Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia (2016) 000–000

Physics Procedia

www.elsevier.com/locate/procedia

44th Annual Symposium of the Ultrasonic Industry Association, UIA 44th Symposium, 20-22 April 2015, Washington, DC, USA and of the 45th Annual Symposium of the Ultrasonic Industry Association, UIA 45th Symposium, 4-6 April 2016, Seattle, WA, USA

Directional receiver for biomimetic sonar system

Francesco Guarato[a,]*, Heather Andrews[a], James F. Windmill[a], Joseph Jackson[a], Anthony Gachagan[a]

[a]*Centre for Ultrasonic Engineering, University of Strathclyde, 204 George Street, Glasgow G1 1XW, UK*

Abstract

An ultrasonic localization method for a sonar system equipped with an emitter and two directional receivers and inspired by bat echolocation uses knowledge of the beam pattern of the receivers to estimate target orientation. *Rousettus leschenaultii*'s left ear constitutes the model for the design of the optimal receiver for this sonar system and 3D printing was used to fabricate receiver structures comprising of two truncated cones with an elliptical external perimeter and a parabolic flare rate in the upper part. Measurements show one receiver has a predominant lobe in the same region and with similar attenuation values as the bat ear model. The final sonar system is to be mounted on vehicular and aerial robots which require remote control for motion and sensors for estimation of each robot's location.

Peer-review under responsibility of the Ultrasonic Industry Association.

Keywords: receiver design; beam pattern; robot navigation; acoustic measurement.

1. Introduction

Vehicular and aerial robots can transport ultrasonic sensors for NDE, Friedrich et al. (2006). They are a cheap solution and useful when exploring dangerous or non-accessible areas. A sonar system to support them with autonomous navigation was developed by Guarato et al. (2012), Guarato et al. (2013). Such a sonar system is able to reproduce bat echolocation, and is equipped with an emitter and two receivers resembling the mutual displacement

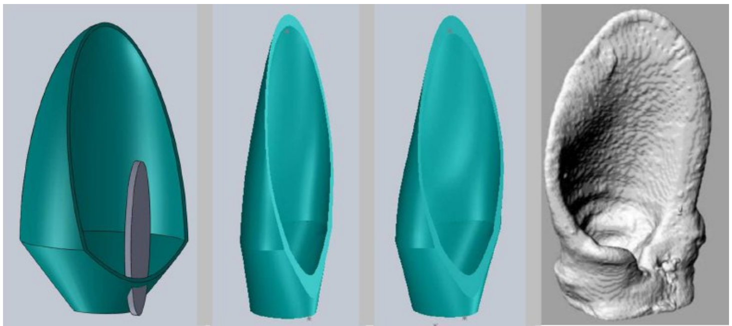
* Corresponding author. Tel.: +44 (0)141 444 7409.
E-mail address: francesco.guarato@strath.ac.uk

1875-3892 © 2016 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Ultrasonic Industry Association.

of mouth and ears, respectively, on a bat head. The localization method implemented on it uses the directional properties of the two receivers to estimate the orientation of a target. As the beam pattern of bats plays a crucial role in echolocation, Lawrence et al. (1982), thus the design of receiver shape in the sonar system is inspired in this paper by a bats' external ear. In particular, in this paper the external ear of a *Rousettus leschenaultii* is considered and some receiver shapes are derived from it. In the receivers' design, parameters such as perimeter, tragus and outward bending of edges are considered and evaluated as important factors in the beam pattern corresponding to the final receiver. Inspiration from bat sonar has led to other sonar systems such as those presented by Reijniers et al. (2007) and Kuc (2012).

2. Bat-inspired receivers

The beam pattern of several receiver structures inspired by *R. leschenaultii*'s left ear was measured. The design of these receivers is modelled on the basic receiver shape by varying the following parameters: perimeter (circular or elliptical), presence or absence of tragus (flat structure in front of the upper opening) and outward bending of upper edges of the receiver. These parameters contribute to approximate the basic receiver shape to that of the *R. leschenaultii*'s left ear. These parameters were considered and their effect on the beam pattern was measured. Fig. 1.A shows the basic receiver. Fig. 1.B Template 1 was obtained from the basic receiver by using an elliptical perimeter and removing the tragus, while Fig. 1.C shows Template 2 where upper edges, in addition to the features of Template 1, were bent outward. These modifications to the basic receiver led to a receiver structure more similar to the *R. leschenaultii*'s left ear, depicted in Fig. 1.D.



1.A **1.B** **1.C** **1.D**

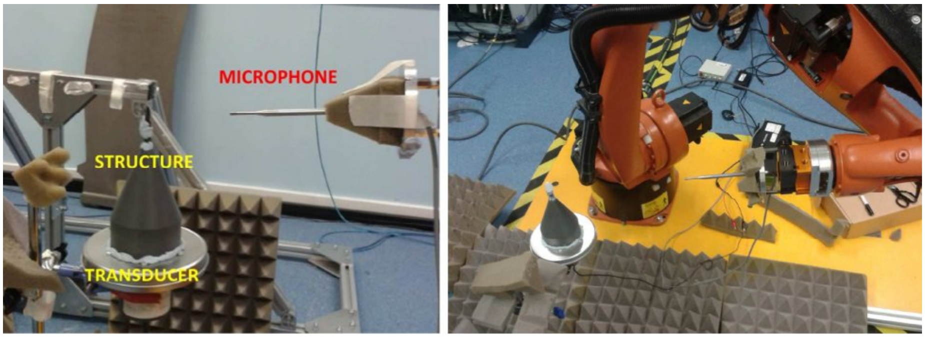
Fig. 1 (A) Basic receiver, (B) Template #1, (C) Template #2 and (D) *R. leschenaultii*'s ear.

3. Beam pattern evaluation

3.1. Measurements

Receiver structures such as those in Fig. 1.A-D were designed in SolidWorks and 3D printed. The beam patterns associated with these receivers were measured using the reciprocity principle, see Shaw (1988) and Fahy (2003). Namely, a 1ms long chirp from 20kHz to 32kHz (which the bat specie uses to echolocate) from an electrostatic transducer (Ultrasound Advice Loudspeaker http://www.ultrasoundadvice.co.uk/index.php/ultrasound/usls last viewed August 3, 2015) was conveyed to the base of each structure through a funnel as depicted in Fig. 2.A. The signal through the structure was recorded with a Brüel & Kjær 4138 microphone at several positions on the surface of a quarter of a sphere. Exact positioning of the tip of the microphone was automatically performed by a KUKA robot (KUKA robotics http://www.kuka-robotics.com/usa/en/ last viewed August 3, 2015), see Fig. 2.B. The sound emission from the transducer was triggered by the robot moving to the next position, monitored and controlled through a program written in LabVIEW. An average of 5 replications of the chirp returned a signal for each position on which a Fourier transform was calculated. For each orientation (θ,φ) and frequency f, the Fourier transform $M(\theta,\varphi,f)$ of measurement signals on the quarter of sphere were compared to a reference signal $R(f)$ (the chirp recorded in front of the transducer with no filtering of any structure to get rid of non-linearity effects due to the transducer itself). Thus the filtering D due to only the beam pattern associated with the structure was returned:

$$D(\theta,\phi,f) = \frac{M(\theta,\phi,f)}{R(f)} \tag{1}$$



2.A **2.B**

Fig. 2 Beam pattern measurement: (A) Microphone recording sound from the transducer and through the receiver structure; (B) KUKA robot controlling microphone position around the receiver structure.

3.2. Evaluation and discussion

For each frequency in the range 20kHz to 32kHz the energy distribution is considered. Fig. 3 shows contour plots detailing the signal attenuation over azimuth and elevation angles for Templates 1 and 2, and thus comparisons to the beam pattern associated with *R. leschenaultii*'s left ear. The main acoustic feature for all receivers is the main lobe extending over azimuth (45° to 170° depending on frequency) and elevation (20° to 45°). Both templates are very directional and also approximate the beam pattern of the bat ear in the attenuation values for each frequency. In particular, Template 2 has a more definite main lobe over orientations at low frequencies, unlike Template 1.

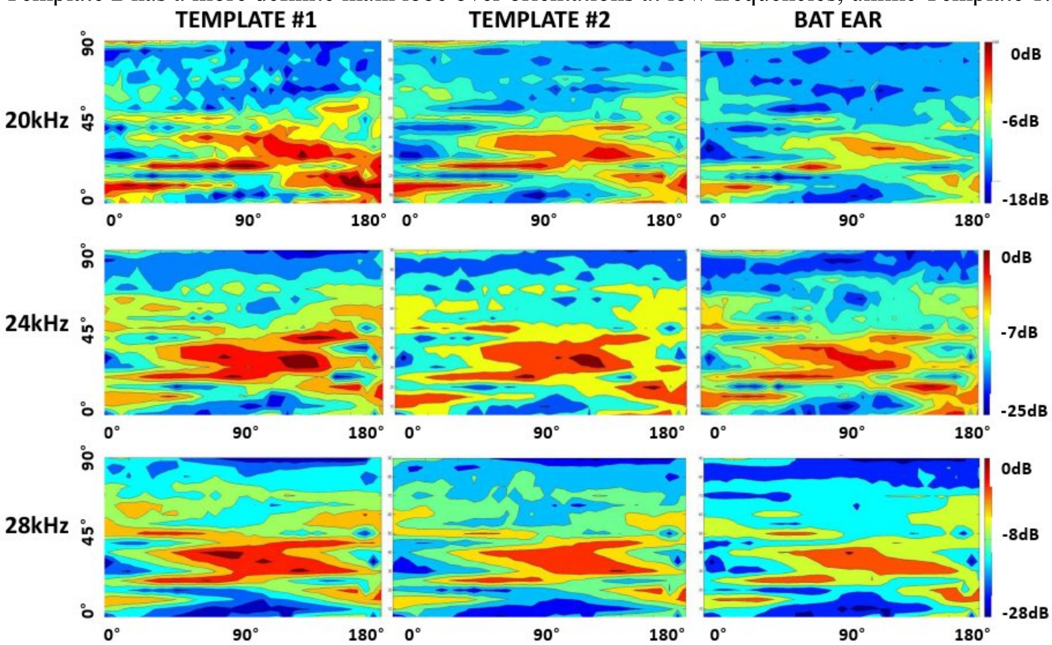


Fig. 3. Contour plots depicting the receivers' beam patterns over azimuth and elevation angles (degrees) and for frequency values 20kHz, 24kHz and 28kHz. The azimuth and elevation intervals correspond to the quarter of sphere in front of the upper opening of each receiver.

Template 2 differs from Template 1 as its upper edges are bent toward the outside, thus forming a more defined beam pattern at low frequencies (20kHz) and a narrower main lobe at high frequencies (as at 28kHz). The beam pattern associated with the basic receiver of Fig. 1.A instead showed no main lobe within the range 20kHz to 32kHz as most of the acoustic energy was directed to elevations 50° to 90°.

Results in Fig. 3 show that the elliptical perimeter is the main feature associated with a directional beam pattern as it provides Templates 1 and 2 with a prominent main lobe whose extension over orientations resembles that of *R. leschenaultii*'s. Finally, the outward bending has a beamforming effect at low frequencies, i.e. 20kHz. On the other hand, the presence of the tragus is not a fundamental feature for the directional properties of these receivers.

The results shown in Fig. 3 were measured by some of the authors and are original in this paper.

In order to evaluate which template best approximates the acoustic behavior of the bat ear in the frequency range 20kHz to 32kHz, the beam patterns of both templates are compared to the one associated with the bat ear in terms of the main lobe's angular extension and its maximum gain value. Table 1 reports the angular domain both in azimuth and elevation of the main lobe for each receiver: to define this domain, a threshold gain value was set in all beam patterns. In addition, Fig. 4 shows the maximum gain values in the frequency range 20kHz to 32 kHz for the beam patterns associated with the two templates and the *R. leschenaultii*'s ear.

Table 1. Angular extension in azimuth and elevation of main lobe for beam patterns at some frequencies.

Frequency	Template 1 Azimuth range	Template 1 Elevation range	Template 2 Azimuth range	Template 2 Elevation range	Bat ear Azimuth range	Bat ear Elevation range
20kHz	[25°, 170°]	[20°, 45°]	[45°, 160°]	[25°, 40°]	[80°, 160°]	[25°, 40°]
24kHz	[30°, 160°]	[20°, 45°]	[20°, 160°]	[20°, 45°]	[20°, 150°]	[25°, 45°]
28kHz	[30°, 160°]	[20°, 45°]	[50°, 160°]	[25°, 45°]	[50°, 160°]	[25°, 40°]

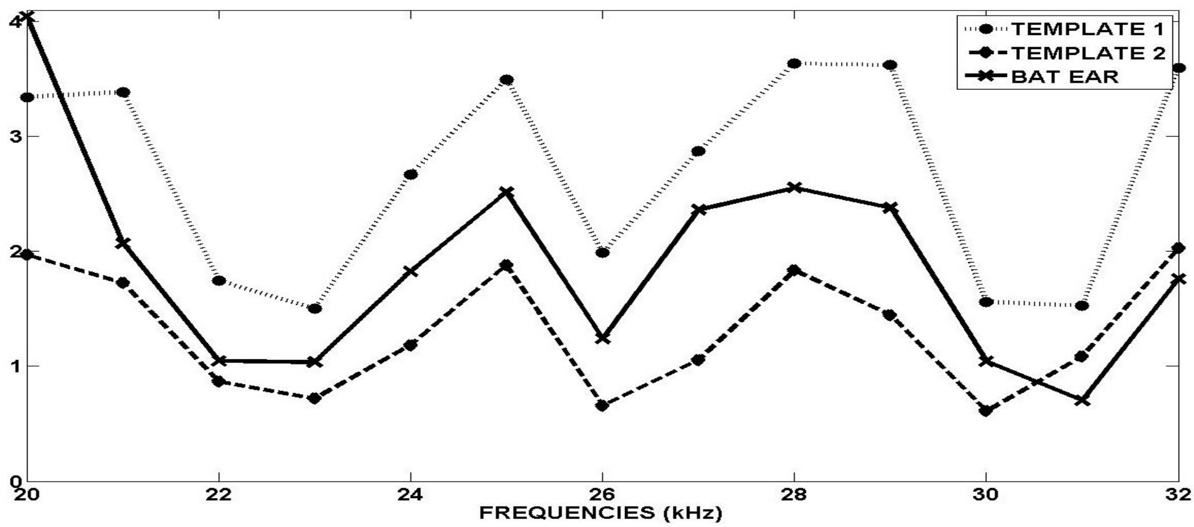


Fig. 4. Maximum value of beam pattern's main lobe associated with Templates 1 and 2 and *R. leschenaultii*'s ear.

The angular extensions in Table 1 show that both beam patterns associated with Template 1 and 2 have a main lobe with similar extension as the bat ear and for the same orientations. In particular, the main lobe associated with Template 2 has the closest angle values as *R. leschenaultii*'s. The beam patterns' maximum values in Fig. 4 for both templates follow the same trend as the bat ear's, though those associated with Template 2 are closer to the bat ear's across frequencies 20kHz to 32kHz.

4. Conclusions and future work

Two receiver structures, Template 1 and 2, were recovered from a basic receiver shape, Fig. 1, modelled on the external receiver of a *R. leschenaultii* bat specimen. Modifications to the basic receiver are the elliptical perimeter and the absence of tragus (Template 1) plus the outward bending of the upper edges (Template 2). These parameters allowed us to measure beam patterns approximating that associated with *R. leschenaultii*'s left ear. To quantify how well these Templates approximated the bat ear in the frequency range 20kHz to 32kHz, i.e. *R. leschenaultii*'s frequency range in echolocation, their directional main lobe was evaluated in its angular extension and maximum gain value across frequencies. Measurements show that Template 2 is a good approximation to this bat ear, and therefore that parameters like external perimeter, tragus and bending of the edges are crucial in the final beamforming.

Acknowledgements

This research is funded by the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement n. [615030], and the EPSRC Grant EP/G038627/1, *New Imaging Systems for Advanced Non-Destructive Evaluation*.

References

Friedrich, M., Galbraith, W., Hayward, G., 4I-1 Autonomous Mobile Robots for Ultrasonic NDE, Ultrasonics Symposium, 2006. IEEE, pp.902-905, 2-6 Oct. 2006.

Guarato, F., Windmill, J., & Gachagan, A. (2012, October). Sonar localization using receiver beam profile features. In 2012 IEEE International Ultrasonics Symposium (pp. 1-4). IEEE.

Guarato, F., Windmill, J., & Gachagan, A. (2013). A beam based method for target localization: Inspiration from bats' directivity and binaural reception for ultrasonic sonar. The Journal of the Acoustical Society of America, 133(6), pp. 4077-4086.

Lawrence B. D., Simmons J. A., Echolocation in bats: the external ear and perception of the vertical positions of targets. Science, 218(4571), pp. 481-483, 1982.

Reijniers, J., & Peremans, H. (2007). Biomimetic sonar system performing spectrum-based localization. IEEE Transactions on Robotics, 23(6), pp. 1151-1159.

Kuc, R. (2012). Echolocation with bat buzz emissions: Model and biomimetic sonar for elevation estimation. The Journal of the Acoustical Society of America, 131(1), pp. 561-568.

Shaw E. A. G., Diffuse field response, receiver impedance, and the acoustical reciprocity principle. The Journal of the Acoustical Society of America, 84, pp. 2284-2287 (1988).

Fahy F. J., Some applications of the reciprocity principle in experimental vibroacoustics, Acoustical Physics, 49(2), pp. 217-229 (2003).