EXPERIMENTAL METHOD FOR THE ACOUSTICAL MODELLING OF THE ECHOLOCATION PROCESS IN BATS.

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1 INTRODUCTION

The ability of bats to orientate, navigate and hunt for prey in complex environments using echolocation has been an active research topic since the seminal work of Griffin\(^1\) in the 1950s. Behavioural studies published during those last five decades have revealed a number of skills possessed by bats which relate to the design and engineering of manmade systems in the areas of sonar, medical imaging, robotic sensorimotor and navigation as well as hearing aids for humans. These skills include:

- The ability of bats to obtain highly accurate information regarding the relative position of separate objects, the number and position of glints on the same object or the surface texture of objects based solely on echolocation\(^2,3,4,5,6,7\).
- Their ability to navigate and localise targets in cluttered and noisy environments using auditory information\(^8,9,10,11\).
- Their ability to adjust the type and parameters of the echolocation call, switch between echolocation and passive sound localisation or, to a limited extent, use both in parallel depending on the task\(^12,13,14,15,16,17\).
- The use of specialised sensorimotor strategies during echolocation\(^18,19,20\).

Hitherto, several models have been put forward that describe the auditory physiology that underlies the aforementioned capabilities. However, most of those models rely on somewhat speculative assumptions as to the actual inputs to the bat’s auditory system. This input is completely described by the pair of acoustic pressure signals reaching the bat’s eardrums during the process of echolocation (barring the possible effect of other secondary mechanisms, e.g. bone conduction). As is described in further detail in the next section, the form of those signals depends on a number of parameters and mechanisms, namely the specific echolocation emission call, the directivity of the emission mechanism, the acoustic properties of propagation medium (air) and the objects surrounding the bat, as well as the acoustic properties of the receiving mechanism i.e. the bat’s external ear and head. Even though the acoustic modelling of each one of those parameters and mechanisms has been, to some extent, studied in isolation (see also the review in the next section), no complete acoustic model exists of the whole process. The objective of this paper is to put forward an experimental method that combines the modelling of all the aforementioned mechanisms and is hence capable of determining the actual inputs to the bat’s auditory system during the task of echolocation. The proposed method is described in Section 2 together with a brief review of relevant previous studies. The actual implementation of the method is currently work in progress and the experimental results obtained up to now are presented in Section 3. Finally, the planned further steps towards the complete implementation of the method are discussed in Section 4.

2 PROPOSED EXPERIMENTAL METHOD

The objective of the proposed experimental technique is described in Figure 1. The bat emits an echolocation signal which results in an acoustic pressure disturbance \(p_{\text{out}}(r,t)\) being created at point...
r and time t. The point r is taken to be on the line joining the (notional) centre of the bat’s head and the (notional) centre of the object under interrogation, at a distance r and azimuth and elevation angles $\theta$ and $\phi$ relative to the centre of the bat’s head. The created wavefront hits the object and an echo signal denoted by $p_{\text{echo}}(r,t)$ is created at point r. The echo travels back towards the bat and reaches its two eardrums after being diffracted by the pinnae and the head of the bat. We denote the pressure signals reaching the bat’s eardrums by the 2x1 vector $p_{\text{ear}}(t)$.

![Diagram](Image)

**Figure 1.** Schematic of the acoustics problem under discussion

The proposed method aims to determine those binaural signals $p_{\text{ear}}(t)$. This is done by splitting the whole process in three parts, each modelled as a linear and time invariant system. Modelling of the process as time invariant limits the applicability of the method to static geometries and hence the model cannot directly describe the echolocation process during the bat’s flight or the Doppler-related information obtained by moving targets (see also the discussion by Simmons and Chen$^{21}$). It does, however, directly apply to cases where the bat echolocates while hovering or perched and it should be expected to give a reasonable approximation to the echoes obtained during certain phases of the bat’s flight.

The first part of the method deals with the determination of the signal $p_{\text{out}}(r,t)$. As is well established, the emission of the echolocation call is significantly directional with the directivity pattern depending on the species and, in certain cases, also on the specific echolocation task$^{22}$. Hence, as is described in equation (1), a recording of a vocalisation $p_{\text{rec}}(r_{\text{rec}},t)$ that is obtained with a microphone directly in front of the bat’s head and at a distance $r_{\text{rec}}$ will need to be corrected by a frequency and angle dependent directivity pattern function $D(\theta,\phi,f)$ and a scaling $A_1$ for the determination of the pressure signal $p_{\text{out}}(r,t)$ at a different angle and distance from the bat’s head$^{23}$. In equation (1), the pressure signals appear in their frequency-domain representation with $f$ the frequency variable. The scaling parameter $A_1$, can be considered to be angle independent if the distances $r_{\text{rec}}$ and $r$ are in the far field of the acoustic radiation but it should be considered frequency dependent for the proper modelling of the air absorption in the frequency range of interest$^{24}$.

$$P_{\text{out}}(r,f) = A_1 D(\theta,\phi,f) P_{\text{rec}}(r_{\text{rec}},f)$$

(1)

Numerous studies$^{25,26,27}$ have appeared in the literature that present measurements of the echolocation call directivity function for various bat species. In most of those studies, the directionality pattern is presented as a function of discrete azimuth directions and a set of discrete frequencies that correspond to the fundamental and harmonics of the call signal of the species under consideration. Evidently, such a coarse frequency discretisation of the directivity pattern would not be sufficient for the determination of the signal $p_{\text{out}}$ by use of equation (1). Some studies have also appeared that attempt the analytical prediction of the directionality pattern. Depending on the species under consideration, those studies either model the emission mechanism as that of two sources spaced by a distance equal to the distance of the bat’s nostrils$^{28}$ or that of a piston source of appropriate dimensions$^{29}$ or a as a combination of the two$^{30}$. The degree of accuracy that could be obtained by the use of such models in equation (1) remains an open question for the authors. It is possible that a direct species-specific measurement of the signal $p_{\text{out}}$ is necessary for an effective implementation of the method. Such a measurement could be facilitated by the elicitation of the echolocation calls using brain microstimulation (see$^{25,26}$ and references therein). We note however
that, even in the absence of accurate knowledge of the signal $p_{out}$, the successful implementation of the following two parts of the method would allow its use for the determination of the binaural inputs corresponding to any given (and possibly artificial) emission signal.

The second part of the method deals with the determination of the signal $p_{echo}$. This practically reduces to the determination of the backscattering transfer function $H_{obj}$ that relates the incident pressure $p_{out}$ to the backscattered pressure $p_{echo}$ at the same position. This is a function of frequency as well as of the orientation of the object and its distance from the point $r$ at which $p_{out}$ and $p_{echo}$ are determined. With knowledge of $H_{obj}$, the signal $p_{echo}$ will be given by equation (2). A set of initial measurements for this part of the method has already been obtained and the results are presented and discussed in the next section.

$$P_{echo}(f) = H_{obj} (\text{orientation, distance}, f) P_{out}(f)$$  \hfill (2)

Finally, the third part of the method is concerned with the determination of the binaural signals $p_{ear}$. This is done by use of the concept of the Head Related Transfer Function (HRTF) and the binaural synthesis techniques\textsuperscript{31,32}. Even though originally studied in the context of human sound localisation, several studies exist that present measurements\textsuperscript{29,39,36,37,38,50} or numerically obtained models\textsuperscript{36} of bat HRTFs. Unlike those studies where the main objective is the identification of the localisation cues generated by the shape of the bat's pinna features, the objective here is to synthesise the binaural input signals on the basis of the free field signal $p_{echo}$. As is described in equation (3), each ear's HRTF for the given angle of azimuth and elevation is equal to the ratio between transfer functions $H_{angle}$ and $H_{ff}$. $H_{angle}$ relates the input to a source emitting sound from the specified direction to the output at the specified ear. $H_{ff}$ relates the input to the same source to the output at an omnidirectional microphone positioned at the free field. It follows that the HRTF is equal to the ratio of the pressure signal $p_{angle}$ created at the ear due to a source emitting a given signal at a given direction to the pressure signal $p_{ff}$ created by the same source emitting the same signal at the point of the centre of the head with no head present.

$$HRTF(\theta, \varphi, f) = \frac{H_{angle}(\theta, \varphi, f)}{H_{ff}(f)} = \frac{P_{angle}(\theta, \varphi, f)}{P_{ff}(f)}$$  \hfill (3)

In the case considered here we take the source to be the echo-creating object. This creates the free field pressure $p_{echo}$ at point $r$. By applying an appropriate scaling by a factor $A_2$ (in a similar fashion as the scaling $A_1$ described above), we can obtain the free field pressure at the point corresponding to the centre of the bat's head (see Figure 1). Each of the pressures $p_{ear}$ will then be given by equation (4), i.e. equal to the product of the HRTF of the corresponding ear with the scaled echo pressure. Concluding the description of the method we note that by virtue of the linearity of equations (1)-(4), the same procedure can be iterated for an arbitrary number of echo-generating objects placed at different positions and orientations in order to give the binaural input corresponding to a collection of objects or a cluttered environment.

$$P_{ear}(f) = A_2 p_{echo}(f) HRTF(\theta, \varphi, f)$$  \hfill (4)

3 EXPERIMENTAL RESULTS

In this section we present a set of measurements of the backscattering impulse response $h_{ob}$ of Section 2. In order to expedite the acquisition of a first set of experimental results, a simplification was imposed on the experimental arrangement. Hence, rather than implementing a data acquisition apparatus with usable frequency bandwidth extending up to the 150-200kHz highest frequency content known to be displayed by certain bat echolocation vocalisations\textsuperscript{10}, we restricted the upper end of the usable frequency range of our measurements to 40kHz. This made possible the use of an off-the-shelf piezoelectric tweeter as a source and of the MLSSA system\textsuperscript{33,34} for the

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measurement of the related impulse responses. Using similar measurements (but with a different source-receiver geometrical arrangement) made by Simmons and Chen\textsuperscript{21} as a reference, we scaled up the dimensions of our echo-generating objects and used three disks of 15mm, 31mm and 37mm diameter and 1.25mm, 7.5mm and 20mm thickness (denoted as “small”, “medium” and “large” respectively). For the measurement, the tweeter was driven by an audio amplifier with frequency bandwidth well in excess of 40kHz and the sampling frequency was set to 160kHz with MLSSA’s anti-aliasing filter set to cutoff at 40kHz. The receiver used was a B&K4135 ¼-inch microphone the output of which was obtained through a B&K2610 measuring amplifier. Both the source and the microphone were mounted on a custom-designed aluminium frame that allowed the precise alignment of the two with the echo-generating object and the rotation of the latter around a chosen axis. The microphone was positioned 22cm in front of the loudspeaker and the echo-generating object 43cm in front of the microphone. The experimental rig was mounted in an anechoic chamber.

In part (a) of Figure 2 we plot the impulse response obtained with a large hard reflective surface used as the echo-generating object. The impulse response can be seen to start with a part that corresponds to the direct path from the loudspeaker to the microphone at approximately the 135\textsuperscript{th} sample. The wavefront then hits the reflector and returns a substantial echo that can be seen at approximately the 540\textsuperscript{th} sample. Later reflections from the measurement apparatus can be seen to occur after that.

![Figure 2](image)

Figure 2. (a) Impulse response for a large reflecting surface, (b) free field equalized response with the time index normalized to the time of direct sound arrival

A free field measurement was also made with no echo-generating object in place. The amplitude of the frequency response corresponding to a windowed version extending from the 130\textsuperscript{th} to the 650\textsuperscript{th} sample of this response is plotted in part (a) of Figure 3. This free field response can be seen to cover a bandwidth extending from 4kHz to 40kHz and to greatly deviate from an ideal flat response as it contains the influence of the tweeter and also of the early reflections due to the mounting apparatus. The inverse of this response was computed and two versions of it are shown in part (b) of Figure 3. The exact inverse response is plotted with a black solid line and as should be expected its magnitude rises at the low and high end of the usable bandwidth due to the roll-off of the anti-aliasing filter and the non-responsiveness of the source. Instead of using a linear phase bandpass filter on this inverse, we use here the technique of frequency varying regularisation\textsuperscript{42} which combines the inversion with the bandpass operation. Effectively, the regularised inverse (grey line in Figure 3) follows the response (both magnitude and phase) of the exact inverse for a specified frequency region (in this case 4-40kHz) and attenuates its response outside this region. The convolution of the regularised inverse with the measured impulse response of part (a) of Figure 2 is plotted in part (b) of the same figure where both the direct path response and the specular reflection appear as delta pulses as they are corrected for the influence of the measurement system and the mounting apparatus (the ringing before and after the delta pulse is due to the bandlimited equalisation operation). Referring to the description of Section 2, the convolution of a given (directionally faithful) recording of an echolocation call with the equalised response of Figure 3 will give the signals $p_{\text{out}}$ and $p_{\text{echo}}$ due to the large reflective surface superimposed with a delay of approximately 400 samples.

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In Figures 4 and 5 (top to bottom lines) we present the results obtained with the three disks described above for 4 orientations of 0°, 30°, 60° and 90° around a vertical axis (with 0° and 90° denoting the cases where the flat face and the cylindrical surface (i.e. the edge of the disk) respectively face the incident sound). In part (a) of Figure 4 we plot the raw results obtained with the medium disk (black line) and compare them with the response corresponding to having no object present (grey line). The disturbance due to the presence of the object is clearly visible but superimposed on the decay tail of the free field response. The response obtained after equalising the responses using the regularised inverse of Figure 3 is plotted in part (b) of Figure 4. The corresponding results for the small and the large disk are plotted in Figure 5. The results demonstrate the basic expected characteristics that are also found in\(^{21}\). A single echo is returned by all disks in the 0° orientation with the magnitude of the echo being in agreement with the size of the face of the disk and its timing advancing forward for the thicker disks. The echo diminishes in magnitude for the 30° and 60° orientations that do not present a flat face to the incident sound and increases again for the 90° orientation in which the incident sound hits the cylindrical surface of the disk. In the 30° and 60° orientations, the single echo is extended to a longer pattern corresponding to the extension of the disk in the range dimension with the leading echo advancing as the leading edge of the disk moves closer to the receiver. The association of measured responses of this type with the geometrical shape and orientation of the backscattering object is to a large extent an open question even though quite a few relative studies exist. Many of those studies are based on the model of Freedman\(^{43,44}\) which is however devised in the context of underwater acoustics and on the basis of a narrow fractional bandwidth assumption. An extension of the model to cover the wide fractional bandwidth case is presented in\(^{45}\) and the application of the model to the backscattering problems in air is discussed in\(^{46}\). The applicability of those models to the results presented is currently being investigated by the authors.
4 CONCLUSION – PLANNED FURTHER DEVELOPMENT

We have described an experimental method that can be used for the determination of the acoustic pressure signals reaching the ears of the bat during the echolocation process and we presented a set of experimental results that implement a part of the method. We plan the further development of this research project in two directions. First, a series of experiments aiming at the validation of the method is currently being undertaken. In these experiments, one source and two receivers are mounted on an object of a chosen shape (a sphere) in a roughly similar layout to the mouth and ears on a bat’s head and the echoes returned at the two ears by a reflecting object are recorded. These signals effectively set the target (corresponding to an artificial rather than real echolocation scenario) that should ideally be obtainable by the application of the proposed method. The method is then applied in the discrete stages described in Section 2 and the signals obtained are compared with the recorded “binaural” signals. The use of such an artificial model for the validation of the method gives us the chance to easily identify and rectify any weaknesses in the application of the method. In a second direction of development, we plan the upgrade of the current apparatus in order to increase of the frequency bandwidth of our measurements to the required 200kHz upper limit. Realistic measurements of echolocation call directionality patterns and bat HRTFs can then be undertaken. The goal is to develop the method as a “black box” that can be directly used to relate any given (realistic or artificial) echolocation signal to the exact binaural input to the bat’s auditory system for any specified parameters of the type, number and orientation of objects under interrogation by means of echolocation. A longer term goal is to examine the possibility of replacing each one of the parts of the experimental method with numerical modelling counterparts, a development that would greatly increase the versatility and application range of the method.

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