Does the elephant trumpet like a trumpet?

Joël Gilbert (1), Jean-Pierre Dalmont (1) and Romain Potier (2)

(1) Laboratoire d'Acoustique de l'Université du Maine – UMR CNRS 6613, Le Mans, France
(2) Zoo de Beauval, Saint-Aignan, France

PACS: 43.80.Ka

ABSTRACT

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. Trumpets are mainly tonal sounds. Elephants tend to trumpet when they are highly stimulated and the quality of trumpeting varies with the context.Some elephant trumpeting sounds are very similar to a trumpet or a trombone sound especially when playing "brassy". This kind of brassy sounds played at high level dynamic, 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. 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 than 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

Research on vocal communication in elephants has increased in recent years, providing an opportunity to present a comprehensive review of research related to their vocal behaviour, and it has been done recently by Soltis (2009). Current data indicate that the vocal repertoire consists of acoustically distinct call types, ''rumbles'' being the most common and acoustically variable. Large vocal production anatomy is responsible for the low-frequency nature of rumbles, with fundamental frequencies in the infrasonic range. Additionally, resonant frequencies of rumbles implicate the trunk in addition to the oral cavity in shaping the acoustic structure of rumbles. The call types can be analysed by using basic acoustic features like duration, mean fundamental frequency, mid position of dominant frequency … (Stoeger-Horwath et al., 2007). Among the broad range of sounds produced by elephants, there are higher frequency sounds called trumpets. Trumpets are produced by a forceful expulsion of air through the trunk. Trumpets are mainly tonal sounds. Elephants tend to trumpet when they are highly stimulated and the quality of trumpeting varies with the context. Trumpets are the subject of our work.

Trumpet calls are loud, conspicuous high-frequency calls. The elephants tend to trumpet when they are highly stimulated and the quality of trumpeting varies with the context. Some elephant trumpeting sounds are very similar to a trumpet or a trombone sound especially when playing "brassy". This kind of brassy sounds played at high level dynamic, are made of a lot harmonics as a consequence of the wave steepening in the bore (Hirschberg et al, 1996). The wave steepening is a cumulative effect obtained during the nonlinear propagation along the internal bore (Gilbert et al, 2008). 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.

The principal vocal organs for all mammals, including humans and elephants, are the lungs, the trachea, the larynx, the pharynx, and the nasal and oral cavities. The stream of air from the lungs is the energy source for vocal production, and the vocal folds are responsible for setting that steady airflow into rapid vibration, producing voiced sound (Fletcher, 2007). The sound is then filtered as it passes through the superlaryngeal vocal tract. The most used model is the source-filter model, where the vibrating vocal folds forced a pulsated flow in the vocal tract (Titze, 1994). The later one is excited in forced oscillations by a volume acoustic source, and the acoustical propagation inside is assumed linear. The mismatch between the prediction of this simple model and the observed structure of trumpets means that different or more complex models will be required to explain the mechanical production of the elephant trumpet (Soltis, 2009).

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 than the nonlinear steepening effect might be significant during elephant trumpeting. The aim of this work is to discuss this speculative hypothesis. And it is tackled from elephant trumpet's signals, and it is estimated by comparison with human voice and brass musical instruments under playing conditions.

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

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

where $\gamma=1.4$ 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.

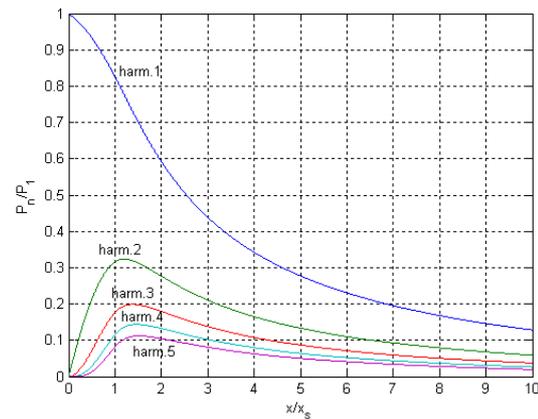- around $x/x_s=1$, the signal is highly distorted close to a shock wave.

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:

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

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.
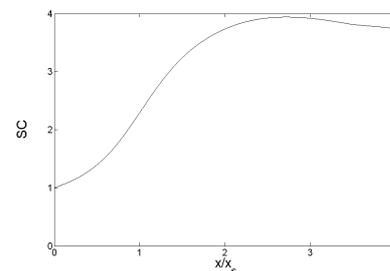

Figure 2. Spectral centroid SC vs the dimensionless propagation distance x/x_s for a weakly dissipative fluid. The fluid is excited at x=0 by a monofrequency source (SC=1 at x=0).

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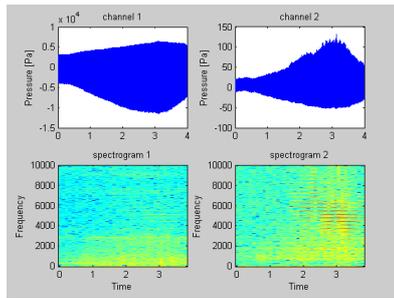
Figure 3. Crescendo of a F4 played with a trombone. Left : time pressure signal (up) and spectrogram (down) of the source signal (channel 1) in the mouthpiece. Right : time pressure signal (up) and spectrogram (down) of the radiated pressure signal (channel 2) one meter far aaway from the trombone bell.
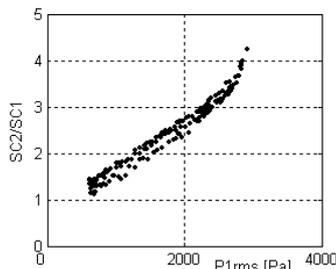

Figure 4. Ratio of the spectrum centroids SC2/SC1 of channel 2 and channel 1 as a function of the rms pressure P1rms of channel 1 (from experimental data Figure 3).

ELEPHANT TRUMPET SOUNDS, FROM SIGNAL TO SPECULATIVE THEORY

Sound analysis

Research on vocal communication in elephants has increased in recent years, both in the wild and in captivity, providing an opportunity to present a comprehensive review of research related to their vocal behaviour. Current data indicate that the vocal repertoire consists of perhaps nine acoustically distinct call types (Soltis, 2009), ''rumbles'' being the most common and acoustically variable. Large vocal production anatomy is responsible for the low-frequency nature of rumbles, with fundamental frequencies in the infrasonic range. Additionally, resonant frequencies of rumbles implicate the trunk in addition to the oral cavity in shaping the acoustic structure of rumbles. Beside "rumbles", one of the other call types is "trumpet" call. Trumpets are loud, co"brassy" trumpet call exhibits a rich harmonic structure. Because of the recording done inside a large hall having a long reverberation time and a noticeable background noise, the possibly existing very high harmonics might be concealed.

Because trumpeting is often associated with intensely social events, expressing the very high level of excitement and importance of the event, it is not easy to ask elephants for trumpet calls! If we are patient and wait for a long time, it is possible to get a wide variety of sounds and to analyze them. We have collected trumpet calls from African elephants in captivity, mainly coming from one young female (20 years old), in the "zoo de Beauval (Saint-Aignan, France). Some of them are perceived as brassy, some others as not brassy. As examples, the spectrogram of a "brassy" and of a "not brassy" trumpet call are displayed Figure 5.
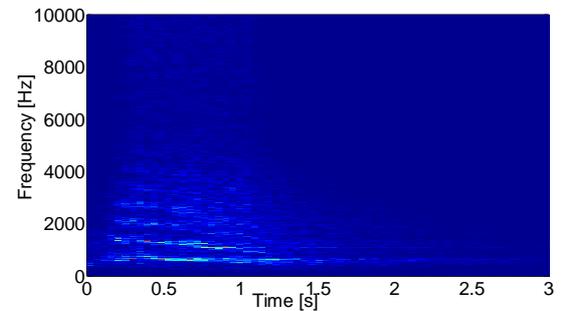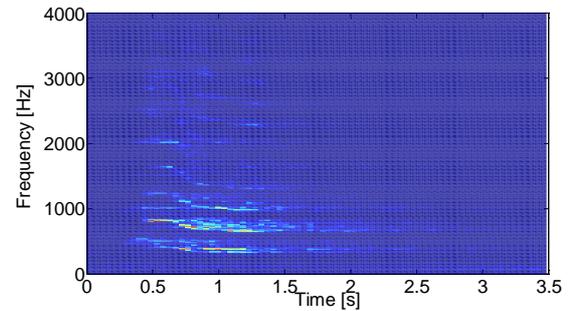

Figure 5. Spectrograms of elephant trumpet calls, a not brassy trumpet call (up) and a brassy one (down).

On one hand, the mismatch between the prediction of the simple model, often called "source-filter model", used for voice production and the observed structure of trumpets means that different or more complex models are required to explain the mechanical production of the elephant trumpet (Titze, 1994; Soltis, 2009). On the other hand, the wave steepening obtained during the nonlinear propagation along the internal bore is known as the explanation of brassy sounds (Hirschberg et al, 1996; Gilbert et al, 2008). Now the question is: is it plausible that nonlinear propagation effects are responsible for the "brassy" behaviour of some trumpet calls? This speculative question is tackled in the following chapter.nspicuous high-frequency calls. They are in the frequency range of 405–5879 Hz with a mean duration of about 1 s. They have a rich harmonic structure with at least seven clearly visible harmonics (study on asian elephants from Nair et al, 2009).

Some elephant trumpeting sounds are perceived very similar to a trumpet or a trombone sound especially when playing "brassy". This kind of brassy sounds played at high level dynamic, are made of many harmonics.

Theoretical considerations and discussion

As written before, a way to evaluate nonlinear propagation relevance is to estimate the critical distance x_s (Equation 1). To do so, the source signal $p_m(t)$ in the entrance of the resonator, that is near the vocal folds, is needed. We are not able to provide this signal for elephants! The only possible thing to do, is to do a rough estimate of $p_m(t)$ features from the radiated pressure $p_{rad}(t)$.

From the radiated pressure of the trumpet call displayed Figure 5, a typical amplitude of 10 Pa is estimated (rms level of 110 dB). Assuming that the signal has been recorded a distance d equal to 4 meters away from the output of the trunk, then the volume flow Q_{out} of the equivalent monopole source located at the trunk end can be estimated from the following equation:

$$P_{rad} = \frac{\rho}{4\pi d}\, j\omega Q_{out}, \tag{3}$$

where ω=2π.F with F=750 Hz. Assuming a pure travelling wave, an estimation of the acoustic pressure amplitude P can be done from the following equation:

$$P = \frac{\rho c}{S} Q_{out},$$ (4)

where $S = \pi R^2$ with R=5 cm.. Then the value obtained for P is around 5750 Pa, and the deduced critical distance x_s (Equation 1) is 1.45 m. At the end, it appears that the shock length distance x_s is something like 1 or 2 meters, which is comparable with the trunk length. It means that nonlinear distortion during propagation inside the trunk is effective. Then the brassy aspect of trumpet calls can be explained as a consequence of nonlinear propagation in the extended vocal tract (including the trunk), behaving in the same way as brassy sounds from trumpet or trombone musical instruments.   .

CONCLUSION

Elephant trumpet calls are powerful sounds having a rich harmonic structure, 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 was obtained by estimating a realistic critical shock length distance x_s: the shock length distance x_s is comparable to the trunk length. 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.

In literature, trumpet calls are sometimes associated with a "second voice" behaviour (Soltis, 2009). As far as we know, we have not found detailed explanations of this "second voice" process. It seems that this assumption comes from the fact that the rich harmonic structure and high fundamental frequency of the trumpet calls can not be explained from the classical source-filter model of voice production. In this paper, by comparison with brass instruments behaviour, it has been seen that the classical model can be retained if the linear propagation approximation is dropped.

AKNOWLEDGMENTS

REFERENCES

Fletcher, N.H. (**2007**), *Animal bioacoustics* in Springer Handbook of Acoustics ed. T.D. Rossing, Ch. 19, pp.785–804 (New York, Springer).

Gilbert, J., Campbell D-M, Myers, A., and Pyle, R. W. (**2007**), "Difference between brass instruments arising from variations in brassiness due to non-linear propagation," Proceedings of International Symposium of Musical Acoustics, Barcelona.

Gilbert, J., Menguy, L., Campbell D-M. (**2008**), "A simulation tool for brassiness studies," J. Acoust. Soc. Am. **123**, 1854-1857

Hamilton, M. F. and Blackstock, D. T., editors (**1998**), *Nonlinea Acoustics*. Academic, New York.

Hirschberg, A., Gilbert, J., Msallam, R., Wijnands, A.P.J. (**1996**). "Shock waves in trombones," J. Acoust. Soc. Am. **99**, 1754-1758.

Nair, S., Balakrishnana, R., Seelamantula, C.S., Sukumar, R. (**2009**). "Vocalizations of wild Asian elephants (Elephas maximus): Structural classification and social context," J. Acoust. Soc. Am. **126**, 2768-2778.

Pierce, A.D. (**1989**), *Acoustics*. Acoustical Society of America, Woodbury, NY, 2nd ed.

Soltis, J. (**2009**), "Vocal Communication in African Elephants (Loxodonta africana)," Zoo Biology **28**, 1–18.

Stoeger-Horwath, A.S., Stoeger S., Schwammer, H.M., Kratochvil, H. (**2007**). "Call repertoire of infant African elephants: first insights into the early vocal ontogeny. J Acoust Soc Am **121**, 3922–3931.

Titze, I.R. (**1994**), *Principles of voice production*. Englewood Cliffs, NJ: Prentice Hall Inc.