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BRASSINESS AND THE UNDERSTANDING OF BRASS INSTRUMENTS

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ABSTRACT

The concept of Brassiness Potential, introduced in 2007 as a parameter related to the timbre of brass musical instruments, has proved useful in brasswind taxonomy. The timbre of a wind instrument depends mainly on the properties built into the instrument by the maker, the actions of the player, and the ambient room acoustics. In the case of brass instruments, the properties of the instrument itself that determine its contribution to timbre are primarily those of its bore profile, an important characteristic of which is its potential to engender non-linear propagation of acoustic energy over the length of the instrument from mouthpiece to bell, especially at high dynamic levels. This paper briefly reviews the definition of the brassiness potential parameter and discusses its utility in the acoustics-related classification brass instruments, taking as an example the differences (past and present) between trumpets and cornets. The theoretical basis for brassiness potential and its exploitation in detail will be a feature of the forthcoming book by the present authors *The Science of Brass Instruments* (Springer 2020): the paper includes a short discussion of its treatment in the book.

1. INTRODUCTION

‘Brass instruments make brassy sounds’. This commonplace description of the most characteristic timbral feature of brass instruments is even more pithy in French: ‘les cuivres cuivent’. Brassiness is apparently the essence of the listener’s perception of the unique sound of brass instruments, since the very word is borrowed from the name of the instrument family.

Since 1997 the three authors of this paper have been collaborating in research on brass instruments. One fruit of that collaboration has been the preparation of a textbook on the science of brass instruments, which will be published at the end of 2020 [1]. An important aim in this work has been to clarify both the scientific basis and the musical significance of the concept of brassiness. The relevant aspect of brass instrument sound production is the way in which the spectral content of a note changes during a crescendo. At low dynamic levels the energy in a brass note spectrum is concentrated in the first few harmonics. As the level rises, upper harmonics become increasingly important, and at a high level the sound develops a hard, brilliant sound in which there is strong harmonic content up to and even well beyond the frequency threshold of audibility. ‘Les cuivres cuivent!’, exclaim the listeners.

A crucial advance in understanding the nature of brassiness was the realisation [2] and experimental confirmation [3] that the extreme spectral enrichment in very loud brass playing was the consequence of distortion due to nonlinear sound propagation in the internal air column of the instrument. This concept proved useful in quantitative comparisons and classifications of brass instruments through the use of a brassiness potential parameter derived from bore profile measurements [4], [5], [6].

The theoretical background to nonlinear propagation in brass instrument tubes is briefly reviewed in Section 2 of this paper, and the definition of the brassiness potential parameter is explained in Section 3. The desirability of a single spectral enrichment parameter which takes into account the effects of both radial scale and viscothermal losses is discussed in Section 4. In Section 5 the musical insights which this type of study can bring are illustrated by a discussion of a question frequently debated by brass players: are the two most common soprano brass instruments, the trumpet and the cornet, really two different instruments with distinct musical personalities?

2. NONLINEAR DISTORTION IN BRASS INSTRUMENTS

The high acoustic pressure amplitude which is generated inside a brass instrument when it is played loudly induces adiabatic fluctuations in air temperature. This results in a local unsteady increase in the speed of sound c in the compression part of the propagating pressure wave, since the speed of sound in air is proportional to the square root of the absolute temperature. Small perturbations therefore propagate with increased velocity c compared to the average speed of sound c_0 . For outgoing acoustic waves the pressure increase also induces a particle velocity v in the direction of propagation of the pressure wave. The expansion part of the wave is slowed down by the same physical effects, and is gradually overtaken by the fast compression part of the wave. The resulting steepening of the wavefront is illustrated in Fig.1.

The equation for the speed of travel of a defined point on the wave is

$$\frac{dx}{dt} = c_0 + \left(\frac{\gamma + 1}{2} \right) v. \quad (1)$$

The steepness of the wave is measured by the time rate of change of the pressure rise, which tends to infinity after a critical distance L_s . At this stage the disturbance is classed as a shock wave.

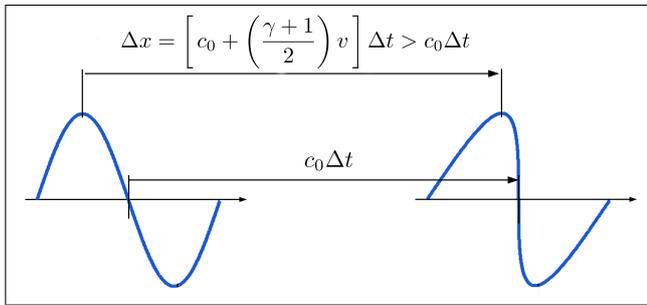


Figure 1. Illustrating the effect of nonlinear propagation on an initially sinusoidal wave travelling from left to right

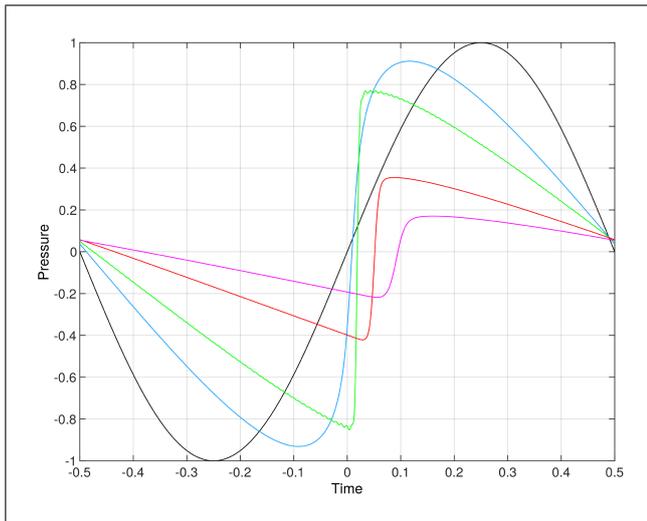


Figure 2. The distortion of an initial sine wave as a function of the propagation distance

The progressive development of nonlinear distortion during the propagation of an initially sinusoidal wave is shown in Fig.2, which is based on a calculation including the effects of viscothermal losses. The black line represents the original undistorted sine wave. The partially distorted shape of the wave after it has travelled some distance is illustrated by the blue line. Unlike water waves at the sea shore, where the peak of the surface water wave overtakes the trough and the wave breaks, the compression wave cannot actually overtake the expansion wave. The green line represents the wave after it has travelled the distance L_s , described as the shock length: the time rate of change of pressure has become theoretically infinite, marking the formation of a shock wave. Beyond ‘infinity’ the wave retains the basic ‘N-wave’ shape characteristic of a shock wave, but the red and magenta curves show that both the amplitude and steepness gradually decrease because of the wall losses.

The distortion in the time domain illustrated in Fig.2 corresponds in the frequency domain to a transfer of energy from the fundamental component to upper harmonics. This process, sometimes called the harmonic cascade phenomenon, is responsible for the increase in perceived brightness of sound which we have called brassiness. When the shock wave reaches the open end of the

pipe, the high frequencies components in the wave are efficiently radiated, while the low frequencies are reflected back into the instrument. The radiated pressure has a waveform corresponding approximately to the time derivative of the pressure signal arriving at the pipe exit. The result is a periodic wave characterised by a series of sharp pressure peaks, and a spectrum with uniform harmonic amplitudes up to very high frequencies. This is the signature of a brassy sound.

3. THE BRASSINESS POTENTIAL PARAMETER

The relative importance of spectral enrichment arising from nonlinear propagation in brass instruments with different bore profiles can be estimated using a brassiness potential parameter B which can be calculated from the bore dimensions [5]. We consider an instrument with an axially symmetric bore profile similar to those illustrated in Figs. 7, 8, and 13. The tube has an overall length L , and a diameter $D(x)$ increasing from a relatively narrow mouthpiece receiver at $x = 0$ to a much wider bell at $x = L$. The mouthpiece is not normally included in the calculation of B , since the internal profile of a mouthpiece is a matter of the individual preference of the player and the same mouthpiece may be used on several different instruments.

As the sound energy spreads across the increasing cross-section of an outwardly-flaring horn, the particle velocity decreases. Neglecting losses within the horn, and assuming that the sound energy is uniform across the tube, conservation of energy leads to

$$\frac{v(x)}{v_{\min}} = \frac{D_{\min}}{D(x)}, \quad (2)$$

where D_{\min} and v_{\min} are $D(x)$ and $v(x)$ at a reference point. For an entire brass instrument, the reference point is defined as the point on the tube axis where the diameter of the instrument is a minimum. This is not at the input of the mouthpiece receiver, but usually just beyond the point where the mouthpiece stem ends when the mouthpiece is inserted into the instrument.

According to Eqn.1 the rate of nonlinear distortion of the wave depends on the value of the particle velocity v . The maximum rate of distortion will therefore occur at the point of minimum diameter, where the particle velocity has its largest value v_{\min} . Substituting the value of $v(x)$ derived from Eqn.2 in Eqn.1 gives an expression for the speed of travel of a given point on the wave at a distance x along the bore:

$$\frac{dx}{dt} = c_0 + \left(\frac{\gamma+1}{2}\right) \left(\frac{D_{\min}}{D(x)}\right) v_{\min}. \quad (3)$$

The sound must travel further in an outward-flaring horn than in a cylindrical tube to undergo the same amount of nonlinear distortion, since the rate of distortion diminishes as the diameter increases. The length of a cylindrical tube of diameter D_{\min} which gives the same degree of nonlinear distortion as a flaring tube with the same minimum

diameter, total length L , and bore profile $D(x)$ is

$$L_{\text{NDeq}} = \int_0^L \frac{D_{\text{min}}}{D(x)} dx. \quad (4)$$

For brass instruments that flare outwards (as virtually all do), the length of the equivalent cylinder will thus be less than the geometrical length of the instrument.

The brassiness potential parameter B is defined as the ratio L_{NDeq} to L_{ecN} , the nominal equivalent cone length of the instrument [1]. That is,

$$B = \frac{1}{L_{\text{ecN}}} \int_0^L \frac{D_{\text{min}}}{D(x)} dx. \quad (5)$$

The brassiness potential parameter B is thus a dimensionless number that for normal brass instrument contours always lies between zero and unity. It is higher for ‘cylindrical’ instruments like the trumpet and trombone, and lower for ‘expanding’ instruments like the flugelhorn and euphonium. For the same input signal, larger values of B mean greater nonlinear distortion and therefore a greater tendency for the timbre to acquire a brassy edge at louder dynamics. It should be borne in mind, however, that a high value of B does not imply that the instrument will always sound brassy: in very quiet playing the spectral enrichment due to nonlinear distortion is insignificant in every brass instrument.

The normalising factor L_{ecN} is included in the definition of B to ensure that brass instruments with different equivalent cone lengths but similar bore profiles have comparable values of B . If a B^b trumpet and a tenor trombone have similar profiles they will have similar B values, although the trumpet is only half the length of the trombone. The 4th natural note on the trumpet has a frequency twice that of the 4th natural note on the trombone, and since the rate of nonlinear distortion is proportional to frequency these two notes will have the same degree of spectral enrichment. The brassiness potential parameter thus compares instruments when each is playing in its normal register. If trumpet and trombone both played a note of the same pitch, the trombone would have more spectral enrichment than the trumpet even if their B and D_{min} values were the same.

4. SPECTRAL ENRICHMENT PARAMETERS AS TAXONOMIC TOOLS

The brassiness potential parameter defined by Eqn.5 has proved useful as a taxonomic tool for the classification of brass instruments. A scatter plot of brassiness parameter against minimum bore diameter, such as that shown in Fig.3, is clearly capable of separating brass instruments into identifiable subgroups. Once areas which are occupied by instruments of recognised design within such a scatter plot are established, instruments of more uncertain identity can be measured and B values computed. Their locations in the scatter plot in relation to other instruments can then be a guide to their potential timbral properties, even if for conservation reasons they cannot be played.

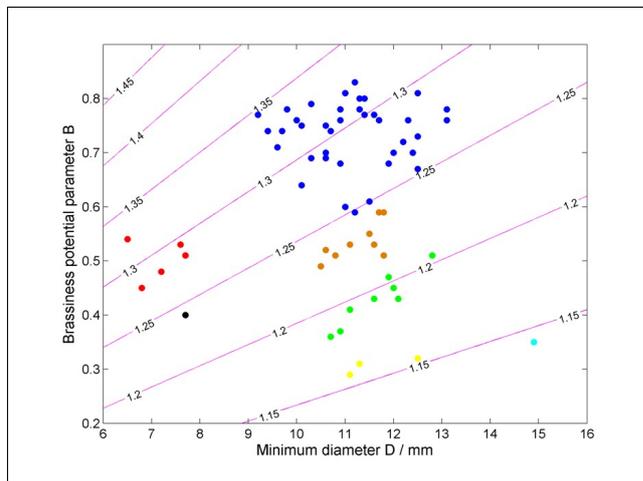


Figure 3. B, D_{min} scatter plot for a selection of brass instruments with widely differing values of brassiness potential parameter: trombones (blue), french horns (red), baritones (brown), euphoniums (green), ophicleides (yellow), serpent (cyan), Wagner tuba (black). Magenta lines are contours of equal spectral enrichment parameter E_1 .

In trumpets, trombones, and french horns, with a high proportion of cylindrical tubing, the distortion which occurs in very loud playing can result in the sudden pressure jump described as a shock wave occurring before the forward travelling wave reaches the bell. The common description of this group of instruments as ‘bright’ (French ‘cuivres clairs’) reflects the extreme brightness of their timbre at high dynamic levels. In flugelhorns, euphoniums, and tubas, most of the tubing when no valves are activated is either conical or flaring, and the rate of distortion is not sufficiently great to allow the full development of a shock wave within the tube. This group of instruments is sometimes described as ‘mellow’ (French ‘cuivres doux’), since the spectral enrichment at high dynamic levels is less pronounced.

It is evident from Fig.3 that ‘bright’ instruments are generally associated with high values of B , while ‘mellow’ instruments have lower B values. There is however a strong effect of absolute bore size on spectral enrichment in the far field for a given dynamic output of instruments with identical values of B . The playing experience of brass players is that, for comparable bores, the narrowest tube will be the brassiest. One reason for this is that the transfer function from the mouthpiece to the radiated sound field increases with the radial scale of the instrument, so that a narrow bore instrument a higher mouthpiece pressure is required to reach a given radiated dynamic level than on a wide bore instrument. For very narrow bores the resulting increase in nonlinear distortion is partly compensated by the increase in viscothermal damping with decreasing radius, which reduces the relative amplitudes of high frequency components in the radiated sound.

It is difficult to quantify exactly the trade-off between B and absolute bore size [6], but some attempts have been made to identify a more general spectral enrichment pa-

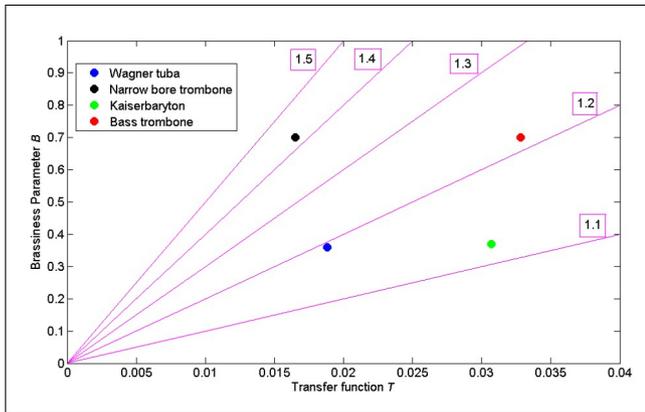


Figure 4. B, T scatter plot of four brass instruments. Magenta lines: contours of equal spectral enrichment E_2

parameter which is a function of both brassiness potential and minimum bore diameter. A practical advantage of the definition of the brassiness potential parameter is that its calculation requires only knowledge of the bore profile, which can be obtained by physical measurement or by modern scanning techniques. From the taxonomic perspective, it would be valuable to be able to define a single spectral enrichment parameter, incorporating the influence of transfer function and viscothermal damping, which could also be calculated from the bore profile.

One suggestion [7] has defined a spectral enrichment parameter E_1 as the spectral centroid of the sound generated at a defined point in the radiated field by a sinusoidal mouthpiece pressure of fixed frequency and amplitude. To facilitate comparison with experimental measurements, a sine wave with frequency 2.5 kHz and amplitude 600 Pa was chosen as the standard input. Measured spectral centroids for several different instruments were in reasonable agreement with results obtained by numerical simulations. An empirical formula

$$E_1(B, D_{\min}) = 1 + \alpha B / D_{\min} \quad (6)$$

was found to predict the E_1 values of most (but not all) of the instruments tested with $\alpha = 5$ mm and D_{\min} in mm. Contours of equal spectral enrichment E_1 are shown on Fig.3. The slope of these contours reflects the fact that E_1 is predicted to increase with increasing B and decreasing D_{\min} . An encouraging agreement with musical experience is that french horns, which are characteristically brassy when played loudly, are in the same range of E_1 as trombones, although the horns have much lower values of B than the trombones. In general, the sloping contours of E_1 appear to correspond well to the distributions of the different musical families.

Another proposal has been to calculate the transfer function T directly from the bore profile, and to plot the brassiness potential parameter as a function of T rather than B [8]. The spectral enrichment parameter E_2 is in this case defined as the spectral centroid of the radiated pressure at a point 50 cm from the bell, for a sinusoidal input whose frequency in kHz is $f_{\text{in}} = 6 / L_{\text{ecN}}$, where L_{ecN}

is the nominal equivalent cone length (in m) of the instrument [1]. The input pressure amplitude is chosen to generate a standard rms pressure of 6 Pa at the measurement point in the radiation field.

The spectral centroids in the radiation field were derived from simulations using these input conditions for ten different brass instruments, and were found to be reasonably well predicted by the simple empirical formula $E_2 = 1 + B/100T$. An example of a B, T scatter plot of four instruments of comparable length is shown in Fig.4. The distinction between narrow and wide bore is now shown as a differences in transfer function. The contours of equal E_2 confirm that the narrow bore tenor trombone has a significantly higher potential for spectral enrichment than the wide bore bass trombone, although their B values are almost identical.

While this approach shows some promise, further refinement of the formula is necessary to take into account the influence of viscothermal damping in very narrow tubes, and to include a more sophisticated treatment of the radiation field. Assessing the musical usefulness of any spectral enrichment parameter will require extensive playing tests.

5. TRUMPETS AND CORNETS

Many musicians are puzzled by the difference between trumpets (Fig.5) and cornets (Fig.6), two instruments which have the same sounding length (about 1.3 m), a common playing range, and a similar playing technique.



Figure 5. Trumpet in B^b (Smith-Watkins, York, 2011) EU (6039)



Figure 6. Cornet in B^b (Antoine Courtois, Paris, 1856-8) EU (3475)

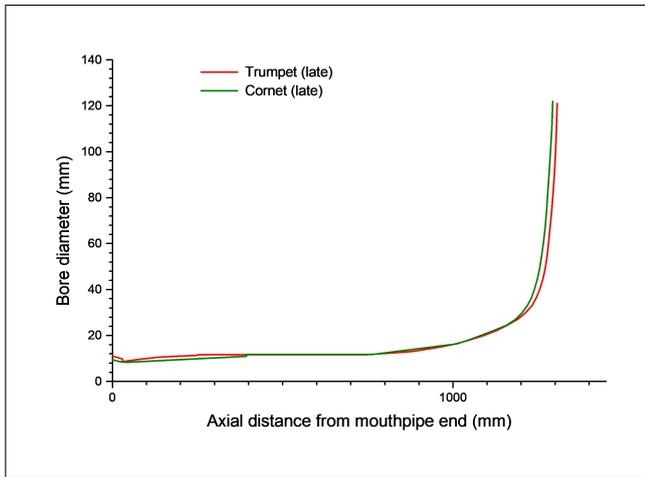


Figure 7. Bore profiles of trumpet in B^b (Yamaha, Hamamatsu, c 2002) and cornet in B^b (Besson, London, 1997)

The accepted view is that the trumpet sounds brighter, while the cornet sounds warmer, but the difference is not always distinctly audible. Their bore profiles at first glance look similar (Fig.7). The resemblance between the bore profiles of these two instruments is in fact so close that it can be questioned whether they should be classed as members of two distinct species or varieties of a single species.

The brassiness potential parameter can help us understand how this state of affairs has arisen. The trumpet whose bore profile is shown in Fig.7, made in 2002, has a B value of 0.58 and a minimum bore diameter of 8.7 mm; the cornet has the same value of B at 0.58 and an only slightly narrower minimum bore diameter of 8.4 mm. So the two instruments can be expected to make a very similar contribution to the playing timbre, which of course also depends on the player's choice of mouthpiece and style of playing.

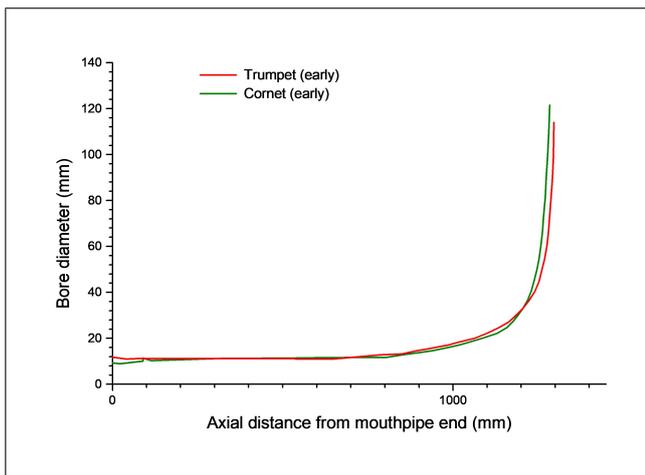


Figure 8. Bore profiles of trumpet in B^b (Kessler, Markneukirchen, late 19th century) and cornet in B^b (Antoine Courtois, Paris, 1856-8) EU (3475)

If we look at a trumpet and a cornet from the nineteenth century, however, the story is different. The trumpet whose bore profile is shown in Fig.8 has a B value of 0.74 and a

minimum bore diameter of 11.0 mm; the cornet has a significantly lower value of B at 0.61 and a narrower minimum bore diameter of 8.9 mm. So the two instruments can be expected to conform to the view that trumpets sound brighter, while cornets sound warmer.

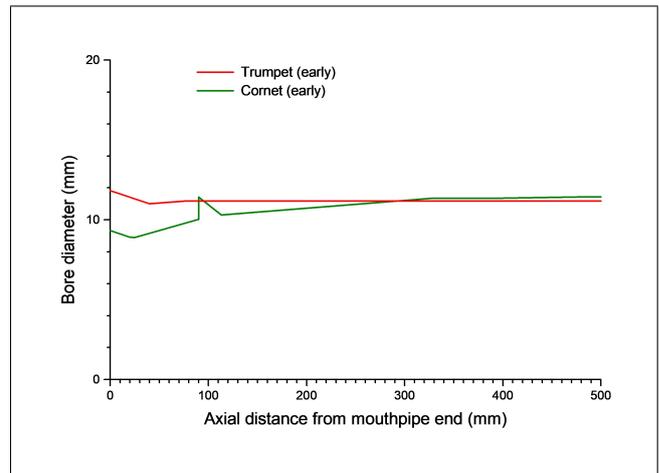


Figure 9. Detail of Fig.8, showing the first 500 mm of the bore profiles

The difference in bore profiles may appear marginal, but a closer view of the parts of the instruments nearest the mouthpiece (Fig.9) reveals a significant difference. In this early part of the tube the trumpet is close to cylindrical, while the cornet has a pronounced taper as the bore expands from the mouthpiece receiver to the valves, which are approximately mid-way along the bore.

Brassiness potential is proportional to the minimum bore, and the contribution to B of any short section of tubing is inversely proportional to its bore diameter, so the narrower parts of the tube are more significant in their contribution to B . For this reason many figures in *The Science of Brass Instruments* [1] and other publications that illustrate detailed bore profiles focus on the narrower early parts of the bores.

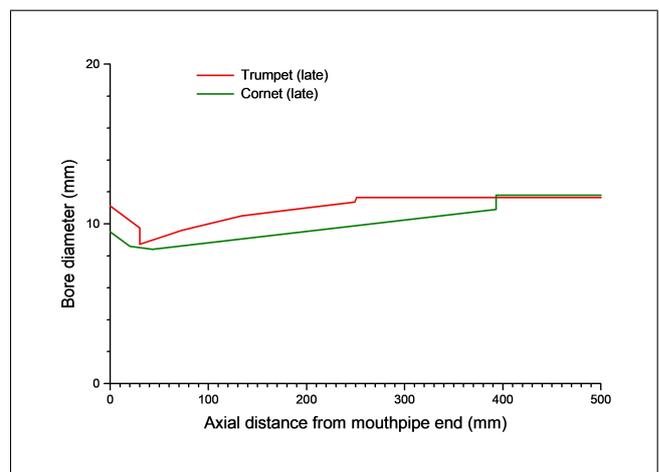


Figure 10. Detail of Fig.7, showing the first 500 mm of the bore profiles

If we look closely at the narrower parts of the bore pro-

files of the modern instruments (Fig.10), we see that the trumpet bore is far from cylindrical, and is much closer to that of the cornet.

The trumpet and cornet, distinct in the nineteenth century, developed in the twentieth to converge. The trumpet has always been used with a mouthpiece with a wider tapered stem than a cornet and thus had a wider mouthpiece receiver. Modern B^b trumpets have a constriction in the mouthpipe which is followed by an approximately conical bore expansion to the valves. Mouthpieces will often be provided by makers with exactly the same cup and rim shape for cornets and trumpets (to ease transition for musicians who play both). Trumpet bell end diameters are on average slightly smaller than those of cornets, but their ranges overlap so bell size is not a distinguishing feature. The most reliable distinction between trumpets and cornets is in the width of the mouthpiece receiver.

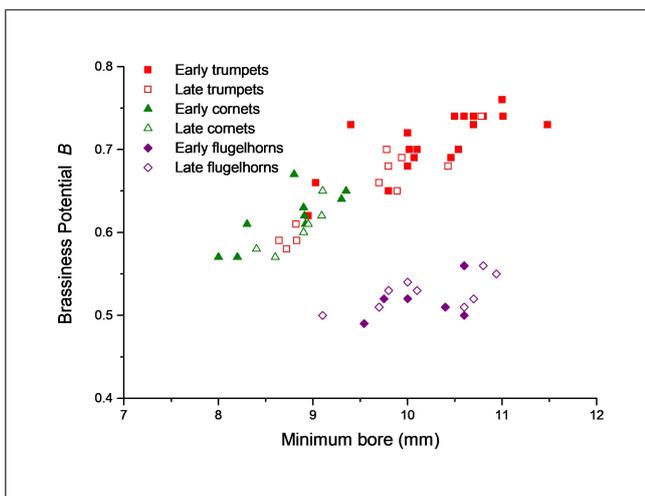


Figure 11. B / D_{\min} scatter plot for typical 19th-century B^b trumpets, 20th-century B^b trumpets, 19th-century cornets, 20th-century cornets, 19th-century flugelhorns, and 20th-century flugelhorns

Looking at the brassiness potentials of a larger population (Fig.11), we see that the convergence has not been uniform. Trumpets show an overall trend to lower values of B , cornets show less change. The design change in trumpets may be a consequence of performance dynamics having risen.

Flugelhorns (Fig.12) have been included in the scatter plot to show that they are a distinct species and not a continuation of the trumpet-cornet spectrum. Fig.13 shows the bore profile of a typical flugelhorn. In all flugelhorns the valves are situated in the windway close to the mouthpiece receiver; a marked expansion of the bore starts from the valve exit, which is typically between 200 and 300 mm from the tube entrance. This is in contrast to trumpets and cornets, where in most models the valves are positioned close to the mid-length of the bore at an axial distance of between 600 and 700 mm. Some related models of instrument have been discussed by one of the present authors [9].



Figure 12. Flugelhorn in B^b (Boosey & Co, London, 1904) EU (4206)

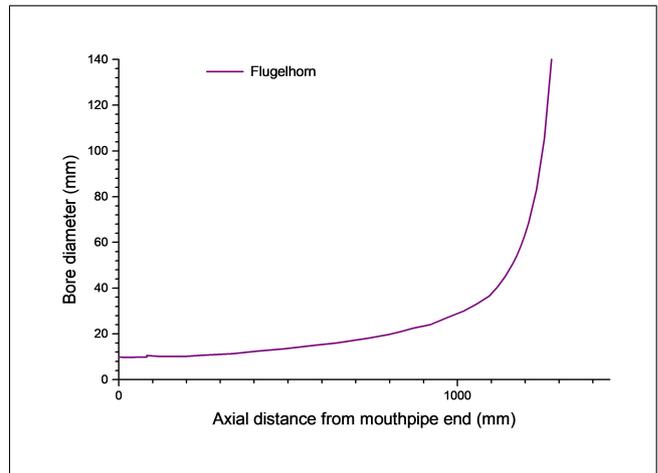


Figure 13. Bore profile of flugelhorn in B^b (Besson, London, c 1908) EU (3592)

6. CONCLUSION

Writing a textbook is an exciting, challenging, and occasionally frustrating task. The excitement comes from exploring afresh the inspiring work of so many colleagues in the international family of scholars and researchers in musical acoustics. The challenge is to provide a synthesis of such a large and impressive body of work which does justice to those who have created it. The frustration is inevitable in a field of activity which is rapidly advancing, so that new and important insights and discoveries are bound to emerge just after the publication deadline.

In the small corner of research reviewed here, there is still much work in progress. The possibility of deriving a single spectral enrichment parameter, deducible from physical measurements of an instrument and including effects of losses, remains an elusive but attractive goal. The extension of the comparison of trumpet and cornet to other types of brass instrument, including the larger brass instruments such as euphonium, saxhorn, and tuba, could also help to answer some perennial musical debates.

As always in musical acoustics, dialogue between scientists and musicians is at the heart of every successful project, and the present authors offer grateful thanks to all the performers and instrument makers whose practical assistance and advice have helped in developing our under-

standing of the brassiness of brasses.

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