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THE CONTRIBUTIONS OF JOËL GILBERT TO THE UNDERSTANDING OF ‘BRASSINESS’

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ABSTRACT

Joël Gilbert was not only an inspired researcher in acoustics but also an excellent and dedicated trombone player. He combined these twin passions in his work on the science of brass musical instruments and was responsible for several important advances in this field. One of his long-term goals was to identify the factors responsible for musically significant differences between brass instruments with different bore profiles. As a musician he was aware that when played loudly a trumpet or trombone develops a characteristic bright or ‘brassy’ timbre, and in 1996 he was a co-author of the classic paper demonstrating that this ‘brassiness’ results from the generation of shock waves in the trombone. Over the next twenty-six years year Joël collaborated with colleagues in France, the Netherlands, the United Kingdom and the United States in experimental, theoretical and computational studies of the scientific basis and musical applications of brassiness. This paper reviews some of the major steps in the development of a spectral enrichment parameter which can be used to predict the brassiness of an instrument from measurements of its bore profile.

Keywords: *brass instruments, brassiness, nonlinear sound propagation, spectral enrichment*

1. INTRODUCTION

The outstanding abilities of Joël Gilbert in both scientific research and practical music-making were the twin foundations of a career which greatly enriched our understanding of how brass instruments function. The present authors had the privilege of working closely with Joël on many aspects of brass instrument acoustics over more than two decades, and this review is dedicated to the memory of an inspiring collaborator, a stimulating co-author, and a much-loved friend.

Figure 1. Joël Gilbert visiting the St Cecilia’s Hall Music Museum, University of Edinburgh in 2020

2. SHOCK WAVES IN TROMBONES

The adjective ‘brassy’ is used colloquially to describe the hard, brilliant timbre characteristic of a loudly played brass instrument. During a crescendo the sound becomes brassier

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because the relative strength of high frequency spectral components increases: this process is described as spectral enrichment. In trumpets and trombones, with a relatively high proportion of narrow bore tubing, strong spectral enrichment makes loud sounds very brassy. Baritones and euphoniums, whose bores expand gradually over most of the tube length, display more modest levels of spectral enrichment and sound much less brassy even when played very loudly.

In 1969 it was suggested by James Beauchamp [1] that nonlinear sound propagation in the internal air column made an important contribution to spectral enrichment in trombones. The first conclusive experimental validation of this hypothesis was carried out by Joël Gilbert in collaboration with colleagues at TUE Eindhoven and IRCAM and reported in the seminal 1996 paper by Hirschberg et al [2]. Further confirmation was provided in 1997 by Gilbert and Petiot [3]. These experiments showed that cumulative nonlinear distortion of the sound wave propagating from the mouthpiece towards the bell in a trombone can result in the almost instantaneous pressure rise characteristic of a shock wave by the end of the slide section (see Fig. 2). The observed timbral consequence is a dramatic level of spectral enrichment in the radiated sound, with significant upper harmonics at frequencies which can extend beyond 40kHz.

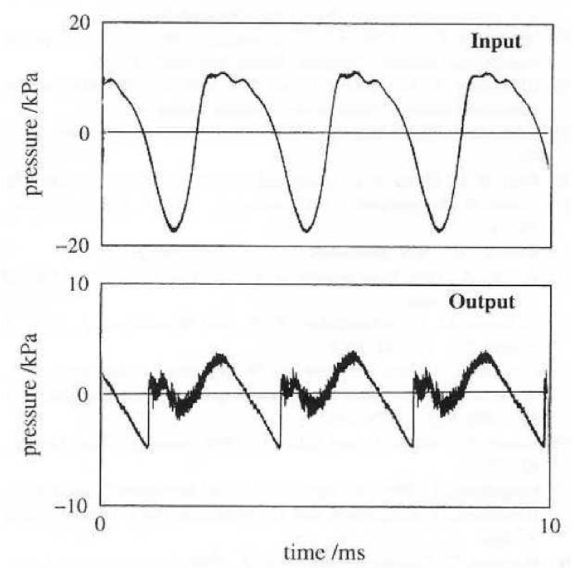

Figure 2. Pressure measurements in the mouthpiece (above) and the end of the slide section (below) in a trombone played fortissimo. From [3].

3. QUANTIFYING BRASSINESS

In 2006 Pyle and Myers [4] suggested that the effect of an expanding bore profile on the rate of spectral enrichment could be expressed in terms of the coordinate stretching function

$$z(x) = \int_0^x \frac{D_0}{D(y)}\, dy, \tag{1}$$

where $D(x)$ is the bore diameter at distance x from the input (diameter D_0). Weak nonlinear propagation theory predicts that the spectral enrichment in an expanding tube of total length L should be approximately proportional to $z(L)$. At the 2007 International Symposium on Musical Acoustics in Barcelona, Gilbert et al. [5] introduced the normalized brassiness parameter

$$B = \frac{z(L)}{L_{\mathrm{ec}}}, \tag{2}$$

with L_{ec} the equivalent cone length of the tube. A comparison was presented between experimental measurements of played crescendos on a variety of brass instruments and values of B calculated from measurements of the bore profiles of the instruments. Ranking of instruments by the brassiness parameter was found to agree with ranking based on the spectral centroids of the radiated sound.

4. SIMULATION TOOLS FOR BRASSINESS STUDIES

Wall losses can play a significant role in the propagation of sound waves in brass instruments, but exact solutions of the weakly nonlinear plane wave equation including losses are not available. Since the decay constant for viscothermal losses in a cylindrical tube of radius a is [6]

$$\alpha \simeq 3 \times 10^{-5} f^{1/2}/a, \tag{3}$$

the effect of losses is greatest in instruments with long sections of narrow tubing. The frequency dependence of the decay constant means that losses reduce the relative strength of upper harmonics in a propagating wave, diminishing to some extent the spectral enrichment due to nonlinear propagation.

In 2000 Menguy and Gilbert [7] proposed a frequency domain simulation method for obtaining numerical solutions of the generalized Burgers equation describing weakly nonlinear propagation in a cylindrical duct. This treatment was extended in 2008 to describe a non-cylindrical duct of circular cross-section by including in the generalized Burgers equation an additional term which is a function of the interior diameter $D(x)$ [8]. This simulation method has proved particularly useful as a tool for studying the balance between nonlinear distortion and wall dissipation in the propagation of loudspeaker-generated sounds in cylindrical and flaring tubes [9]. A time domain version of the simulation tool was presented by Maugeais and Gilbert in 2017 [10].

5. A SPECTRAL ENRICHMENT PARAMETER INCLUDING THE EFFECT OF RADIAL SCALE

The brassiness parameter B introduced in Eqn.2 has proved to be a useful tool in characterizing different brasswind families [11]. It is not, however, sensitive to the absolute radial scale of the instrument: multiplying the value of $D(x)$ by a constant does not change the value of B. Experimental studies have confirmed that narrow bored instruments have a greater degree of spectral enrichment at a given dynamic level that wide bored instruments of similar bore profile [12].

Over the last decade several attempts have been made to derive a spectral enrichment parameter which includes this radial scale effect. Working with Joël Gilbert in early 2022, the present authors developed an approach based on an assumption of constant acoustic power input at the defined entrance plane of the instrument [13]. For the simplified case of a forward travelling sinusoidal plane wave with acoustic pressure P_{in} at the input with diameter D_{in}, the input power is proportional to $(P_{\text{in}} D_{\text{in}})^2$. The rate of nonlinear distortion is proportional to P_{in}, and therefore inversely proportional to D_{in} for the case of constant input power.

The spectral enrichment parameter presented here estimates the increase in the spectral centroid of the sound radiated by an instrument with a known bore profile at a specified dynamic level. A typical brass instrument bore profile is illustrated in Fig. 3. The mouthpiece is a separate component which is not included in the calculation. The entrance to the tube is at $x = 0$, and the exit is the plane of the bell at $x = L$. The mouthpiece shank typically penetrates around 20 mm into the tube, so the input plane is taken to be at $L = 20$ mm. The effective length over which spectral enrichment is estimated is $L' = L - 20$ mm.

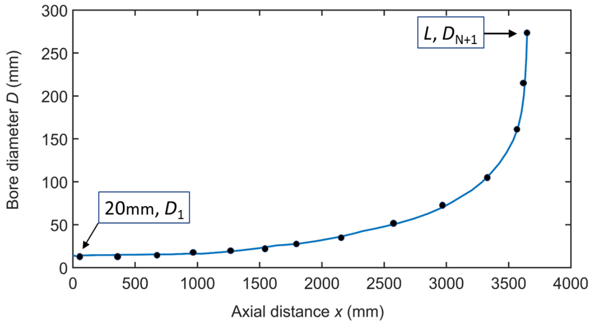

Figure 3. Bore profile $D(x)$ for a tuba. Black circles indicate typical measurement points.

In the absence of spectral enrichment, a sine wave input would give an output with a normalized spectral centroid SC = 1. The increase in the spectral centroid due to nonlinear propagation over the effective length L' is taken to be proportional to the coordinate stretching function $z(L')$ defined in Eqn.1. The radial scale effect is included by dividing by D_{in}. Division by L' is carried out so that the predicted enrichment in long and short instruments relates to notes in their normal playing registers. With linear dimensions in millimetres, the spectral enrichment parameter is defined as

$$E = \frac{Cz(L')}{L' D_{\text{in}}} = \frac{C}{L'} \int_{x=20}^{x=L} \frac{1}{D(x)}\, dx. \tag{4}$$

The value of the constant C depends on the choice of playing frequency and input power.

In practice, bore profile measurements of brass instruments usually give the input and output diameters of N contiguous bore sections of arbitrary lengths l_n, as indicated schematically in Fig.3. The input diameter is $D_1 = D(20)$, and the diameter at the bell is $D_{N+1} = D(L)$. The spectral enrichment parameter is derived using the approximation

$$E \approx \sum_{1}^{N} \frac{C l_n}{2L'} \left(\frac{1}{D_n} + \frac{1}{D_{n+1}} \right). \tag{5}$$

6. TESTING THE SPECTRAL ENRICHMENT PARAMETER USING THE SIMULATION TOOL

The spectral centroid estimator defined by E in Eqn. 4 was derived using a highly simplified model of sound propagation in a brass instrument. A first test of its potential usefulness was carried out by Joël Gilbert using the frequency domain simulation tool described in Sect. 4. The simulations used measured bore profile data for 34 brass instruments displaying a very wide variety of bore profiles. The set of instruments included ten $2^{1}/_{4}$-ft instruments with nominal fundamental pitch B$^{\flat}$3, eleven $4^{1}/_{2}$-ft instruments with nominal fundamental pitch B$^{\flat}$2, seven 9-ft instruments with nominal fundamental pitch B$^{\flat}$1, and six 18-ft instruments with nominal fundamental pitch B$^{\flat}$0. The simulations used a sinusoidal input with a frequency proportional to the nominal fundamental frequency of the instrument, ranging from 1.25 kHz for the 18 ft instruments to 10 kHz for the $2^{1}/_{4}$-ft instruments. The input pressure amplitude was chosen to generate a constant output power of 30 mW. For most of the instruments the input frequency was well above the bell cutoff frequency, and backward reflection at the bell plane was neglected.

The results of the simulations are shown in Fig.4. For each instrument studied, the spectral centroid *SCsim* of the simulated wave at the bell plane is plotted against the predicted spectral centroid value $1+E$. The constant C in the definition of E can be treated as a fitting parameter: in this case a value C = 2.2 mm was found to show a reasonable agreement between the simulated and predicted spectral centroids over a very wide range of brass instrument types.

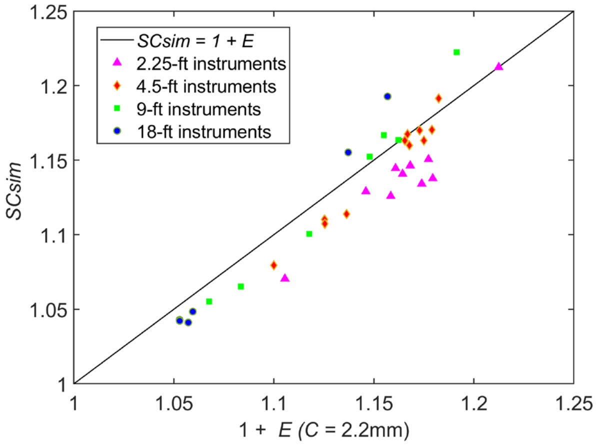

Figure 4. Simulated values of the spectral centroid *SCsim* at the output of 34 brass instruments driven by a sinusoidal input signal, plotted against values of $1+E$ calculated from bore profile measurements.

7. CONCLUSION

The spectral enrichment parameter E defined in this paper is intended primarily as a tool for characterizing and classifying members of the extensive and heterogeneous family of brass instruments. It is derived purely from bore profile measurements, and estimates the extent to which nonlinear sound propagation is expected to enrich the spectrum of the radiated sound.

The spectral centroid of the sound generated by a performer on a specific instrument will be determined not only by the bore profile, but also by the amplitude, frequency, and waveform of the mouthpiece pressure. For practical use in taxonomy the value of the constant C in Eqn.4 has been chosen to be 88 mm. This results in a convenient numerical scale for ranking instruments by spectral enrichment parameter: E values calculated for 1370 instruments range from 1.9 to 9.8. Figure 5 shows that instruments within musically defined subclasses form distinct but sometimes overlapping clusters on an (E, D_{in}) plot.

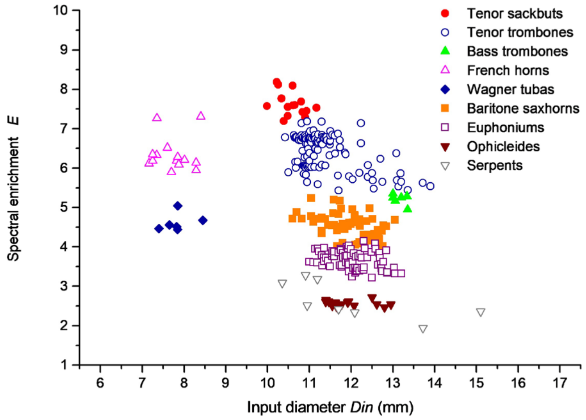

Figure 4. Scatter plot of spectral enrichment parameter E versus input diameter D_{in}.

Experimental tests exploring the relationship between E values and the spectral centroids of notes played in a musical context are now being conducted. Preliminary results from one of these studies will be reported in another paper at this meeting [14].

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