Sussex Research Online

Is nonlinear propagation responsible for the brassiness of elephant trumpet calls?

Article (Unspecified)

Gilbert, Joël, Dalmont, Jean-Pierre, Potier, Romain and Reby, David (2014) Is nonlinear propagation responsible for the brassiness of elephant trumpet calls? Acta Acustica united with Acustica, 100 (4). pp. 734-738. ISSN 1610-1928

This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/50505/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

http://sro.sussex.ac.uk

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 100 (2014) 734 – 738

DOI 10.3813/AAA.918752

Is Nonlinear Propagation Responsible for the Brassiness of Elephant Trumpet Calls?

Joël Gilbert[1)], Jean-Pierre Dalmont[1)], Romain Potier[2)], David Reby[3)]

[1)] LUNAM Université, Université du Maine, LAUM (Laboratoire d'Acoustique de l'Université du Maine UMR CNRS 6613), Le Mans, France. joel.gilbert@univ-lemans.fr

[2)] Zoo de Beauval, Saint-Aignan, France

[3)] School of Psychology, University of Sussex, Brighton, UK.

Summary

African elephants (Loxodonta africana) produce a broad diversity of sounds ranging from infrasonic rumbles to much higher frequency trumpets. Trumpet calls are very loud voiced signals given by highly aroused elephants, and appear to be produced by a forceful expulsion of air through the trunk. Some trumpet calls have a very distinctive quality that is unique in the animal kingdom, but resemble the "brassy" sounds that can be produced with brass musical instruments such as trumpets or trombones.

Brassy musical sounds are characterised by a flat spectral slope caused by the nonlinear propagation of the source wave as it travels through the long bore of the instrument. The extent of this phenomenon, which normally occurs at high intensity levels (e.g. fortissimo), depends on the fundamental frequency (F0) of the source as well as on the length of the resonating tube.

Interestingly, the length of the vocal tract of the elephant (as measured from the vocal folds to the end of the trunk) approximates the critical length for shockwave formation, given the fundamental frequency and intensity of trumpet calls. We suggest that this phenomenon could explain the unique, distinctive brassy quality of elephant trumpet calls.

PACS no. 43.80.Ka

1. Introduction

Vocal communication in African elephants has received considerable attention in recent years (see [1] and [2] for recent reviews), leading to substantial advances in our knowledge of this iconic species' vocal repertoire, including a better understanding of the mechanisms of production of the calls [3, 4, 5, 6], their acoustic variability [3, 7, 2] and their function [8, 3, 7]. The vocal repertoire of the African elephant (Loxodonta africana) consists of several acoustically distinct call types, characterised by distinct combinations of duration, fundamental frequency, and resonance frequencies, pointing to distinct modes of production. Rumbles, the most common calls, have received much attention [3, 2, 4]. Rumbles are characterised by an extremely low fundamental frequency (approx. 16–18 Hz [3]) which directly reflects the extraordinary size of the elephant vocal folds [4]. Additionally, investigations of the resonance frequencies of rumbles indicate that the trunk is involved in addition to the oral cavity in shaping the spectral envelope of most, but not all, calls [3, 6]. Rumbles have been shown to encode information on individual identity [3], supporting the complex social recognition of large number of conspecifics [9, 8], over distances up to several kilometres [3].

At the other end of the fundamental frequency range, the trumpet call is also very distinctive. Trumpets are given by young and adult animals in a wide range of contexts, but typically when they are highly aroused [10] and the quality of the calls varies with the context [10, 1, 2]. Yet trumpet calls have received considerably less attention than rumbles, and the production mechanisms underlying their acoustic variation are much less well understood. Trumpets are loud, higher frequency sounds, that are assumed to be produced by a forceful expulsion of air through the trunk. In most mammals, including humans, the vocal apparatus comprises the lungs, the trachea, the larynx, the pharynx, and the nasal and oral cavities. According to the source-filter theory of voice production ([11, 12, 13], see [14] for a review of its application to nonhuman mammals), most voiced vocalizations result from a two-step production process. At the level of the larynx the sound source corresponds to the modulation of the airflow generated by the vocal folds, whose vibration determines the fundamental frequency (F0) of the vocalization. This source signal subsequently travels through the supra-laryngeal cavities of the vocal tract that act as a filter, adding 'formants' to the spectral envelope of the radiated vocalization. A key assumption of the original source-filter

---

Received 29 January 2014,
accepted 29 April 2014.

theory of voice production is that the source and the filter are independent, with no feedback of the vocal tract resonance on the vibratory regimes of the vocal folds, and a linear propagation of the signal through the filter element [11].

The production of elephant rumbles appears to follows the source-filter theory and linear acoustics: very large vocal folds (e.g. 10.4 cm [4]) are predicted to produce a proportionally low F0 (18.4 Hz, [4]), and the exceptionally long vocal tract (composed of the oral cavity and the trunk, for a total length estimated between 2.5 and 3.2 m [1, 3, 4]) accounts for the extremely low vocal tract resonances measured in these calls [3, 1]. Explaining the production of the trumpet call is much more challenging: not only is the very high F0 rather incompatible with the dimensions of the vocal folds (having led to the suggestion that a secondary source may be involved [1]), but the unusual brassy quality of the radiated signals is rather unique among vertebrate vocalisations.

The origin of the name of the call reflects its quality: most elephant ’trumpet’ calls sound very similar to the sounds produced by brass instruments such as trumpets or trombones, especially when they are played in a “brassy” mode. Such brassy sounds, typically played at high intensity levels, have strong upper harmonics as a consequence of the cumulative effect of nonlinear propagation along the long internal bore of the instrument [15] resulting in a steepening of the soundwave [16]. A key parameter for predicting the severity of this nonlinear steepening is the critical shock length distance [15] associated with the profile of the initial source signal (F0, amplitude and wave shape). When the length of the bore approaches this critical value, as is the case in brass instruments played at fortissimo level, the strong distortion of waves during their propagation inside the bore affects the spectral content of the radiated signal, conferring its distinctive brassy quality [17]. The exceptional length of the elephant’s trunk opens up the possibility that the nonlinear steepening effect might be significant during elephant trumpeting, as in brass instruments. Note that nonlinear propagation can be taken into account to explain subtle effects at intermediate dynamic levels in brass instruments [18].

Here we discuss this hypothesis by drawing a parallel between the production of brassy sounds in musical instruments and the production of trumpet calls in elephants. First we briefly review the physics of nonlinear acoustical propagation at the origin of the production of brassy sounds in musical instruments; second we discuss the possible relevance of nonlinear propagation to the production and resulting acoustics of elephant trumpet calls.

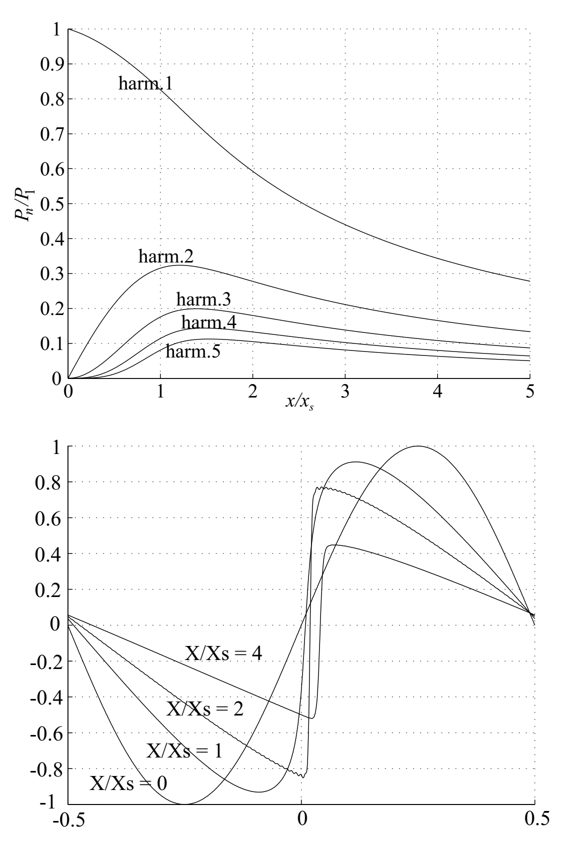

Figure 1. (a) Relative pressure amplitude of harmonic components (harm 1, harm 2 etc.) as a function of the relative distance of propagation x/x_s (varying from 0 to 5) for a wave generated by a monofrequency source (at $x = 0$). The graph represents the dimensionless ratio of the first five Fourier coefficients Pn (corresponding to the first five harmonics of the propagating signal) over the value of the pressure amplitude P1 at $x = 0$ (corresponding to the amplitude of the original pure sinusoid source), plotted against the dimensionless propagation distance x/x_s for a weakly dissipative fluid. (b) A period of the relative pressure signal as a function of dimensionless time. The graph represents four signals: the original pure sinusoid source (at $x/x_s = 0$), and the signal at $x/x_s = 1$, 2, and 4.

2. Nonlinear propagation in tubes

Most phenomena involving the propagation of audible acoustic waves in tubes are concerned with smallamplitude disturbances, where nonlinear effects are typically of minor significance. In this context the basic equations of fluid flow can be linearised into the simpler time-domain wave equation [19]. There are, however, situations when small nonlinear terms in the equations can lead to novel and substantial phenomena. One such example is the phenomenon of wave distortion along propagation in tubes, which, in extreme cases (achieved in long tubes approaching a critical distance) can lead to the formation of shockwaves. Indeed, due to the increase in the speed of sound with temperature and convective effects, the top of the compression side of the wave tends to catch up with the foot of the wave, leading to the formation of the shockwave ([19], illustrated in Figure 1). If we consider the frictionless, simple wave propagation of a source pressure (at $x = 0$) along a pipe of uniform cross section and with with perfectly rigid walls, the critical distance x_s around which shockwave will be formed can be predicted by the following equation (based on the classical method of characteristics [19]):

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

where $\gamma = 1.4$ is the Poisson constant, P_{at} is the atmospheric pressure, c is the speed of sound in the air, p_m is the acoustic pressure at the source ($x = 0$), and the term $(\partial p_m / \partial t)_{\max}$ is the maximum value of the derivative of the acoustic pressure over a period.

Comparing the geometrical length L of the tube to the critical distance x_s allows us to predict if nonlinear propagation effects are likely to be relevant [15]. If L is much shorter than x_s, the linear theory of acoustic propagation is sufficient. However, if L approaches or surpasses x_s nonlinear propagation must be considered.

Figure 1 (adapted from Gilbert *et al.* [20]) illustrates how the steepening of the wave in the time domain (Figure 1a) is represented by the 'harmonic cascade' phenomenon in the frequency domain (Figure 1b). As the wave moves away from a sinusoidal profile towards a distorted, saw-tooth profile, the energy from the fundamental (harm 1) is redistributed towards the upper harmonics (harm 2, harm 3 etc.). The relative distribution of energy between the harmonics (harm 1, harm 2 etc.) changes as a function of the ratio of the propagation distance (x) over the critical distance x_s. For small values of x/x_s, the amplitude P1 of the fundamental decreases as energy is transferred to higher harmonics. When x/x_s approaches 1, the amplitude P2, P3 etc. of the upper harmonics increases dramatically as a shock wave is formed. While the shock wave phenomenon persists for a range of higher x/x_s ratios, its amplitude decreases slowly (remaining significant for x/x_s ratios of at least 5, as illustrated on Figure 1a and 1b). Due to wall and volumic losses, the phenomenon is reversed as x/x_s further increases: the amplitudes Pn decrease and the profile of the wave tends back towards a sinus for very long tubes characterised by very high values of x/x_s.

This harmonic cascade phenomenon, which takes place during propagation inside the tube, affects the spectral composition of the radiated sound by shifting energy towards the upper harmonics and modifies the perceived tone colour of the signal. As explained above, this phenomenon is at the basis of the production of brassy sounds in brass instruments: the brightness of the sound generated at high dynamic level is mainly due to the nonlinearity of the wave propagation in the pipe [15]. While, independently of its amplitude, the source signal produced at the mouthpiece is rather sinusoidal (with a weak harmonic content [21] its nonlinear propagation along the tube results in a distorted wave with high, broadband harmonic content. This phenomenon is illustrated in Figure 2, which contrasts spectrograms of two signals obtained from a 3m long hose-pipe fitted with a trombone mouthpiece. The first spectrogram corresponds to a non-brassy sound achieved by playing softly, and the second spectrogram corresponds to a brassy sound achieved by playing loudly. In the first signal (Figure 2a), because the low intensity of the source wave (produced by the vibrating lips at the mouthpiece) implies a critical distance x_s much longer than the hose pipe (equation 1), there is no noticeable nonlinear propagation effect in the tube. Consequently, the spectral envelope of the radiated signal is driven by the spectral content of the source and unaffected by nonlinear distortion, and the sound is characterised by relatively strong lower harmonics, and a relatively "fluty" quality. In contrast, in the second signal (Figure 2b), the high intensity of the source wave implies a critical distance comparable to the length of the hose pipe. The strong nonlinear propagation in the tube dramatically distorts the signal and reduces the spectral slope of the radiated signal: the sound is characterised by relatively strong higher harmonics, and a strong "brassy" quality.

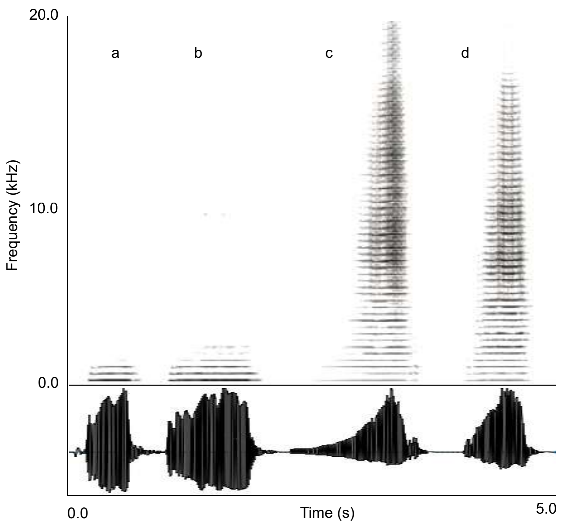

Figure 2. Spectrograms of four sounds produced with a 3 m hose pipe. (a) and (b) are lower amplitude, "non-brassy" sounds produced with a low intensity source, and not involving nonlinear propagation. (c) and (d) are higher amplitude, "brassy" sounds produced with a high (increasing) intensity source, and involving nonlinear propagation. Note the redistribution of acoustic energy towards the higher harmonics. All sounds have been normalised to 100% to highlight the relative energy distribution across the frequency domain. Sounds were recorded using a Zoom H4N digital recorded (44.1kH, 16bits, uncompressed format), at a distance of 1 m). The dynamic range of the spectrogram is 30 dB.

3. Acoustic analyses of Elephant trumpet sounds

We recorded 28 trumpet calls from one 20 year-old female African elephant at the Zoo de Beauval (Saint- Aignan, France), with a Zoom H4N recorder. Naturally occurring calls were recorded at feeding time, without interacting with the animal. Calls were recorded in stereo at a 44.1k Hz sampling rate with 32 bit resolution and saved in uncompressed WAV format. Narrow-band spectrograms were produced using PRAAT 5.3.59 [22], using a view

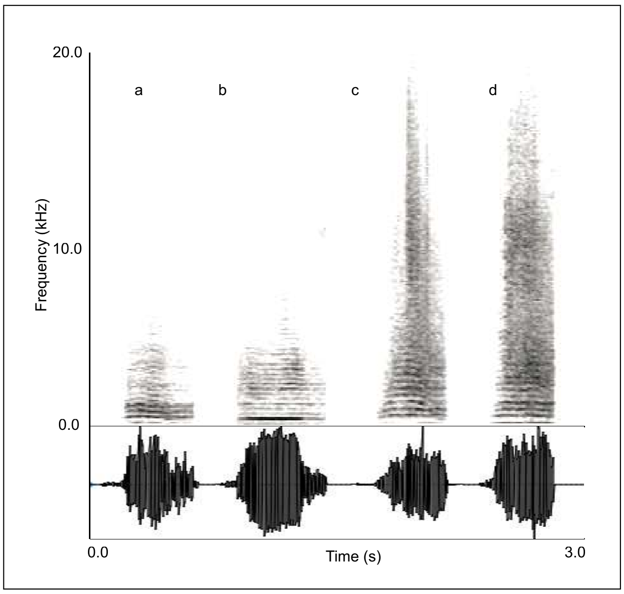

Figure 3. Spectrograms of four trumpet calls recorded from a female African elephant. (a) and (b) are lower amplitude, "non-brassy" trumpet calls probably not involving nonlinear propagation. (c) and (d) are higher amplitude, "brassy" trumpet calls probably involving nonlinear propagation. Note the redistribution of acoustic energy towards the higher harmonics. All calls have been normalised to 100% to highlight the relative energy distribution across the frequency domain. Brassy calls were typically characterised by higher SPL than 'tonal' calls. The "tonal" trumpet calls have F0s of (a): 290 Hz and (b): 262 Hz, while the brassy calls have F0s of (c): 352 Hz and (d): 335 Hz. The dynamic range of the spectrogram is 30 dB.

range of 0-10k Hz and a window length of 0.1s. Of these 28 calls, 13 had a relatively tonal quality, 13 had a typical brassy quality (assessed perceptually, see representative spectrograms in Figure 3), and two contained both tonal and brassy sections. While the amplitude of the calls was not systematically measured, when both call types were recorded in the same sequence, brassy trumpets typically had a higher amplitude than non-brassy trumpets.

The mean fundamental frequency (measured using the pulse detection algorithm implemented in the "voice report" function in PRAAT) averaged 355.5 Hz across the 28 calls, a value comparable to that published in studies of African elephant trumpets (300 Hz: [1]). One of the brassy calls had a very noisy quality and an exceptionally high F0 (660 Hz). The fundamental frequency of the tonal trumpets (337.4 Hz) was significantly lower than that of the brassy trumpets (382.6 Hz) $t_{22} = 2.96$, $P < 0.007$.

As discussed above, a key factor for evaluating the relevance of nonlinear propagation is to estimate the critical distance x_s (equation 1) at which it is likely to occur given a F0. For this, we need to estimate the amplitude of the glottal source $p_m(t)$ at the entrance of the resonator. Since data from excised larynx experiments is only available for low frequency vibratory regimes characteristic of rumbles and observed in the absence of a vocal tract [4], and because it is not possible to measure $p_m(t)$ during trumpeting in a live elephant, we must rely on a rough estimate of $p_m(t)$ obtained from the measured radiated pressure $p_{\mathrm{rad}}(t)$.

Approximating the nostrils' opening as a monopole source, its volume flow Q_{out} is estimated from the following equation (see for example [23]):

$$p_{\mathrm{rad}} = \frac{\rho}{4\pi d} \mathrm{j} 2\pi F0 Q_{\mathrm{out}}. \tag{2}$$

Assuming a plane travelling wave inside the trunk, the acoustic pressure amplitude P can be derived from

$$P = \frac{\rho c}{S} Q_{\mathrm{out}}, \tag{3}$$

where S is the nostril area in cm^2.

Using a F0 of 382 Hz (corresponding to the average F0 in the brassy calls of the elephant), an estimated nostril area of $S = 25\,\mathrm{cm}^2$ (2 nostrils with a 4 cm diameter, Roland Frey, pers. comm.), and an amplitude of $\sim$6 Pa (110 dB SPL, measured from one trumpet call recorded at 3 m by JG), P is estimated at $\sim$13500 Pa, and applying equation (1), the deduced critical distance x_s is $\sim$1.25 m. This critical distance indicates that, for the amplitude and F0 specified above, nonlinear propagation is likely to substantial for tubes from 1 m up to at least 6 m. This range is compatible with the unusual length of the elephant vocal tract (oral cavity and trunk) in this species, suggesting that nonlinear distortion during propagation inside the trunk is highly likely in high intensity trumpet calls.

This study does not claim to provide proof that nonlinear propagation is involved in the production of trumpet calls by elephants, but rather to show that the phenomenon is compatible with the dimensions of the elephant vocal tract (assuming that the sound source is located upstream from the trunk) and with acoustic characteristics of the calls: brass instruments and elephants share a key characteristic: a very long, tubular resonator favourable to nonlinear propagation, and both can produce high amplitude sounds characterised by a rich harmonic structure and a distinctive "brassy" quality. In fact, skilled trombone players can produce highly realistic elephant trumpet calls. Finally, it is important to note that other non-linear phenomena evidenced in studies of human voice production (reviewed in Herbst et al., in press) may generalize to vocal production in elephants and partially contribute to the observed increase of upper harmonics in the radiated sound. An increase in subglottal pressure in voice production or mouth pressure in wind instruments is likely to increase the duration of the closed phase of vocal fold vibration, with more abrupt vocal fold collisions and separations inducing more abrupt cessation and acceleration of glottal airflow. Moreover, interactions between the vocal tract and the sound source, where the positive reactance of the vocal tract caused by the inertance of the air column can influence also the wave shape of the glottal air pulse (especially in elephant trumpet calls where F0 is likely to be above the first vocal tract resonance, see [24, 25]). Finally, the narrowing of supralaryngeal structures may cause skewing of the glottal flow pulse [26].

Further work is now clearly needed to locate the glottal source in elephant trumpeting, and if the laryngeal vocal folds are involved to explain how such large folds can produce a relatively high F0. Moreover, further work is also warranted to systematically measure the amplitude and frequency characteristics in calls from a sufficient number of elephants in order to compare the covariation of acoustic parameters in vocalisations with that predicted by the models of production outlined above. Finally, the relevance of nonlinear propagation should also be considered in other species producing high intensity, high pitched calls and possessing relatively unusually vocal tract, including birds with long tracheas such e.g. geese (*Anser sp.*) trumpeter swans (*Cygnus buccinator*).

Acknowledgement

The authors would like to thank the team responsible for the elephants at the Beauval zoo, and Marc Brossier for their assistance during the recording of the trumpet calls. We also thank the reviewers and Christian Herbst for extremely useful comments on an earlier version of the manuscript.

References

[1] J. Soltis: Vocal communication in African elephants (Loxodonta africana). Zoo. Biology **28** (2009) 1–18.

[2] J. H. Poole: The behavioral context of African elephant acoustic communication. – In: The Amboseli Elephants: A Long-Term Perspective on a Long-Lived Mammal. C. J. Moss, H. J. Croze, P. C. Lee (eds.). University of Chicago Press, 2011.

[3] K. McComb, D. Reby, L. Baker, C. Moss, S. Sayialel: Long-distance communication of social identity in African elephants. Animal Behaviour **65** (2003) 317–329.

[4] C. T. Herbst, A. S. Stoeger, R. Frey, J. Lohscheller, I. R. Titze et al.: How low can you go? Physical production mechanism of elephant infrasonic vocalizations. Science **337** (2012) 595–599.

[5] C. T. Herbst, J. G. Svec, J. Lohscheller, R. Frey, M. Gumpenberger, A. S. Stoeger, W. T. Fitch: Complex vibratory patterns in an elephant larynx. J. Exp. Biol. **216** (2013) 4054–4064.

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

[7] K. McComb, D. Reby, C. Moss: Vocal communication and social knowledge in African elephants. – In: The Amboseli Elephants: a long-term perspective on a long-lived mammal. C. J. Moss, H. J. Croze (eds.). Chicago University Press, Chicago, 2011.

[8] K. McComb, C. Moss, S. Durant, L. Baker, S. Sayialel: Matriarchs act as repositories of social knowledge in African elephants. Science **292** (2001) 491–494.

[9] K. McComb, C. Moss, S. Sayialel, L. Baker: Unusually extensive networks of vocal recognition in African elephants. Animal Behaviour **59** (2000) 1103–1109.

[10] J. K. Berg: Vocalizations and associated behaviors of the African elephant (Loxodonta africana) in captivity. Z. Tierpsychol. **63** (1983) 63–79.

[11] G. Fant: Acoustic theory of speech production. De Gruyter, 1970.

[12] M. J. Owren: Acoustic classification of alarm calls by vervet monkeys (Cercopithecus aethiops) and humans (Homo sapiens). I: Natural calls. J. Comp. Psychol. **104** (1990) 20–28.

[13] W. T. Fitch: Vocal tract length and formant frequency dispersion correlate with body size in rhesus macaques. J. Acoust. Soc. Am. **102** (1997) 1213–1222.

[14] A. M. Taylor, D. Reby: The contribution of source-filter theory to mammal vocal communication research. J. Zool. **280** (2010) 221–236.

[15] A. Hirschberg, J. Gilbert, R. Msallam, A. P. J. Wijnands: Shock waves in trombones. J. Acoust. Soc. Am. **99** (1996) 1754–1758.

[16] M. F. Hamilton, e. Blackstock, D. T.: Nonlinear acoustics. Academic, New York, 1998.

[17] A. Myers, R. W. Pyle, J. Gilbert, D.-M. Campbell, S. Logie, J. P. Chick: Effects of nonlinear sound propagation on the characteristic timbres of brass instruments. J. Acoust. Soc. Am. **131** (2012) 678–688.

[18] L. Norman, J. Chick, D. Campbell, A. Myers, J. Gilbert: Player control of ‘brassiness’ at intermediate dynamic levels in brass instruments. Acta Acustica united with Acta Acustica **96** (2010) 614–621.

[19] A. D. Pierce: Acoustics. 2nd ed. Acoustical Society of America, Woodbury, NY, 1989.

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

[21] S. Bromage, J. Gilbert, C. D.-M.: Open areas of vibrating lips in trombone playing. Acta Acustica united with Acustica **96** (2010) 603–611.

[22] W. Bo, A. Van Hirtum, X. Pelorson, L. Xiaoyu: The influence of glottal cross-section shape on theoretical flow models. J. Acoust. Soc. Am. **134** (2013) 909–912.

[23] A. Chaigne, e. Kergomard, J.: Acoustique des instruments de musique. Belin, Paris, 2008.

[24] M. Rothenberg: Acoustic interaction between the glottal source and the vocal tract. – In: Vocal Fold Physiology. K. N. Stevens, M. Hirano (eds.). University of Tokyo Press, Tokyo, 1981, 305–328.

[25] I. R. Titze: A theoretical study of F0-F1 interaction with application to resonant speaking and singing voice. J. Voice **18** (2004) 292–298.

[26] I. R. Titze: Nonlinear source-filter coupling in phonation: theory. J. Acoust. Soc. Am. **123** (2008) 2733–2749.

[27] N. H. Fletcher: Animal bioacoustics. – In: Springer Handbook of Acoustics. T. D. Rossing (ed.). Springer, New York, 2007, Ch. 19, pp.785–804.

[28] J. Gilbert, D.-M. Campbell, A. Myers, R. W. Pyle: Difference between brass instruments arising from variations in brassiness due to non-linear propagation. Proceedings of International Symposium of Musical Acoustics, Barcelona, 2007.

[29] C. T. Herbst, D. M. Howard, J. G. Svec: The sound source in singing - basic principles and muscular adjustments for fine-tuning vocal timbre. – In: The Oxford Handbook of Singing. G. Welch, othets (eds.). Oxford University Press, Oxford, UK, in press.

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

[31] I. R. Titze: Principles of voice production. Prentice Hall Inc., Englewood Cliffs, NJ, 1994.

[32] I. R. Titze: Theory of glottal airflow and source-filter interaction in speaking and singing. Acta Acustica united with Acustica **90** (2004) 641–648.