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The influence of bore profile on spectral enrichement due to nonlinear sound propagation in brass instruments

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Abstract

One of the characteristic features of the sound of a brass instrument is the way in which the timbre becomes brighter during a crescendo. The spectrum of a quiet note on any brass instrument is dominated by the lowest three or four harmonic components; as the loudness is increased upper harmonics become relatively more significant. In instruments with a large proportion of cylindrical tubing the spectral enrichment is particularly dramatic, leading to the “brassy” timbre of a fortissimo note on a trombone. An important contributing factor in the generation of very high frequency spectral components is nonlinear sound propagation in the bore of the instrument. This paper presents the results of recent experimental studies of the propagation of high amplitude wave packets in cylindrical tubes with dimensions similar to those in trumpets and trombones, and discusses the significance of the results for predictions of the rate of spectral enrichment based on measurements of the bore profile of such instruments.

Keywords: brass instruments, nonlinear acoustics, wave steepening, shockwaves

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1 Introduction

When a brass wind musical instrument is played loudly the amplitude of the pressure oscillation in the mouthpiece can reach several kPa [1]. At such high pressure amplitudes linear acoustic theory is inadequate to describe the propagation of sound in the air column of the instrument. A sinusoidal wave of high amplitude travelling along a cylindrical tube gradually changes shape, the wavefront steepening until at a critical distance a shock wave is formed [2]. The distance to shock formation is given by [3]

$$X_s \approx \frac{2\gamma P_{atm} c}{(\gamma+1)(\delta p(in)/\delta t)_{max}} \tag{1}$$

where $p(in)$ is the input acoustic pressure, P_{atm} is atmospheric pressure, c is the speed of sound in air and γ is the ratio of specific heats for air. Since X_s is inversely proportional to the rate of change of the input pressure, it will be reduced by an increase in either the amplitude or the frequency of the pressure.

The formation of a shock wave inside the bore of a brass instrument gives rise to a timbre very rich in upper harmonics, often described as “brassy”. Even at lower dynamic levels, for which the distance to shock formation exceeds the length of the air column, nonlinear distortion can play a significant role in increasing the high frequency content of the radiated sound. The rate of spectral enrichment during a crescendo varies widely among different types of brass instrument, and Myers et al [5] have proposed the adoption of a Brassiness Potential Parameter B as a tool for brass instrument taxonomy. This parameter is defined as

$$B = \frac{1}{L_{ecl}} \int_0^L \frac{D_0}{D(x)} dx \tag{2}$$

where L_{ecl} is the equivalent cone length of the instrument, D_0 is the diameter at the entrance and $D(x)$ is the bore profile. B estimates the fractional increase in the length to shock formation which is expected in a flaring bore due to the fact that the pressure amplitude of the travelling wave decreases as the bore diameter increases.

The Brassiness Potential Parameter has proved useful in distinguishing between major classes of instruments such as trombones, French horns and tubas. In some cases however predictions based on the calculation of B do not accord with musical experience. For example, the value of B derived using Eqn.2 does not depend on the absolute value of the bore diameter: a narrow bore trombone has the same value of B as a wide bored trombone with the same relative bore profile. Musicians agree however that a narrow bored instrument becomes “brassy” at a lower dynamic level than a wide bored one. In fact the degree of spectral enrichment generated by nonlinear propagation does depend on the absolute value of the bore diameter, although the result is a balance between two competing effects. In order to radiate sound at a specified dynamic level, for example *forte*, a higher pressure amplitude must be generated in the mouthpiece than would be necessary to achieve the same radiated level with a wide bored instrument. The higher mouthpiece pressure implies a higher rate of nonlinear steepening. On the other hand, if the tube becomes too narrow viscothermal losses become dominant, damping out the higher frequencies created by nonlinear steepening.

In order to obtain a clearer understanding of the processes affecting the development of spectral enrichment in brass instruments, Chick et al [6] carried out a number of experiments on high amplitude sound propagation in cylindrical tubes with lengths and diameters typical of the cylindrical sections of trumpets and trombones. Results of these experiments were compared with numerical simulations of sound propagation using weak nonlinear shock theory. It was shown that the interaction between nonlinear distortion and loss mechanisms was responsible for the degree of spectral enrichment resulting from propagation of a high amplitude sound wave in a cylindrical tube. Reasonable agreement was found between experiment and simulations, although some discrepancies were identified. The present paper revisits this issue using a somewhat different experimental approach in an attempt to clarify the relative significance of the different processes which modify the timbre of the nonlinearly propagating sound wave.

2 Experimental setup

The experimental arrangement used to initiate and examine nonlinear sound propagation in a cylindrical tube is shown in Fig.1. A JBL 2264 horn loudspeaker driver was coupled to the input of a section of stainless steel tube with internal diameter 8 mm by means of a brass coupling tube with the same internal diameter. A cylindrical hole bored radially through the wall of the coupler allowed a G.R.A.S. 1/4" high pressure microphone (Mic.1) to be inserted, its face flush with the internal wall of the main coupler channel. The stainess steel tube had a wall thickness of 2 mm and was manufactured to ASTM A269/A213, with a uniform semi-polished surface finish on the internal wall. The tube length was extended by adding two additional sections, using similar brass couplers with inserted microphones (Mic.2 and Mic.3). The final section of stainless steel tube, which was inside an anechoic chamber, was terminated by a final open brass coupler and microphone (Mic.4). The distance between the centre lines of each adjacent pair of microphones was 1.49 m.

Signal generation and data acquisition were carried out using a National Instruments PXI interface controlled by a Signal Express program. In contrast to the continuous sine waves used in previous studies, the signals used in the experiments described here consisted of wave packets containing between 10 and 20 cycles of a constant amplitude sine wave with frequency between 1 kHz and 5 kHz. The duration of the signal was short enough to ensure that the forward propagating wave packet had completely passed the first three microphones before the first reflection returned to Mic.3. It was thus possible to observe both the nonlinear distortion and the reduction in amplitude of the forward propagating wave alone over a distance of just under 3 m.

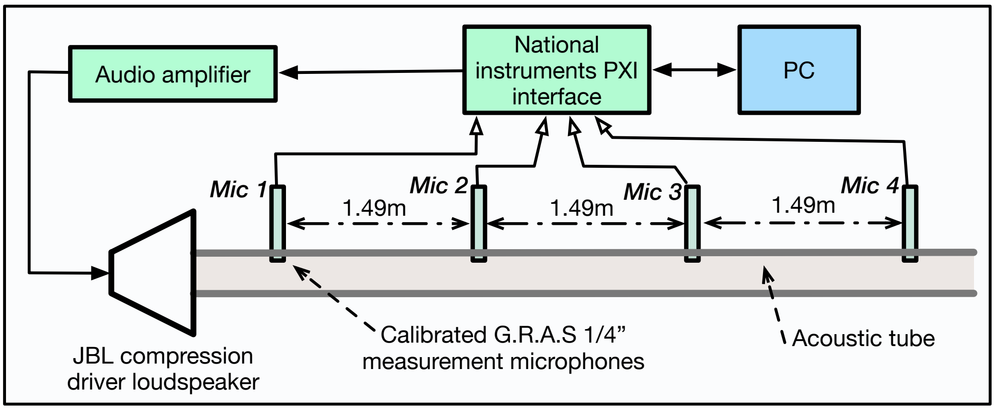

Figure 1: Experimental setup for measurement of nonlinear propagation in cylindrical tube

3 Results

The three graphs in the left hand column of Figure 2 show the pressure signals recorded by the first three microphones. The steepening of the rising edge of the waveform as the wave travels past Mic.2 and reaches Mic.3 is clearly evident, while the accompanying spectral enrichment can be observed in the corresponding frequency spectra in the centre and left hand columns. Similar evidence of nonlinear propagation distortion and spectral enrichment is displayed in Figs.3 and 4 for sine wave packets with frequencies 3 kHz and 5 kHz respectively.

The losses which occur during propagation can be observed directly by examining the diminution in amplitude as the wave passes the successive microphones. Chick et al [6] found that the measured transfer function between microphones equivalent to Mic.1 and Mic.2 in the present arrangement was about 2 dB lower than that predicted by simulation, suggesting that the numerical program might be slightly underestimatimg the losses. The effect of linear viscothermal losses on a wave of frequency f can be approximated by introducing a complex wavenumber [7]:

$$k' \approx 2\pi f/c - j\alpha, \tag{3}$$

with

$$\alpha \approx 3 \times 10^{-5} f^{1/2}/a. \tag{4}$$

Using this value for the loss parameter leads to the prediction that for $f = 1$ kHz the signal at Mic.2 should be 3.1 dB lower than at Mic.1, while the drop from Mic.1 to Mic.3 should be 6.1 dB. The corresponding experimental values from the right hand graph in Fig. 5 are 3.1 dB and 6.7 dB. From the simulated results shown in Fig. 6 it can be deduced that the loss values at distances corresponding to Mic.2 and Mic.3 are 3.1 dB and 6.1 dB respectively. The theoretical, experimentally measured, and simulated values are thus all in satisfactory agreement.

The experimentally derived losses shown in Fig. 5 display an interesting dependence on input level. The dependence is very slight at 1 kHz: the SPL drop from Mic.1 to Mic.3 increases by only 0.25 dB as the input level increases from 109.7 Pa to 2490 Pa. At 3 kHz the increase over a similar range of input levels is 2.0 dB, while at 5 kHz the increase is 2.1 dB. It is unlikely that

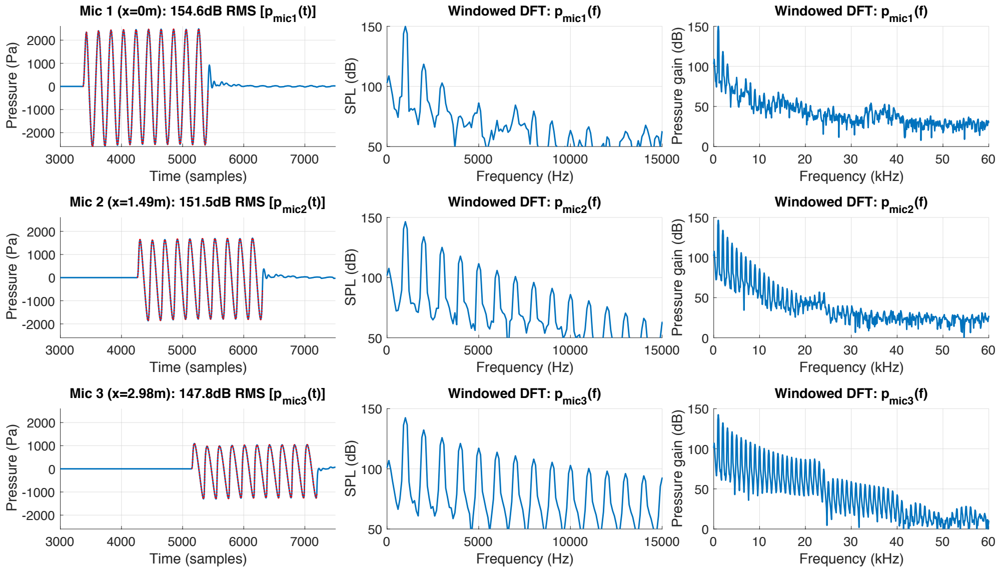

Figure 2: Pressure signals and frequency spectra for a high amplitude 1 kHz sine wave

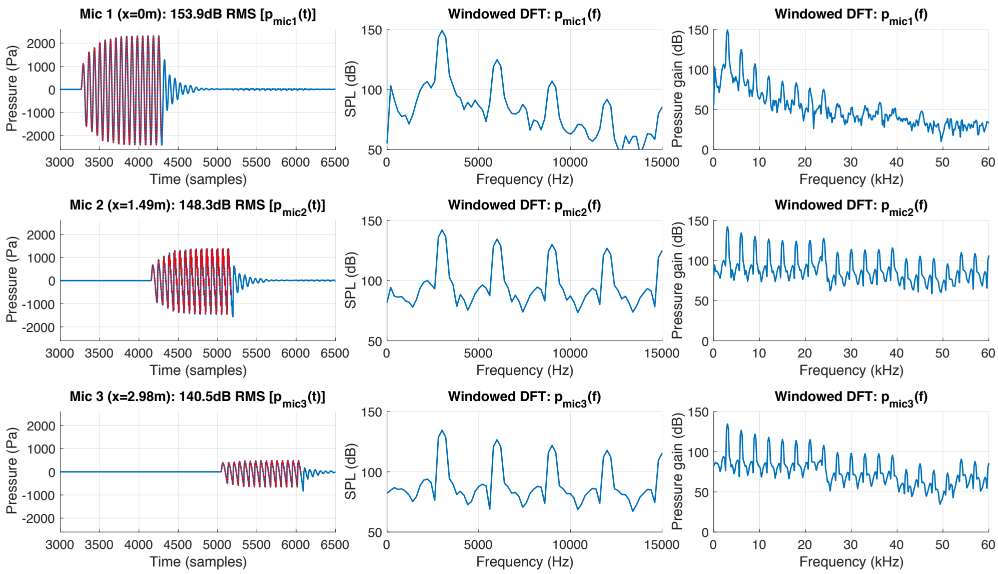

Figure 3: Pressure signals and frequency spectra for a high amplitude 3 kHz sine wave

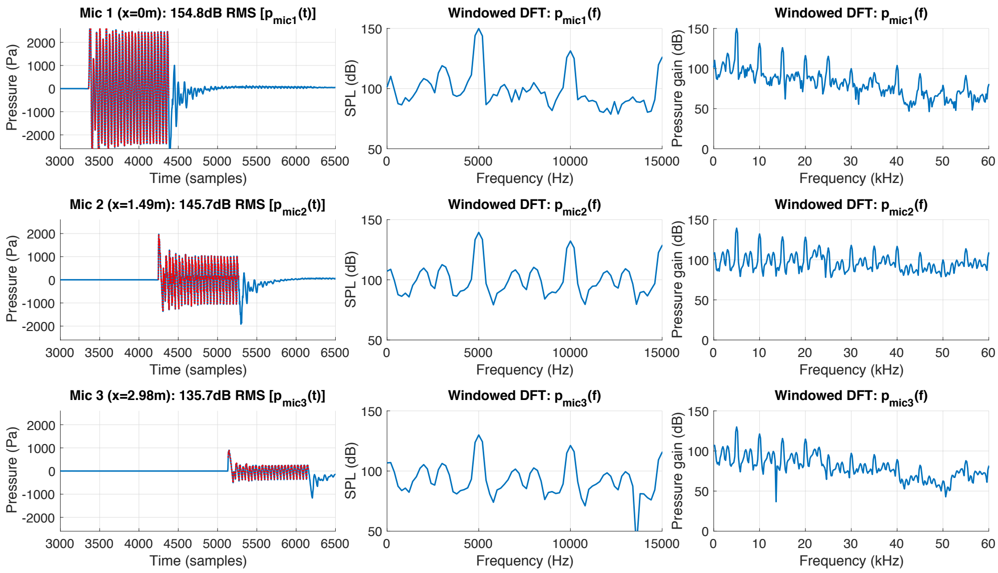

Figure 4: Pressure signals and frequency spectra for a high amplitude 5 kHz sine wave

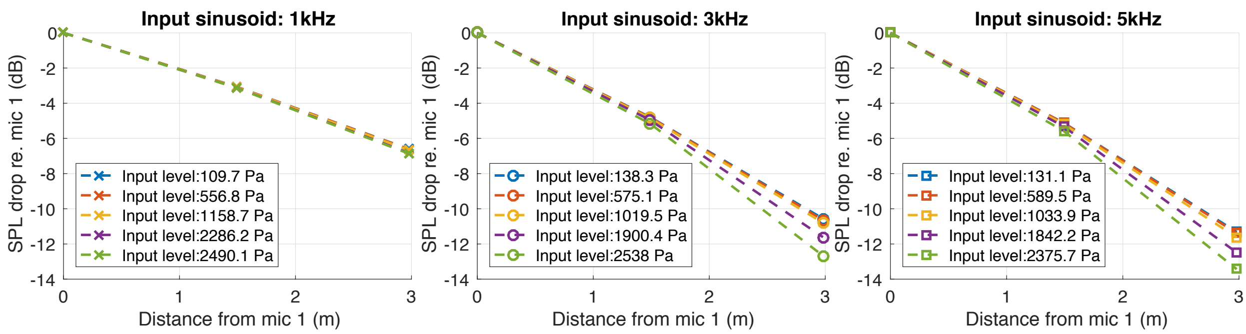

Figure 5: pressure measured at each microphone normalized to pressure at Mic.1, showing effect of losses during propagation

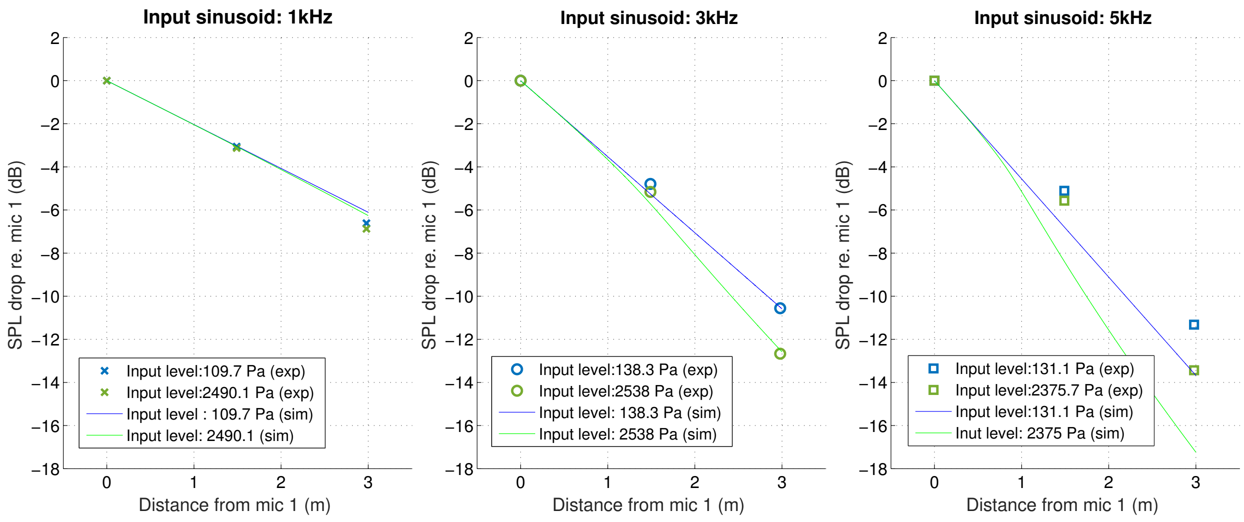

Figure 6: Solid lines: Simulated pressures for low and high input levels as a function of distance from the source, normalized to pressure at Mic.1. Symbols: corresponding experimental values

this change is due to a change in the loss parameter at high levels, since similar effects can be observed in the simulated curves shown in Fig. 6. These simulations, using the method described by Gilbert et al [4], assume that the loss parameter does not depend on input level.

Figure 7 shows how the spectral centroid of the simulated pressure signal evolves with distance from the input. The spectral centroid derived from experimental measurements carried out at the highest input level are also shown (circles and dashed trend line). Simulations and measurement are again in broad agreement, although the measured spectral centroid is consistently a little higher that the simulated curve.

4 Discussion

The experimental measurements of energy loss and spectral evolution are in fairly good agreement with the results simulated on the basis of weak shock theory. An interesting observation which could have significant implications in understanding the behavoiour of brass instruments at very high dynamic level is the nonlinear increase of losses with increasing distance from the input which is evident at frequencies above 1 kHz. Such frequencies are well above those of normal playing pitches, but even at fudamental frequencies of a few hundred hertz much of the energy in very loud playing is in the frequency range above the 10th harmonic. Indeed this is the most likely reason for the nonlinearity of the loss curves in Fig. 6. As the input level is increased, the nonlinear propagation effects transfer a larger fraction of the sound energy into the high frequency region where losses are more severe.

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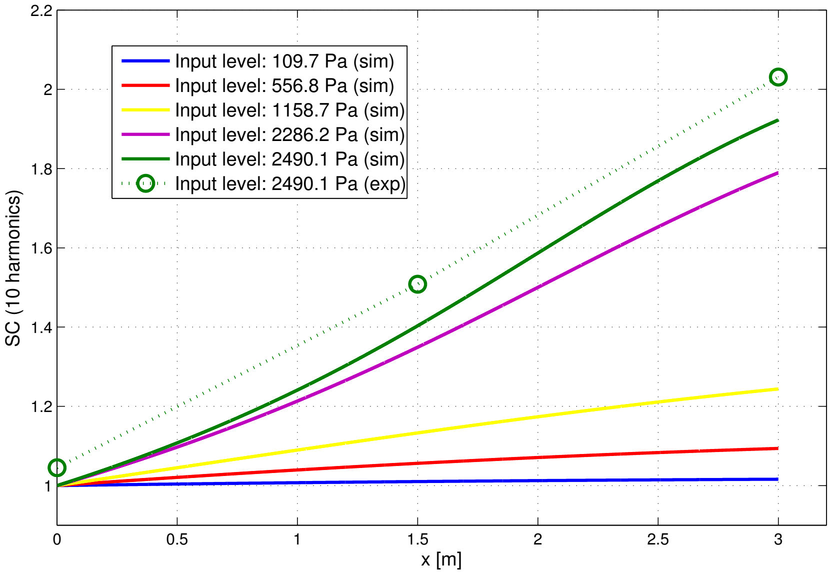

Figure 7: Solid lines: simulated spectral centroid as function of distance from input for different input pressures at 1 kHz. Circles and dotted line: experimental values of high amplitude spectral centroid at three positions and 1kHz.

the subject of this paper, and for carrying out the simulations which are reported in it. Toros Senan is also thanked for his contributions to the analysis and discussion of the results. The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union Seventh FrameworkProgramme FP7/2007-2013, under REA Grant Agreement No. 605867 supporting the BATWOMAN ITN project.

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