A NUMERICAL STUDY OF THE ROLE OF THE NOSE-LEAF IN THE KING HORSESHOE BAT

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The biosonar system of bats utilizes physical baffle shapes known as noseleaves around the sites of ultrasound emission for diffraction-based beamforming. Previous work has characterized the sensitivity of the noseleaf of the king horseshoe bat (Rhinoplophus rex) as a function of direction by presenting data on impulse responses or transfer functions. Such results have typically been obtained over a limited angular range and with limited angular resolution. Here, a numerical study of the noseleaf of the King Horseshoe bat is presented to show that the noseleaf has a frequency-dependent effect on the acoustic far field beam pattern. By means of measuring a similar beamwidth of main lobes in constant frequencies (CF) as well as in frequency modulation (FM), it shows that at the lowest frequency in FM band, the beam pattern contained a single, comparatively broad lobe. The vertical (elevation) width of the beam decreased strongly monotonically in response to increasing frequency towards CF band. Once the frequency get to CF, The vertical width of the beam has little response to increasing frequency in CF band. The overall angular extent of these lobes remained largely unchanged. This behavior is consistent with basic physical principles: The larger an aperture is relative to the wavelength, the narrower a beam it is capable of producing. It is also consistent with this expectation that a synergism between the quick narrowing scan effect in FM band and stable narrower beamforming in CF band to produce an excellent echolocation.

1. Introduction

The directivity is key to the performance of all technical devices which are based on far-field wave phenomena. Previous work has characterized bats to emit ultrasonic biosonar pulses through the nostrils and shape the beam by their baroque noseleaves surrounded\textsuperscript{1,2,3,4}. Directivity gain as a function of azimuth and elevation which depict a direction in three-dimensional space has been obtained in several harmonic ultrasonic pulses. In this work, a computational physics method was developed to evaluate the acoustic properties of the noseleaf of the king horseshoe CF-FM bat.

2. Computational methods

With the full complexity of the natural shapes, high-resolution, three-dimensional digital models of noseleaf shapes from a specimen of King horseshoe bat were obtained using microcomputer tomography, by means of a cone-beam volumetric reconstruction method (Feldkamp algo-
rithm) and a digital image processing method\textsuperscript{5,6}. Based on the digital models of noseleaf shapes, we developed a computational method combining three-dimensional finite-difference time domain (FDTD) and finite element methods (FEM) to evaluate the acoustic properties\textsuperscript{7,8} of the CF-FM bat.

### 2.1 Generation of a digital noseleaf shape

Biological samples of noseleaf and other baffle structures were taken from real bat preserved in fridge, mounted in a real-like appearance and firmed to x-ray micro tomography (Skscan-1172). We apply an x-ray filtering before beam hardening artefacts were evident in the reconstructions. Shadow images at a resolution of 1024*1024 were collected over 180° of noseleaf rotation performed with 0.9° steps, according to the size of the imaged object. Image magnification was adjusted and resulted in pixel resolutions at a range from 10 to 20 micrometres. Cross-section images were reconstructed by a cone-beam algorithm. Clearly diacritical noise and imaging artifacts were dismissed by manual preprocessing of the cross-section images. The images were then smoothed with Gaussian convolution-kernel and thresholded prior to mesh generation in three dimensions. The parameters for smoothing and thresholding were based on experience for each data set. Two types of meshes were generated from the thresholded stacks of cross-section images: trigonal surface meshes and hexahedral (cuboid) volume meshes of the ambient air volume of tissue. Trigonal surfaces meshes were generated using an implementation of the marching cubes algorithm provided by the Visualization Toolkit VTK\textsuperscript{9} and served primarily for visualization of the surfaces. Cuboid volume meshes were generated by a custom algorithm similar to the first stage which the voxel array was scanned with cuboids. At each possible, nonoverlapping cuboid position, the algorithm tests the voxels at all corners of the cuboid, a description of the current cuboid is added to the tissue structure if it was classified as air. A cropping logic for shared cuboid faces was achieved which takes advantage of the ordered structure of the volume element grid and was used to generate visual renderings of the boundaries of the meshed domain. The structure volumes themselves were used as an model for the computational methods. After this, By jamming tissue between the sella and anterior-leaf surfaces facing the nostrils, We get a modified noseleaf shape.

### 2.2 Acoustical simulations

Acoustical simulations based on detailed morphology models of bat have been proposed to produce frequency domain estimates of the acoustic near field as well as of the far-field radiation pattern using finite element methods\textsuperscript{5}. Here we developed a three-dimensional finite-difference time domain method to yield a full wave time domain solution for predicting the instantaneous acoustic near field\textsuperscript{6}. The entire computational domain was partitioned into a regular interior (FDTD) region and a boundary Berenger’s perfectly matched layer (PML) region\textsuperscript{10}. The interior region was a cuboid shaped volume full of ambient air of the noseleaf shape derived directly from the corresponding voxel shape representation. Boundary conditions on the surface of the noseleaf represented perfect reflection. The boundary region was the PML utilized as the absorbing boundary conditions to eliminate the artificial reflection from the truncated boundary of unbounded medium. The instantaneous sound pressure $p$ and vector of particle velocity $\vec{u}$ satisfy the following acoustic Euler equation and the equation of continuity regarding the acoustic wave propagation in the computational domain media:

$$\nabla p = -\rho \frac{\partial \vec{u}}{\partial t} - \alpha \vec{u},$$

$$\nabla \cdot \vec{u} = -k \frac{\partial p}{\partial t} - \alpha p,$$  \hspace{1cm} (1)

Here, $\rho$ is the density and $k$ the compressibility of air. The attenuation coefficients $\alpha$ is the usual compressibility attenuation in acoustic media and the attenuation coefficient $\alpha^*$ associated
with density is generally zero for an acoustic medium. In the PML medium the two attenuation items included here are introduced as the artificial nonphysical attenuation parameters.

The FDTD numerical estimates were implemented by the “leapfrog” update scheme on the second-order accurate central difference approximation of the two partial differential equations. The time step size \( \Delta t \leq \Delta h / (\sqrt{3} c) \) is chosen by the well-known “Courant Condition”, where \( \Delta h \) is the discrete space step equals to the edge length of the shape voxel, \( c \) is the sound speed. Two identical Gaussian pulse point sources positioned in the opening of the nostrils were given by:

\[
p(t) = \exp\left[-\frac{(t-t_0)^2}{\tau^2}\right],
\]

Here, the pulse width \( \tau \) is determined by the studied maximum frequency \( f_{\text{max}} \) with \( \tau = 1 / (2 f_{\text{max}}) \), \( t_0 \) is the time offset, giving the excitation initial “turn on” small and smooth.

In addition to the general benefits of being able to give considerable physical insight into the near-field transient radiation, the use of FDTD numerical method and Gaussian pulses offers another important specific advantage for this work: a single simulation run can give near-field acoustic complex pressure amplitude predictions for frequencies spanning the entire frequency range (16 to 29 kHz in 500 Hz steps) known to be covered by the biosonar pulses’ short, broad multi-harmonics by taking the Fourier transform on instantaneous near-field pressure. The resulting acoustic complex near-field amplitude estimates on the outer layer of FDTD lattice nodes were then projected out into the far-field projection using the Kirchhoff integral formulation:

\[
p(\vec{r}) = -\frac{1}{4\pi} \int_{S'} e^{j b R} \vec{n} \cdot \left[ \nabla P + j b \left( 1 + \frac{j}{b R} \right) \frac{\vec{R}}{R} \right] ds',
\]

where \( \vec{R} \) is the vector between the surface element \( ds' \) and the position \( \vec{r} \), \( n \) is the outward-pointing surface normal, \( P \) the field value on \( S' \), and \( b \) the wave number. The product \( \vec{n} \cdot \nabla P = \frac{\partial P}{\partial \vec{n}} \) is the derivative of the field \( P \) with respect to the surface normal \( \vec{n} \). The magnitude of the projected field values was normalized over all directions \( (\theta, \phi) \) for each frequency \( f \) to produce the real-valued, normalized radiation pattern \( D(\theta, \phi, f) \). The directivity index of the two shapes was computed to assess the impact of the sella on the radiation pattern. The directivity index can be computed as follows:

\[
DI(f) = 10 \log_{10} \frac{4\pi}{\int_{0}^{2\pi} \int_{-\pi/2}^{\pi/2} D^2(\theta, \phi, f) \sin \phi d\phi d\theta}.
\]

A sequence of instantaneous near-field sound pressure spacial distribution “snapshots” obtained for the noseleaf differed pronouncedly at different time steps. In the absent of the sella, the frontal half field of the near-field sound pressure distribution overall resembled the field of a new strong pulse and only appeared disturbed to some extent below the sella. For the natural shape, at about 200 time steps the initial wavefront had just reached the upper edge of the sella. Below this edge a second strong wavefront was produced at about 300 time steps and then travelled out forward. The acoustic wave in the median sagittal cutting plane of the sella was clear a convergent plane-like wavefront (natural shape near-field snapshots at 400, 500 and 600 time steps). Qualitatively another similar convergent trend was also discernible in a coronal plane of the noseleaf. In general, for times beyond 200 time steps the wave magnitude in the front half field of the natural shape overall stronger than that of the modified shape, particularly in front of the sella.

The majority of bats are echolocating bats which employ the biosonar system for their vital activities. Functionally relevant system features for these biological tasks are the system behavior in the far field which can be described completely by the radiation pattern. Since the radiation pattern is created from the ultrasonic wavefield diffracted by the physical surface of the noseleaf, the im-
pact of the sella on the radiation pattern could be experimentally assessed by removing the sella in the three-dimensional digital representation of the natural noseleaf shape. This experimental manipulation led to a noticeable effect on the radiation beams. The patterns for the natural shape were strongly influenced by the sella. The coverage patterns of the natural shape in the middle sagittal plane indicated that the main lobes were significantly shaped in elevation. These patterns are much similar to the vertical coverage pattern of baffle reflector radar antennas.

3. Discussion of the results

The results obtained here seem to indicate that the sella in the noseleaf of the King horseshoe bat works as a focus-reflecting baffle. By means of measuring a similar beamwidth of main lobes in CF as well as in FM, Experimental evidence for this comes from the near-field sound focused and reflected forward in the volume inside the sella.

![Figure 1. Far-field directivity in a range of frequencies from 17.5kHz to 29kHz at the step of 500Hz.](image)

3.1 Near-field discussion

The instantaneous near-field sound pressure magnitude increase in the front half field could be interpreted as an amplification through in-phase reflection. A similar reflection is also seen in the Egyptian slit-faced bat (*Nycteris thebaica*)\(^6\), where the near-field magnitude increases significantly right in front of the sella and anterior-leaf surfaces facing the nostrils. Not only does the sella seem to act on the near field through similar mechanisms, its effect on the far-field radiation patterns is likewise similar, it focuses the beams and hence leads to improved spatial tuning with increasing frequency. It may be speculated that the differences in far-field radiation patterns for the two shapes are entirely due to the impact of the sella. The sella inner surface has a central-section curve with a geometrical focus in its median sagittal plane and curved envelopes in the perpendicular planes. A method based upon conservation of energy and the simple laws of geometrical optics has been described for the calculation of such a baffle surface illuminated by a point source at its focus point to perform both the functions of shaping the beam in one plane and uniformly narrowing in the perpendicular planes for determining a shaped beam of prescribed directional coverage pattern. The so-called central-section curve is used as a rule to give necessary field distribution for the shaped beam. Our data show that the radiation patterns for the natural noseleaf which are shaped and overall narrowed follow a prescribed shaped coverage pattern. It should be pointed out, modeling the sella as a baffle surface can be only regarded as a first approximation despite the fairly good agreement between the estimated patterns and the prescribed shaped pattern in this particular case\(^14\).

3.2 Directivity discussion

The directionality of the radiation patterns for the natural shape presents the bat with an opportunity to generate different radiation patterns of the biosonar pulse: at frequencies from 16 to 29 kHz, the directionality increases with sound frequency. Their short broad echolocation calls of low intensity are designed to overcome the masking effects of the emitted call overlapping with echoes
that return with very short time delays and reduce background echoes, allowing greater resolution of the target. In the noseleaves of the King horseshoe bat, the shaped beam configuration is implemented through the shape of the noseleaf and, in particular, the sella studied here. The vertical width of the beam decreased strongly monotonically in response to increasing frequency towards CF band. This may be interpreted as a sensory adaptation to improve the biosonar performance, allowing the animal to obtain a more complete coverage insonification with high directionality which eliminates the potential clutter or phantom caused by a close-in prey and provides better target resolution at higher frequencies for the bat’s echo reception. This finding is in fairly good agreement with the focus function of noseleaves in terms of clutter rejection. It may hence be hypothesized from the coincidence among this morphological structure, the biosonar characteristics and the niche occupied by the bat that the sella is specific for the biosonar pulse and the animal’s ecological niche. However, this still needs further study of the experimental verification.

Figure 2. Vertical beamwidth in different frequencies at a threshold of 80% of the peak.

4. Conclusions

By means of measuring a similar beamwidth of main lobes in CF as well as in FM, We shows that at the lowest frequency in FM band, the beam pattern contained a single, comparatively broad lobe. The vertical width of the beam decreased strongly monotonically in response to increasing frequency towards CF band. Once the frequency get to CF, The vertical width of the beam has little response to increasing frequency in CF band. The overall angular extent of these lobes remained largely unchanged. It is also consistent with this expectation that a synergism between the quick narrowing scan effect in FM band and stable narrower beamforming in CF band to produce an excellent echolocation.

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