresponding to a specified dynamic level. The pressure transfer function T = p_{out} / p_{in} increases with increasing radial scale. The input pressure required for a fixed output dynamic level will therefore be less in a wide bore instrument than in a narrow bore instrument, and the wide bore instrument will have less spectral enrichment than the narrow bore instrument.

A second attempt at a spectral enrichment parameter [7] replaced the characteristic radial scale length by the transfer function *T* derived from simulation:

$$E_2 = 1 + B / (100T).$$

The fit between simulated spectral centroids and values estimated from E_2 was satisfactory for a small number of instruments, but this method did not provide an estimation method which could be easily used without extensive computation. In Section 3.4 a new approach is outlined which approximates the transfer function by the square of a characteristic radial scale length.

3.4 A Simplified Spectral Enrichment Parameter for Practical Use

An approximate estimate of the absolute radial scale is made by taking the geometric mean of the input and output diameters:

$$D_{gm} = (D_{min}.D_{max})^{1/2}.$$

A new semi-empirical formula provides an acceptable fit between simulated and estimated values of spectral enrichment for instruments with tube lengths around 1.5m:

$$E_3 = 1 + 545B / (1000D_{gm})^2.$$

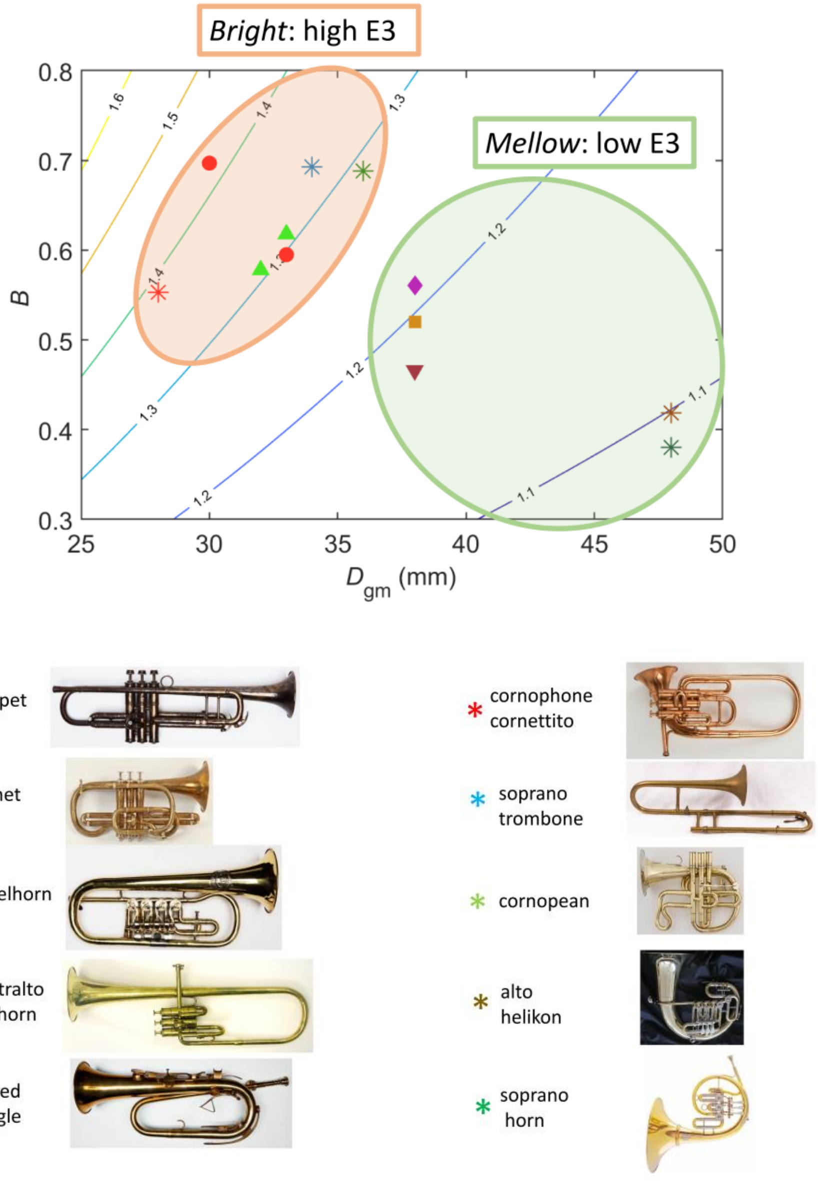


Figure 6: Scatter plot of brassiness potential parameter *B* against radial scale factor D_{gm} for trumpets and Instruments of similar effective length. Magenta lines show contours of equal spectral enrichment parameter E_3

Figure 6 shows a scatter plot including a number of instruments from recognised brass instrument families (shown by solid markers), together with a number of more unusual instruments (shown by asterisks). The trumpets are, as expected, clearly in the sub-class of bright instruments. The cornets, which play an important role in the brass band, are not clearly distinguished from the trumpets, and are also classed as bright. The flugelhorn, saxhorn, and keyed bugle come into into the mellow category, in accord with musical judgments of timbre. Interestingly, the *B* value for the flugelhorn is only slightly less than for one of the trumpets: its mellow character is due more to its comparatively large radial scale than to the shape of its relative bore profile.

The scatter plot can also be used to predict the musical behaviour of instruments which do not fall into any of the recognised brass instrument families. This is potentially useful in understanding and classifying museum specimens and other historic instruments, which may well be unplayable because of damage or conservation requirements. The cornophone cornettito, shown by the red asterisk in Figure 6, is clearly a bright instrument, with a value of E_3 intermediate between those of the two trumpets. The soprano trombone (blue asterisk) and the cornopean (light green asterisk) are also unambiguously bright. The alto helikon (brown asterisk) and the soprano horn (dark green asterisk) are two curiosities which are extremely mellow.

4. CONCLUSION

The physics underlying the spectral enrichment in loudly played brass instruments is extremely complicated, and many factors which could affect the detailed timbral behaviour of a specific instrument are not taken into account in the simplified model underlying the semi-empirical approach described here. The most important additional factor is probably the viscothermal wall losses which drain energy from a sound wave propagating in a brass instrument tube. Since these losses increase with increasing frequency, they are expected to reduce spectral enrichment, and their effect could be significant in very narrow bored sections of tubing.

The numerical factor in the definition of E_3 given above was derived from preliminary measurements on 1.5m long instruments. Further studies will be required to establish the applicability of a formula of this type over the wide range of different families, effective lengths and radial scales which are found in the very diverse and fascinating world of brass instruments.

5. REFERENCES

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