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Brassy sounds, from trombone to elephant

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ABSTRACT

Brass instruments like trumpets or trombones sound "brassy" especially when they are played at high level dynamic. These brassy sounds are made of a lot harmonics as a consequence of the wave steepening in the bore. The wave steepening is a cumulative effect obtained during the nonlinear propagation along the internal bore. A parameter to judge the severity of the nonlinear steepening is the critical shock length distance associated to a given input pressure profile. When the length of the bore is comparable to this critical distance, highly distorted waves can be observed in the bore, and it is the case for brass instruments played at fortissimo level. On one hand it is clearly the case for brass instruments. On the other hand the question is open for reed instruments even if, strictly speaking, they are not able to produce brassy sounds. But it is sensible to investigate if nonlinear propagation in reed instruments may result into a perceptible effect. Besides musical instruments, the question can be asked in vocal communication of animals. One of them is particularly interesting, the elephant! Elephants produce a broad range of sounds from very low frequency rumbles to higher frequency trumpets. Trumpets are produced by a forceful expulsion of air through the trunk. Some elephant trumpeting sounds are very similar to a trumpet or a trombone sound especially when playing "brassy". The internal bore of the vocal system of the elephant, from the vocal folds to the open end radiating the sound - thrunk end - is several meters long, like brass instruments. The vocal system is so long that the nonlinear steepening effect might be significant during elephant trumpeting. This hypothesis is discussed from elephant trumpet's signals, and estimated by comparison with human voice and brass musical instruments under playing conditions.

INTRODUCTION

Brass musical instruments like trumpets or trombones sound "brassy" especially when they are played at high level dynamic. These brassy sounds are made of a lot harmonics as a consequence of the wave steepening in the bore. The wave steepening is a cumulative effect obtained during the nonlinear propagation along the internal bore (Hirschberg, 1996). On the other hand the question is open for reed instruments even if, strictly speaking, they are not able to produce brassy sounds. But it is sensible to investigate if nonlinear propagation in reed instruments may result into a perceptible effect (Gilbert, 2010a). Besides musical instruments, the question can be asked in vocal communication of animals. One of them is particularly interesting, the elephant! Elephants produce a broad range of sounds from very low frequency rumbles to higher frequency trumpets. Trumpets are produced by a forceful expulsion of air through the trunk. Some elephant trumpeting sounds are very similar to a trumpet or a trombone sound especially when playing "brassy".

The aim of this paper is to review nonlinear propagation effects in brass instruments, reed instruments and elephant from recent works, after having reminded theoretical backgrounds of nonlinear acoustics (Hamilton, 1998).

BRASSY SOUNDS AND ACOUSTICAL NONLINEAR PROPAGATION, BACKGROUNDS

Acoustics is ordinarily concerned only with small-amplitude disturbances, so nonlinear effects are typically of minor significance. Then the basic fluid-dynamic equations are linearised and lead to the linear wave equation (Helmholtz equation in frequency domain). There are, however, when a small nonlinear term in the equations can lead to novel and substantial phenomena like wave distortion along propagation. We therefore can assume the propagation of a simple wave into a uniform region. Starting from a source pressure at x=0 and assuming a frictionless simple wave propagation along a pipe of uniform cross section, we can obtain an analytical prediction of the wave distortion. The calculation is based on the classical method of characteristics (Pierce, 1989). Due to the increase in speed of sound c with the temperature and the convective effects, the top of the compression side of a wave tend to catch up with the foot of the wave. It appears that the ratio of the pressure fluctuations p_m to the mean atmospheric pressure P_{at} is not the relevant parameter to judge the severity of the nonlinear steepening. Theory predicts that for distance x larger than the critical distance x_s given by

$$x_s = \frac{2\,\gamma\,P_{at}\,c}{(\gamma+1)\left(\partial p_m / \partial t\right)_{\max}}. \tag{1}$$

where γ=1.4 is the Poisson constant, a shock wave is formed. Comparing the calculated x_s to the geometrical length L of the tube is an efficient way to estimate if nonlinear propagation effects have to be taken into account or not (Hirschberg, 1996). If x_s is much larger than L, linear theory of acoustic propagation is rightfull.

The study of weakly nonlinear propagation in a dissipative viscothermal homogeneous fluid assuming a onedimensional flow in a nonuniform duct leads to first-order nonlinear differential twin equations called the “generalized Burgers equation” for the forward-traveling wave, and for the backward-travelling wave respectively (Gilbert, 2008). The two waves are assumed to propagate in opposite directions, independently in the linear limit. They are nonintegrable, and there is almost no chance of general analytical progress (Hamilton and Blackstock, 1998). That is why numerical methods such as the one described in Gilbert et al (2008) should be used. As an illustration, the harmonic components, Pn, as a function of x/x_s varying from 0 to 10 for a wave generated by a monofrequency source, are displayed Figure 1. The wave deformation along the propagation, from sine wave to a decreasing amplitude sawtooth wave, is obtained:

- for small values of x/x_s, the amplitude P1 is slightly decreasing, and energy is transferred to higher harmonics Pn from 0.

- for high values of x/x_s, all the amplitudes Pn are decreasing. Very far away, the shape is becoming sinus again.

- around x/x_s=1, the signal is highly distorted close to a shock wave.

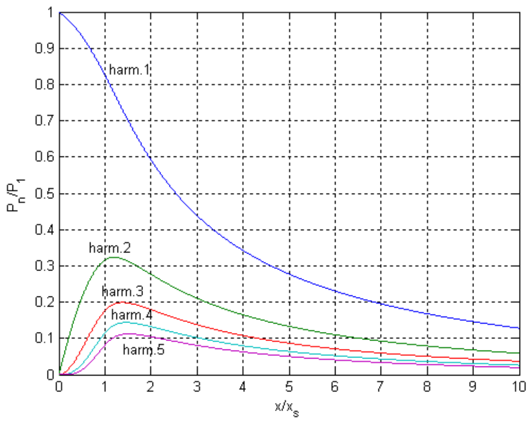

Figure 1. First five Fourier coefficients P_n (divided by P_1) vs the dimensionless propagation distance x/x_s for a weakly dissipative fluid.
The fluid is excited at x=0 by a monofrequency source.

The spectral enrichment can be globally estimated from the following dimensionless parameter, called the spectral centroid SC:

$$SC = \frac{\sum_n n.P_n}{\sum_n P_n}. \qquad (2)$$

Figure 2 shows the rapidly increasing and then slowly decreasing evolution of SC, respectively, before one and after three shock formation distance values corresponding to the results displayed in Fig. 1.

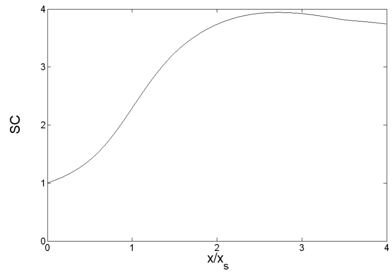

Figure 2. Spectral centroid SC vs the dimensionless propagation distance x/x_s for a weakly dissipative fluid. The fluid is excited at x=0 by a monofrequency source (SC=1 at x=0).

The brightness of the sound generated by brass instruments at high dynamic level, called brassy sounds, is mainly due to the essential nonlinearity of the wave propagation in the pipe (Hirschberg, 1996). A way to investigate the brassiness of brass instruments is to analyse crescendos by analysing the corresponding increase of SC (see Figure 3 and 4). A characteristic spectral enrichment parameter can be extracted for each recorded sound (Gilbert, 2007). Indeed there is a wave deformation along the propagation inside the brass instrument from a source signal in the mouthpiece. The source signal, which is not exactly a sinus, but having a small harmonic contains anyway (small SC value), is distorting itself toward something having periodically shock waves, and then having a broadband harmonic contains (high value of SC).

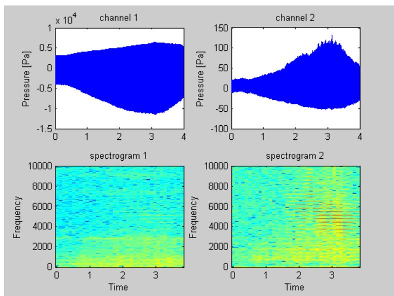

Figure 3. Crescendo of a F4 played with a trombone.
Left : time pressure signal (up) and spectrogram (down) of the soource signal (channel 1) in the mouthpiece. Right : time pressure signal (up) and spectrogram (down) of the radiated pressure signal (channel 2) one meter far aaway from the trombone bell.

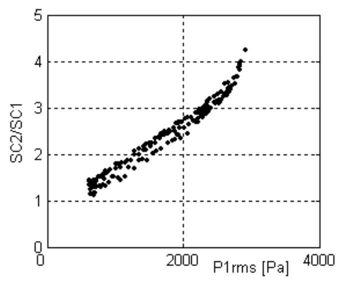

Figure 4. Ratio of the spectrum centroids SC2/SC1 of channel 2 and channel 1 as a function of the rms pressure P1rms of channel 1 (from experimental data Figure 3).

FROM TROMBONE TO ELEPHANT

Brass instruments

Thirty years ago the pioneering work of Brauchamp (1980) showed that nonlinear effects were significant in brass instruments bores. Since (Hirschberg, 1996; Msallam, 2000 ; Thompson, 2001) it has been demonstrated that nonlinear sound propagation in brass instruments resulted in musically significant modification of the timbre of the radiated sound, the so called “brassy sounds” which characterise the sounds of brass instruments played at very high dynamic levels. Part of the demonstation has been settled from the estimation of shock length distances x_s (equation 1) estimated from acoustic pressure signals measured in the mouthpiece, distance comparable with the length of the instruments themselves.

It has been also recognised that different subgroups of the brass family can be distinguished by the rate at wich nonlinear distorsion develop during a crescendo and by a brassiness potential parameter B (Gilbert, 2007) defined from theoretical considerations of nonlinear propagation in nonuniform ducts. As a consequence, these parameters can be seen as a useful tool to classify the brass instruments from the ability to play brassy sounds without playing them (Myers, 2007): the bright instruments such as the trumpet and the trombone are different from more mellow brass instruments such as the flugelhorn and the saxhorns. The first ones have an almost cylindrical pipe segment just downstream the mouthpiece (high B value). About the second ones, the conical bore in this region impies a faster decay of the wave which reduces the nonlinear wave steepening (small B value).

Reed instruments

Obviously reed instruments are not known for generating “brassy sounds”, but one can imagine that nonlinear propagation may have some importance in such instruments when they are played at high dynamic levels. It has been demonstrated recently (Gilbert, 2010a) that some nonlinear propagation effects can appear in a clarinet played fortissimo, especially if the musician.optimizes his embouchure. Indeed the clarinet player is able, by employing slight changes in embouchure, to control over the shape of the acoustic source signal in the mouthpiece, in order to control the level of nonlinear propagation effects in the clarinet. It has been done in practice by looking at a control oscilloscope screen.

By using an artificial mouth played at unrealistic high level of mouth pressure (from 10 to 15 kPa) and having an embouchure not optimised, nonlinear propagation effects in the clarinet have been observed too (Figure 5, adapted from Gilbert, 2010a).

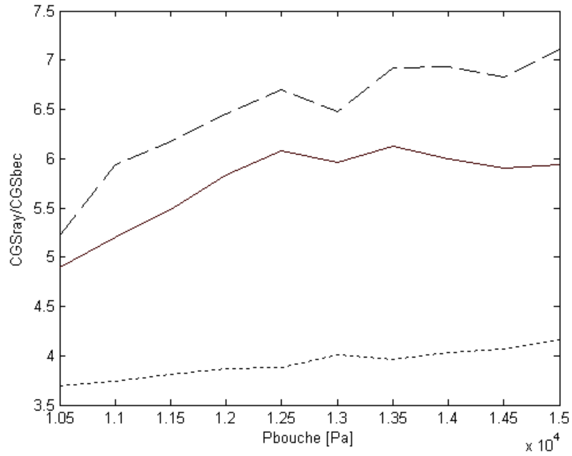

Figure 5. Ratio of the spectrum centroids *CGSray/CGSbec* as a function of the mouth pressure *Pbouche* (in Pa), CGSray (resp. CGSbec) corresponding to a radiated pressure (resp. acoustic source pressure in the clarinet mouthpiece)
The thee curves : (- - - -), radiated pressure estimated from linear propagation simulation, (_ _ _) radiated pressure estimated from nonlinear propagation simulation, (—) measureed radiated pressure..

Elephant

Besides musical instruments, the question can be asked in vocal communication of animals (Fletcher, 2007). Elephant trumpet calls (Soltis, 2009) are powerful sounds having a rich harmonic structure (Figure 6, adapted from Gilbert, 2010b), sounding like brassy sounds of musical instruments. Note that it is quite easy to imitate elephant trumpet calls with a trombone! To answer the speculative question about nonlinear propagation effects in trumpet calls, a first answer has been obtained by estimating a realistic critical shock length distance x_s (equation 1): the shock length distance x_s is comparable to the trunk length (Gilbert, 2010b). Even if the calculation of x_s is a bit questionable (no way to gat the acoustic source signal close to the vocal folds), it means that nonlinear distortion during propagation inside the trunk is relevant, and the brassy aspect of trumpet calls can be explained as a consequence of nonlinear propagation in the extended vocal tract (including the trunk). In other words, the explanation of the brassy aspect of the elephant trumpet calls seems to be the same as the explanation of the brassy sounds from trumpet or trombone musical instruments.

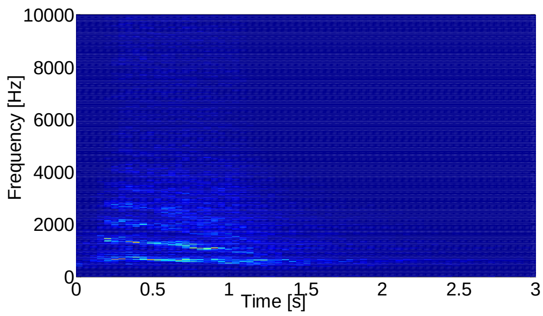

Figure 6. Spectrograms of a brassy elephant trumpet call.

CONCLUSION

The brightness of the sound generated by brass instruments at high dynamic level, the brassy sounds (“sons cuivrés” in French), is mainly due to the essential nonlinearity of the wave propagation in the pipe. If, strictly speaking, reed instruments are not able to produce brassy sounds, nonlinear propagation may result into a perceptible or measurable effect in their radiated sounds. Besides musical instruments, elephants produce trumpet calls. Trumpets are produced by a forceful expulsion of air through the trunk. Some elephant trumpeting sounds are very similar to a trumpet or a trombone sound especially when playing “brassy”. The internal bore of the vocal system of the elephant, from the vocal folds to the open end radiating the sound - trunk end - is several meters long, like brass instruments. The vocal system is so long that the nonlinear steepening effect might be significant during elephant trumpeting.

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