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Hamidreza Nemati, Ehsan Dehghan-Niri, "Pioneering a biomimetic approach for the acoustic near-field measurement of aye-aye biological auditory system," Proc. SPIE 12041, Bioinspiration, Biomimetics, and Bioreplication XII, 1204109 (20 April 2022); doi: 10.1117/12.2613158

Event: SPIE Smart Structures + Nondestructive Evaluation, 2022, Long Beach, California, United States

Pioneering a biomimetic approach for the acoustic near-field measurement of aye-aye biological auditory system

Hamidreza Nemati[a] and Ehsan Dehghan-Niri[a]

[a]Intelligent Structures and Nondestructive Evaluation (ISNDE), Civil Engineering Department, New Mexico State University, Las Cruces, NM, USA

ABSTRACT

The aye-aye *(Daubentonia madagascariensis)* is the largest nocturnal primate in the world and possesses a number of distinct adaptations. The most striking feature of the aye-aye is perhaps its exceptional near-field auditory system adopted to support its unique tap-scanning process. This tap-scanning technique represents prominent evolutionary innovations in the animal's biological auditory system. The current study provides an initial insight into proposing a biomimetic approach to determine how different morphological features might impact the aye-aye's acoustic near-field auditory system. The experimental setup comprised a miniature piezoelectric hammer mounted on a Universal Robotics manipulator (UR5) (the integrated system provides a controlled tapping process) and a prepolarized capacitive measurement microphone (to capture the acoustic sound coming from each tap on the wooden sample). The pinnae of the aye-aye were 3D printed using a CT scan obtained from a carcass. The results show that the biomimetic setup can successfully be used for evaluating the near-field auditory system of aye-ayes.

Keywords: aye-aye, pinna, acoustic near-field, tap-scanning, biomimetic setup

1. INTRODUCTION

Over the past decades, biologists and engineers have investigated novel morphologies and physiological operations in an attempt to produce engineered systems that possess unique features that resemble living systems or function like them.[1] Generally speaking, biological systems are immensely complex, yet, with a thorough understanding, they can provide fundamental insight that can result in the pioneering of new ideas in science and engineering. Bioinspired engineering based on auditory and biosonar systems in nature has been the center of many kinds of research. Several animals use their auditory sensing system for different purposes such as communication, foraging, finding mates, etc.. This auditory system has been evolved over the past million years. Some examples of these animals that use self-generated acoustical cues when foraging are bats, aye-ayes, woodpeckers, and dolphins. This behavior is very similar to what is usually done in Nondestructive Evaluation (NDE), a process where an active acoustic wave is generated and the response from a material (e.g., echo) is used to characterize material properties as well as to detect and distinguish defects in parts. In spite of remarkable advances in NDE technologies, it is argued that these technologies are incredibly weak compared to what the aforementioned animals have developed after millions of years of evolution. For example, the evolved near-field auditory system of aye-ayes, and woodpeckers allows them to locate abnormalities beneath the tree's bark with complex material and geometry. While, not all such anomalies are detectable in acoustically difficult and cluttered environments, such as the forest, by current NDE devices.

Among the above-mentioned animals, the aye-aye has by far the most phenomenal near-field acoustic-based sensing and detection abilities, making it particularly valuable to the pioneering new NDE technologies. The aye-ayes *(Daubentonia madagascariensis)* are unique among primates both behaviorally and morphologically. They have a number of morphological characteristics that allow them to access structurally defended foods, and due to their peculiar feeding, ecology, and diet, they are considered as an exceptional example of adaptation among

Further author information: (Send correspondence to Ehsan Dehghan Niri)
H.N.: E-mail: hnemati@nmsu.edu, Telephone: +1 575 621 3001
E.D.N.: E-mail: niri@nmsu.edu, Telephone: +1 575 646 3514

Bioinspiration, Biomimetics, and Bioreplication XII, edited by Raúl J. Martín-Palma
Mato Knez, Akhlesh Lakhtakia, Proc. of SPIE Vol. 12041, 1204109
© 2022 SPIE · 0277-786X · doi: 10.1117/12.2613158

mammals.[2,3] These morphological features include continuously-growing incisors, an elongated, thin, and highly flexible middle finger, and an advanced auditory system.[4–6] According to a long-term field study on aye-ayes, larvae hidden in small cavities and debond-shaped areas under tree bark is one of the most favorable meals for them.[7] The only living member of the family Daubentoniidae has claws on each digit but the thumb,[8] a mean adult body mass of 2.5kg,[9] a head body length of 30-37 cm and a tail length of 74-90 cm[10] (see Figure 1). The aye-ayes also have the largest ears relative to head size.[11] They exhibit a tapping behavior as they hunt for these insects and wood-boring larvae, known as 'percussive foraging' or 'tap-scanning'. The percussive foraging requires a special auditory system and allows aye-ayes to locate small cavities a few centimeters underneath tree bark.[12] In other words, as the animal moves along the wood surface, it taps the wood rhythmically with its unusual middle digit. While keeping the nose near the tree's surface, their large flexible ears rotates forward in a cupped shape.[8] After detecting and locating the cavity under the tree's surface, an aye-aye makes a hole using its front teeth before bringing the larvae out using the same middle finger.Tap-foraging behavior has attracted special attention from researchers because it involves a fascinating combination of specialized senses and behaviors,[2,8,12–15] but solid observational data is still lacking. More specifically, the aye-aye's near field acoustic sensing capabilities had never been reported until recently.[2,13] While several biological aspects contribute to the aye-aye's exceptional auditory system, the main objective of this research will focus on studying the features that affect the aye-aye's near-field acoustic sensing.

Figure 1: An aye-aye during tap-scanning (photo: David Haring, Duke Lemur Center)

2. METHODS

As it was briefly explained, this foraging technique depends highly upon the aye-ayes' well-developed auditory sensitivity.[16,17] The actuation part of the tap scanning process is the animal's middle finger. The animal's rate of tapping has been recorded about 97.7 ± 19.9 ms during foraging, which is equivalent to 10 ± 2 Hz, and each tap was reported to have dominant energy between 2 and 27 kHz.[2] The test was undertaken on a temperate softwood. However, it is reported that the aye-ayes might extract insect larvae from decaying wood on dead or living trees, fallen deadwood, and rarely living trees.[7,18] So, their feeding behavior has become synonymous with deadwood foraging. Moreover, certain structural qualities of deadwood may influence or enable better percussive foraging. In this research, a commercially available lumber named Pseudotsuga menziesii with the dimension of $30 \times 30 \times 5$ cm was used as the deadwood to perform the tapping process. The next section briefly describes the experimental setup.

2.1 Experimental Setup

The tapping mechanism has been mimicked using a robotic arm manipulator (UR5). Figure 2 shows the experimental setup. The aye-aye pinna, with and without ear canal, was 3D printed using a CT scan obtained from a carcass. A miniature piezoelectric hammer (PCB - Model 086E80) was connected to the UR5 arm. The UR5 was programmed in a way to perform the tapping in a semi-automatic manner. To this end, a 25×25 gridline was defined in x and y directions to scan the area of interest on the lumber under the study. In order to ensure that there would be no interference of the UR5 arm with the acoustic field, an extension was used. Further, a holder was designed to keep the piezoelectric hammer fixed during the tapping. To capture and record the acoustic impact emitted from each tapping spot, a prepolarized capacitive measurement microphone (Model 377C01 and 426B03 preamplifier) with a nominal diameter of 6.3 mm and a frequency range of 4 Hz to 80 kHz was inserted into the artificial pinna at the aye-aye's tympanic membrane and 15 cm away from the woodblock. The output signals were fed into a conditioner which was digitized with a 10 MHz sampling rate and 16 bits resolution using Lecroy oscilloscope. It is worth noting that the signals might include some random noise or other types of sound source or material-related uncertainties. To filter out these uncertainties, the tapping has been repeated three times at each point, and the averaged value has been analyzed as the output signal.

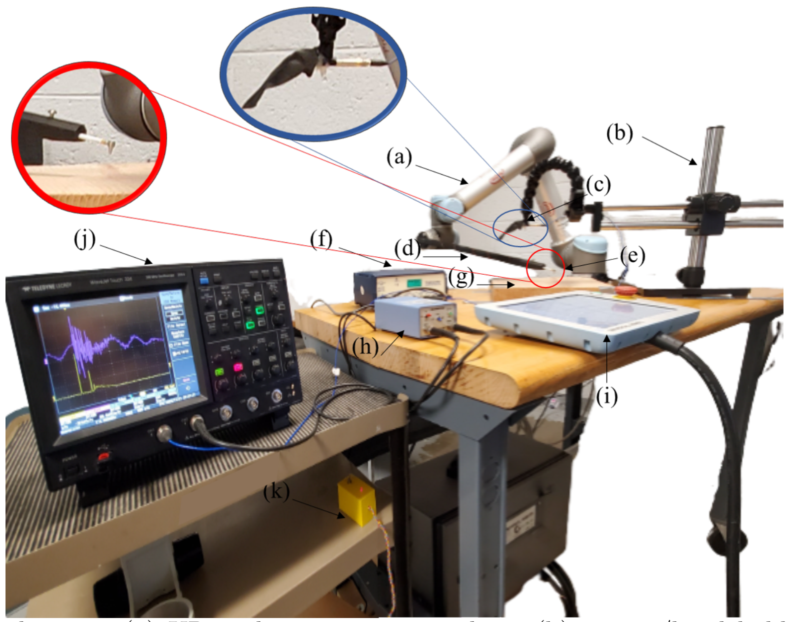


Figure 2: Experimental setup: (a) UR5 robotic arm manipulator (b) pinnae/head holder and 3D coordinate adjustable frame (c) 3D printed pinna with 1/4" free-field, prepolarized 377C01 microphone (d) extension and the hammer holder (e) miniature instrumented impulse hammer (f) four-channel power supply unit (signal conditioner) (g) woodblock (h) The ultrasonic preamplifier (i) UR5 12" touchscreen (j) oscilloscope (k) control switch.

3. RESULTS

Some preliminary results were obtained[13] using the same experimental setup introduced in the previous section. Two sets of tests were performed on a microphone attached to a 3D printed pinna in cupped and upright positions. The microphone response was normalized to the maximum value of the impact to eliminate the uncertainty associated with the sound source (i.e., simulated tapping). Moreover, to eliminate the effect of the microphone and determine the response magnification due to the pinna, the response of the microphone with the pinna is divided by the microphone alone response in both cases. The pinna's effect on the acoustic near-field was evaluated in time and frequency domains. The 4,300 Hz frequency was selected as it is one of the most frequent peak frequencies in the upper range of the frequency spectrum. As can be seen in Figure 3, at the focal point, a high magnification factor of 55 (34 dB) was measured. These results indicate that the aye-aye can substantially enhance its acoustic near-field sensitivity through a cupped conformation during tap-scanning by improving the signal-to-noise ratio (SNR). Moreover, an increase in peak frequency and creating the focal area can be due to a change in the near-field receiving beam pattern. More details of the study are available at the authors' recent article.[13]

The rest of this study investigates how the external ear and the ear canal affect the aye-aye's auditory sensing system. The 3D printed parts were mounted on the UR5 as explained in the Experimental Setup section (see Figure 2 (c)). Firstly, the sound field of the microphone alone was evaluated. In the next step, the effects of

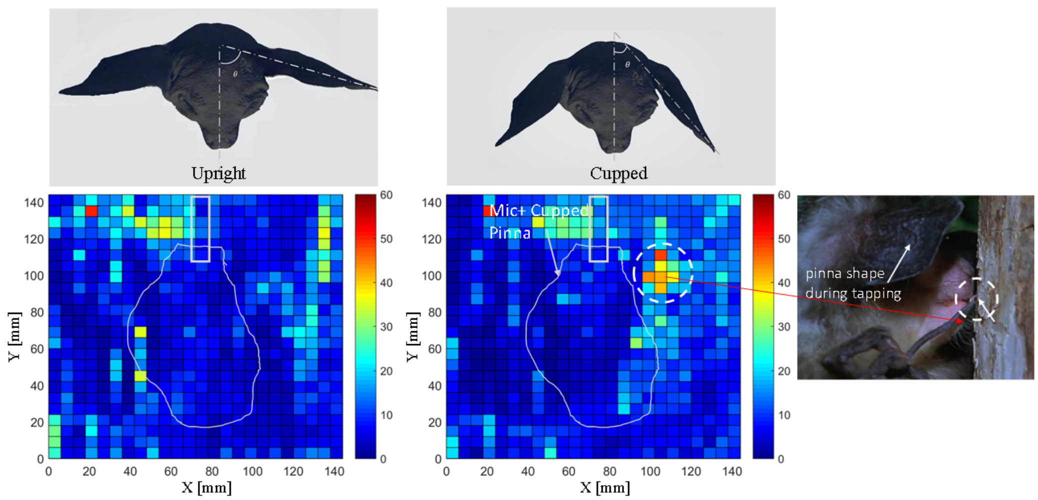
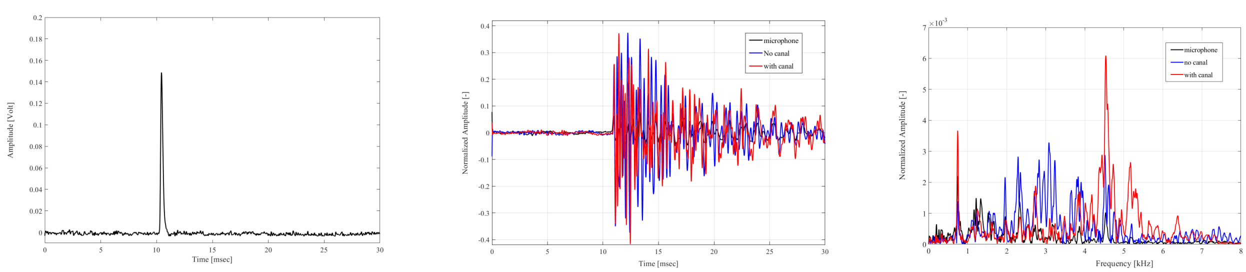


Figure 3: Peak Frequency Magnification factor of the aye-aye pinna for 4300 Hz in Upright and Cupped shape[13]

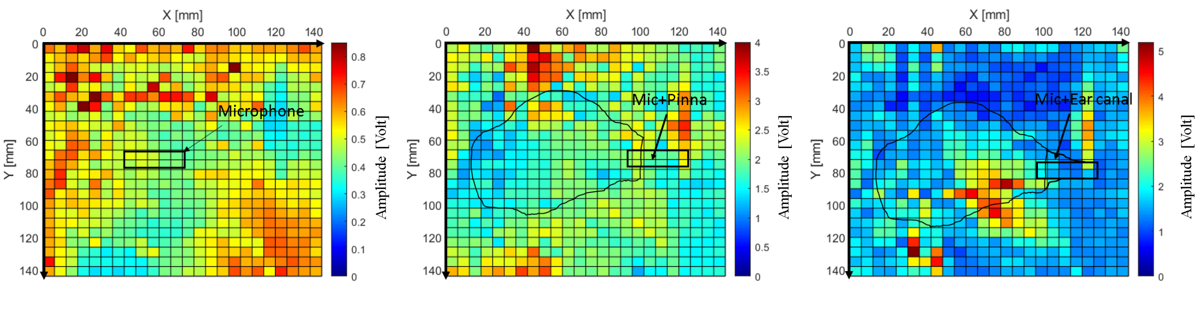
the pinnae and ear canal in the aye-ayes' near-field auditory system were considered in a cupped position. It is noteworthy to mention that the estimated angle in which the parts have been mounted on the holder was selected based on qualitative observation and the morphological descriptions provided in literature.[13,19] Figure 4 demonstrates the response associated with the tapping simulation at a focal point. From the signals gathered, one can clearly see the magnifying effect in the presence of pinna and the ear canal. The receiver peak frequency was shifted to higher frequencies in both cases. Increasing the dominant frequency will increase the auditory sensitivity during tap-scanning due to the lower wavelength. Furthermore, a smaller wavelength would result in an enhanced sensitivity of the auditory system to smaller cavities. This sensitivity improves the detection capability of the aye-aye and potentially the bioinspired taping technique developed in this research.



(a) (b) (c)

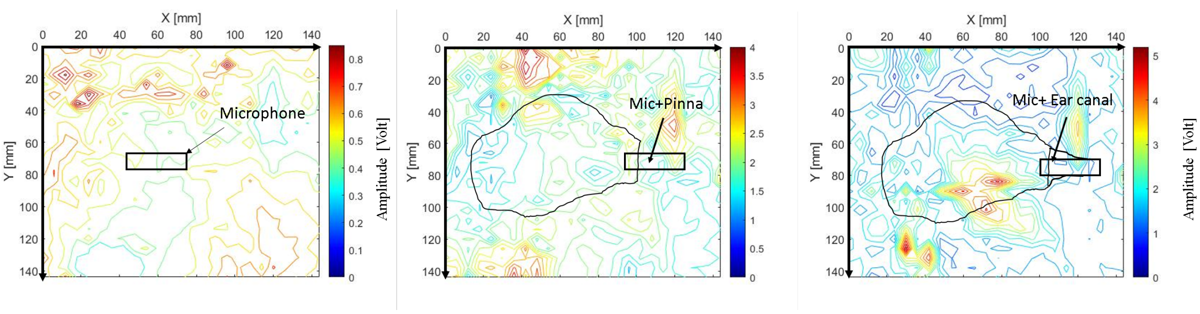
Figure 4: Example of received signals: (a) piezoelectric hammer, (b) normalized microphone response, and (c) frequency response of normalized microphone response.

To investigate the effect of the pinna with and without pinna on the acoustic near-field, the performance of the proposed tapping system was studied using temporal analysis. As already mentioned, an average of maximum values of normalized received signal envelopes for the three simulated tapping sources at each gridded point was calculated to measure the acoustic sound field in time domain. Firstly, the acoustic near-field of the microphone alone was measured (see Figure 5 (a)) to remove the uncertainty due to tapping intensity and allow a more reliable measurement. Figure 5 (b) pinpoints that by adding the pinna to the proposed setup, the acoustic near-field response was substantially enhanced in terms of SNR. As can be seen, at the potential focal areas, the response intensity increases up to 12 dB resulting from the pinna. Adding the ear canal to the pinna even improves the acoustic near-field sensitivity where the magnification factor increases up to 5, which is equivalent to a 14 dB increase in SNR (see Figure 5 (c)). Figure 6 represents the corresponding contour plot of the normalized acoustic field provided in Figure 5. The contour plot of the microphone acoustic field shows the directionality pattern of the microphone. Due to this behavior, the independent measurement of microphone acoustic near-field is essential in this research to isolate the effect of the pinna. The counter plots of the acoustic field generated in the time domain reveals that a focal area around the tapping point was observed. This observation proves that the cupped pinna, either with or without the canal, can substantially improve the SNR for a specific peak frequency. This magnification phenomenon might be one of the main factors allowing the aye-aye to show exceptional detection capability during its tap foraging process.



(a) (b) (c)

Figure 5: Acoustic near-field of normalized response: (a) microphone alone, (b) pinna without canal, and (c) pinna with canal.



(a) (b) (c)

Figure 6: Corresponding counter plot of the normalized acoustic field: (a) microphone alone, (b) pinna without canal, and (c) pinna with canal.

4. CONCLUSIONS

The setup described in this study attempts to experimentally measure the acoustic near-field of aye-aye biological auditory system. The aye-aye's acoustic sensing, actuation and auditory perception have evolved to create exceptional near field acoustic sensing capabilities. A unique acoustic-based foraging behavior known as 'tap-scanning' or 'Percussive foraging' enables the animal to uniquely distinguish the different tones emitted from the wood during tapping. A bipomimetic approach was used to simulate the tapping process and measure the acoustic near-field of the aye-aye. current work investigates the effect of some morphological features of the aye-aye's external ear in the aye-aye's exceptional near-field acoustic sensing and detection capabilities. To this end, the pinna with and without ear canal was 3D printed and used in the proposed setup through a cupped conformation. The results obtained from the biomimetic setup suggest that these morphological features can substantially enhance the acoustic near-field sensitivity of the aye-aye by creating some focal areas near the tapping spots to enhance the SNR and the spatial resolution. Further study is undergoing to investigate the effect of pinna's material and other morphological features such as the animal's head. As the next step, the proposed setup could be modeled and simulated in finite element analysis software like COMSOL Multiphysics to investigate all possible parameters that might affect the animal tap scanning behavior. The pioneered tap-testing system can then be used to detect and classify defects in wooden materials.

5. ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation CAREER AWARD under Grant No. 2047033. This work was also performed in part at the Duke University Shared Materials Instrumentation Facility (SMIF), a member of the North Carolina Research Triangle Nanotechnology Network (RTNN), which is supported by the National Science Foundation (Grant ECCS-1542015) as part of the National Nanotechnology Coordinated Infrastructure (NNCI). The CT scan of Merlin's non-living body provided by Shared Materials Instrumentation Facility at Duke University initially allowed us to perform this study in the Intelligent Structures and Nondestructive Evaluation (ISNDE)laboratory at NMSU. The great help of Dr. Erin Ehmke from DLC is gratefully acknowledged. The authors would also like to thank David Haring from DLC for providing the photo of the aye-aye during tap-scanning.

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