

Bats' Acoustic Detection System and Echolocation Bionics

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Abstract—Bats' acoustic detection system was introduced, including the nose-leaf for emission, two ears as receive antennas and the stimulus data flow in the auditory system. The waveform design and signal processing method in the echolocation system was analyzed in details. Further more, a bionic model was established based on the main function of bat's ear. The model was simulated for bat's echolocation stimulus. Simulation results imply that the bionic signal processing method is high accuracy, sharp resolution and robustness in localization. Echolocation bionic design can be a new way to promote the capability of artificial sonar and radar system.

I. INTRODUCTION

Echolocation bats can form a fine acoustic image for target localization and classification from its acoustic echo. Echo detection is their primary sensory for guiding during flight in cluttered, three-dimensional environments and for capturing flying insects in complete darkness. In addition to providing information about how far away a target is, the bat's sonar conveys information about the relative velocity and size of the target, the azimuth and elevation, and even the texture of the target [1]–[3]. The complex neural computations needed to extract all this information from the target echo occur within a pea sized brain. Moreover, these animals perform tasks with total power consumption (including flight) measured in watts, not hundreds of watts [4] [5]. In addition, both bats and dolphins live in very social environments, using echolocation in group situations without any obvious problems with interference. The special ability of bat's echolocation has drawn many researchers' attention in several fields such as biology, psychology, aeronautics, electrical engineering and so on since 1790s [6]. Recently, echolocation bionics is developing to be a very important field, especially in biometric sonar and radar research [7] [8]. Indeed, an echolocating bat can pursue and capture its target with a facility and success rate that would be the envy of a radar engineer. Before 1990s, attentions are focused on the auditory path and nerves by physiology scientists [9] [10]. In 1992, Brown University provided a simplified model called SCAT (Spectrogram Correlation And Transformation) model to describe the computational function of bat's echolocation

system based on biological results [11]. Later, Edinburgh University analyzed the SCAT model and gives some improvements [12]. Based on SCAT model, Tohoku University presented a model to echolocate multiple targets in 3-D Space from a single emission using EEDNF (External Ear Dependent Notch Frequency) [13-14]. There are also some other methods for direction [15] [16]. Except modeling, realization is another research aspect. Analog and digital are two methods to realize the model. These two methods are using VLSI (Very Large Scale Integration) [17] [18] and FPGA (Field Programmable Gate Arrays) [19] [20], respectively. Because of the special ability of the echolocation system, the United Airforce has started a research on its bionic application in reconnaissance aircraft [21]. In Europe, a CIRCE (Chiroptera-Inspired Robotic Cephaloid) project is provided to develop echolocation robot [22] [23]. Research on echolocation bionics is helpful in both military and civil applications [24] [25].

II. WAVEFORM DESIGNING AND GENERATION IN BAT'S EMISSION SYSTEM

Bat uses its mouth (or nose) to broadcast echolocation sounds and its two ears as receive antenna. The emitted sounds consist of burst waveforms whose characteristics are highly diverse, varying with both species and being situation specific. The facial features in bats can shape the sonar beam, even if they are not directly adjacent to the sound emission sites. Noseleaf is a based supporter of the smart emitter. It has been frequently hypothesized to affect the angular distribution of the emitted sound energy in bats. The resonance frequencies of the noseleaf furrows themselves are remarkable because they differ from the frequencies all previously known specializations in these animals pertain to. This suggests that the animals have specialized processing for different frequencies in their pulses implemented by means of physical effects in the acoustic domain.

A digital three-dimensional shape representation of the noseleaf of the rufous horseshoe bat (*Rhinolophus rouxi*) using microcomputer tomography was obtained by CILIA project [26-27]. Fig. 1(a) and (b) show the sound pressure and

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frequency selectivity of the resonance respectively. Fig 1(a) described the spatial selectivity of the resonance: sound pressure amplitude (magnitude of the time-harmonic solution to the Helmholtz equation) for 60 kHz in the near field coded by gray (color) value on a linear scale. Arrows indicate the local spatial maxima inside the lancet furrows, while Fig. 1(b) illustrated frequency selectivity of the resonance: normalized sound pressure amplitudes in the lower (dashed line) and upper (thin solid line) right lancet furrow as a function of frequency. The frequency band displayed extends beyond the range known to be used by the bat (marked by downward triangles) in order to show the resonance behavior unequivocally. Superimposed on the resonance curves in (b) is the maximum change in the directivity function relative to its global maximum in percent (thick solid line) and the inset shows a schematic spectrogram of a CF-FM biosonar pulse.

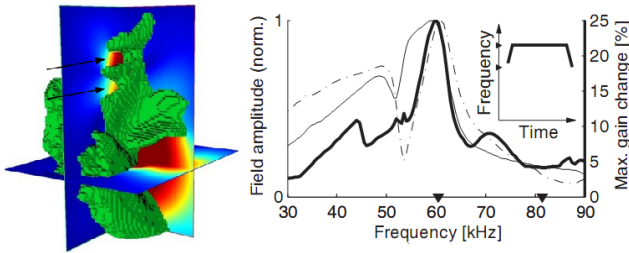


Figure 1. The sound pressure and frequency selectivity of the resonance [26]

Except for smart beam-forming, the emission system is also an adaptive waveform designer. As shown in Fig 2, each pulse consists of a long constant-frequency (CF) component followed by a short frequency-modulated (FM) component, also each component containing four harmonics (H_{1-4}). So there are eight signals in a single pulse (CF_{1-4} , FM_{1-4}) [28]. In the emitted sound, the second harmonic (H_2) is always predominant and the frequency of CF_2 is about 61 kHz. For FM_2 , the frequency sweeps down from 61 kHz to about 49 kHz. H_3 is 6-12 dB weaker than H_2 , and H_1 and H_4 are 18-36 and 12-24 dB weaker than H_2 , respectively [29]. The CF component is used to get speed information of the target while FM for fine detection and imaging. When bat flies towards or near a stationary object, the frequency of the echo becomes higher than the emitted pulse due to the Doppler Effect. This steady shift is called the DC component of the Doppler shift. When the bat flies towards a flying insect the Doppler shift of the echo consists of a DC component proportional to the relative velocity and a periodic frequency modulation proportional to the speed of wing beat (Fig. 2C). This periodic is called the AC component of the Doppler shift. The AC component is complicated because the insect's four wings move in complex patterns and in different phase relationships relative to the bat. The echo from the flying insect is also modulated in amplitude. The DC component of Doppler is also used for compensation of FM signal processing. The wide band FM signal, however, is suited for ranging, localizing and characterizing a target because of the distribution of its energy over many different frequencies. Different parameters of echoes received by the bat carry different types of information about a target.

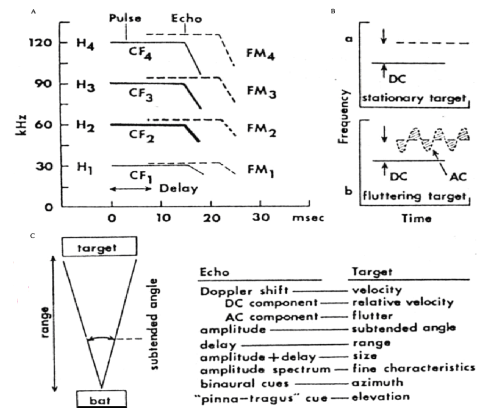


Figure 2. Orientation sounds (biosonar pulses) of bat and the information carried by the signals

The transmitted sound can also be adjusted adaptively according to the detecting results. The capture process of a bat can be divided into three stages (Fig 3) that are searching phase, approach phase and terminal phase. The pulse period is long with most CF component and gets shorter and shorter with more FM component in tracking phase for real-time imaging.

In searching phase, the emission is about 10 pulses per second to look for insects. When a prey is detected, approach phase begins and the signal density is increased to about 150 pulses per second. Bat gets real-time position and distance of the target. When the distance is about 2 meters, bat started tracking and gain control take effect. In this phase, bat should get fine information from the echo for recognition and decide whether the target is a prey or something else. As shown in Fig.3, when bat gets closer and closer to the target, the pulse density become larger and larger. At the same time, the CF components decrease and FM components increase to get more fine information of the target. In the terminal phase, maximum PRI achieved for real-time localization.

The previous discussion indicates that the emission system of echolocation bat has several special abilities. First, compared with large artificial antenna array, bat's smart beam-forming is achieved by its small noseleaf. Second partial is the velocity-dependent and range-dependent adaptation of the transmitted waveform. These two characteristics can take good lessons for cognitive radar design [30-32].

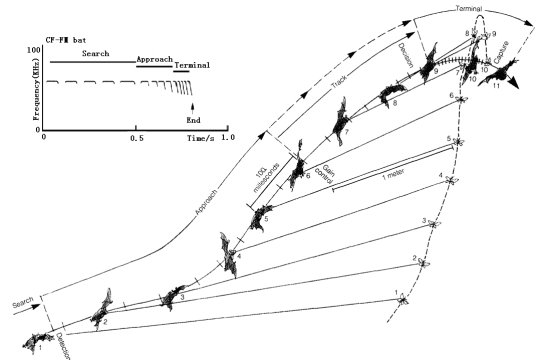


Figure 3. The capture process of bat and adaptive waveform conversion

III. ECHOLOCATION RECEIVER AND SIGNAL PROCESSING SYSTEM

Bat has two ears as receive antennas. The interaural time difference (ITD) and interaural intensity difference (IID) between these two ears can be used to get direction of the targets (Fig. 4). The structures of bats' pinna have attracted the interest of both the acoustics and the electromagnetic research communities. One of the primary interests in the acoustics area is to produce a compact, lightweight ultrasonic beam former for use in airborne robotics. This interest is inspired by the highly efficient and accurate target localization capability observed in some bat species.

James A. Flint has presented a novel antenna that physically resembles the ear of a bat [33-35]. The device consists of a circular ground plane with a central monopole element. An equilateral triangular conducting plate is curved around the ground so that the base of the triangle is electrically connected to the perimeter of the circle and is of the same length. The input characteristic is similar to the monopole above ground, providing there are a sufficient number of modes in the triangular plate at the frequency of interest. Certain frequencies yield a high gain and a radiation pattern with low side lobes.

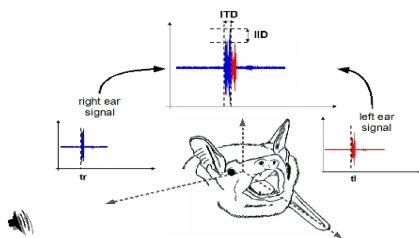


Figure 4. The ITD and IID of bats' two ears

Through pinna, the echoes get to middle ear, in which the auditory information is processed. The eight components (CF1-4 and FM1-4) of the orientation sound of the bat all differ from each other in frequency, and are analyzed in parallel at different regions of the basilar membrane (Fig. 5, bottom). The signals are then coded and sent into the brain by peripheral neurons. In the brain, the signals are sent up to the auditory cortex through many auditory nuclei where signal processing takes place. For simplicity, we may consider that there are eight channels for the processing of these signal elements: CF1 channel, CF2 channel, and so on. The CF2 channel is very large relative to any other channel and is associated with an extraordinarily sharply tuned local resonator in the cochlea for fine frequency analysis (Fig. 5).

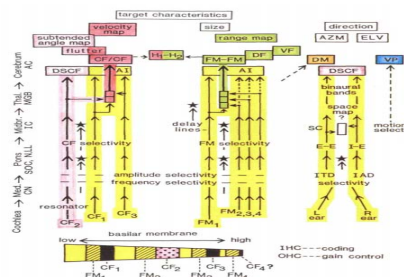


Figure 5. The principles of auditory information processing

The echo processing in bats' auditory can be divided into 4-stages (Fig. 6) [36-38]: The first stage represents cochlear that acts as a cascade of band-pass filters splitting the stimulus into a number of frequency channels. The second stage is the inner hair cell performs automatic gain control as well as half-wave rectification of the sound. Chopper cell in the third stage smoothes each band and detect the peaks of the smoothed envelope. Cross-correlation is achieved by coincidence cell in the fourth stage. Distance information can be picking up from correlation result.

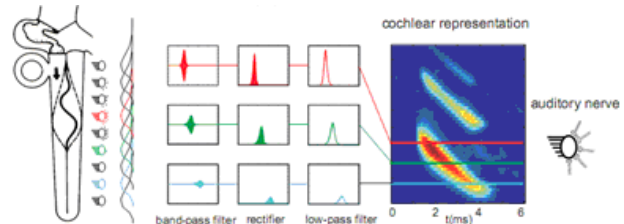


Figure 6. Signal processing data flow in the auditory

The main function for the cochlear is frequency separation. Difference frequencies in the stimulus will excite their particular points along the basilar membrane. These resonances make different frequencies pass through special pathways to make frequency coding. A real cochlear contains thousands of pathways that act as a cascade of band-pass filters, which splits the stimulus into a number of frequency channels.

The inner hair cell plays a crucial role in the operation of the auditory system: it is responsible for converting the mechanical vibrations in the cochlea into electrical impulses in the auditory nerve. The output of the inner hair cell is a transmitter substance which synapses with the auditory nerve thereby producing spikes which are then transmitted down the auditory nerve fibres. It is the auditory nerve that drives neurons in the auditory brainstem. As a consequence of this importance this cell plays a vital role in the function of the pitch detection system. The inner hair cell has a number of behavioral features, which are important to its role in the auditory system. These features are half-wave rectification, saturation, and adaptation. The rectification process is self-explanatory and adaptation is a process similar to automatic gain control.

The stellate cell comes in two parts: the dendrite and the cell soma (nucleus). The dendrite acts as a low pass filter with a cutoff frequency of approximately 3 kHz and the stellate cell soma is the spiking part of the cell.

The coincidence cells are situated in the Inferior Colliculus and detect phase locking within the stellate chopper cell array. This cell has similar properties to a stellate cell soma. The output spikes from stellate group are summed and then scaled to give the equivalent to a voltage signal. This voltage signal is fed into the input of the coincidence cell. When phase locking occurs, the coincidence cell receives brief, high intensity input potentials. This high intensity signal drives the cell's membrane potential to exceed a threshold value, which results in an output spike being produced.

IV. ECHOLOCATION BIONICS AND THE SIGNAL PROCESSING MODEL

Echolocation bionics of the bat includes emitting nose, the receiving ear, the flight motion, the signal processing in the brain and so on. The researches in IEE of CAEP are focused on modeling and realization of the auditory nerve which is the most complex part [39] [40]. A computational model is established based on physiological research results and the whole processing system is implemented on a signal FPGA [41].

This intelligent bionic signal processing model based on auditory nervous contains two major blocks called spectrogram correlation and spectrogram transformation. These two blocks are used to get low and high resolution range profiles respectively for multi-scale detecting. In the spectrogram correlation block, a cochlear filter bank is adopted for encoding the bats' transmission and multiple echoes, in which the input is divided into several parallel pathways. Each frequency channel consists of an inner hair for half-wave rectification, followed by a stellate cell for low-pass filtering and peak-detection, and then a coincidence cell used as cross-correlator. The outputs of all frequency channels are fused in the auditory nervous centre to get the absolute range of the targets. The spectrogram transformation takes place across all frequency channels to improve range resolution and reconstruct fine range structure of the target. The signal data flow is as Fig. 7.

In the simulation, the situation is simplified by assuming that the transmission is an linear frequency modulated (LFM) signal sweeping downwards from 135kHz to 10kHz in 2ms with constant amplitude. First, the emission itself is processed as the model assumes that the ear pick up the emitted cry and use this signal to make the receive self-calibrating. Four scattering points located at ranges of 0.374m, 0.442m, 0.816m and 0.833m were hit by the emission and the delay times are 2200 μ s, 2600 μ s, 4800 μ s and 4900 μ s respectively. The first group of echoes represents two closely locating targets with a separation time of 400 μ s, and second group represents two-glint points of a complex surface and delay separation of these two components is 50 μ s.

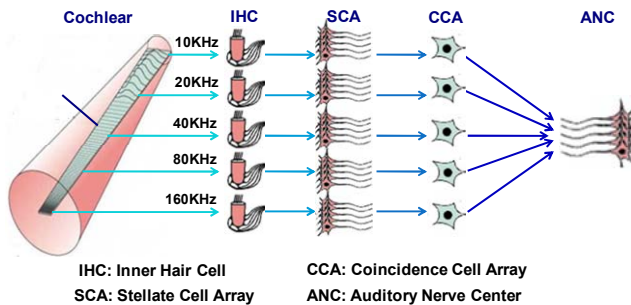


Figure 7. Signal processing model of the echolocation auditory

The emission and its echo chirps are fed into the model as input. First, this signal is divided into 101 paths by the band pass cochlear filter bank (stage 1). The center frequencies f_c of these filters space from 120 kHz to 12 kHz with logarithmical distribution. All the filters have same Q values. Each output of

the band pass filter is half-wave rectified by the inner hair cell (stage 2) and then low-pass filtered by stellate cell dendrite (first part of stage 3). The low-pass filter's cut off frequency is 3 kHz and achieved by 2st-order Butterworth IIR filter. All the above are the external ear. The first two targets with a separation of 68mm can be directly separated by the filter banks. But from the processing results of the second group of echoes, we can't see the last two scattering points.

The smoothed envelopes from the external ear are change into spikes in the pick detection component. For the first two echoes, the spikes were divided in to two groups indicating that there are two scattering points. But there is only one group of spikes for the last two echoes. The spikes generated by the emission are correlated with that of the echoes. The correlation results in each channel are summed up in the coincidence cell and four peaks that mark the distance of the targets appeared in time axis. The four scattering points are separated at last. The measured time delay according to the output of the model are 2201 μ s, 2599 μ s, 4805 μ s and 4910 μ s. The relative error for each distances are below 1 percent.

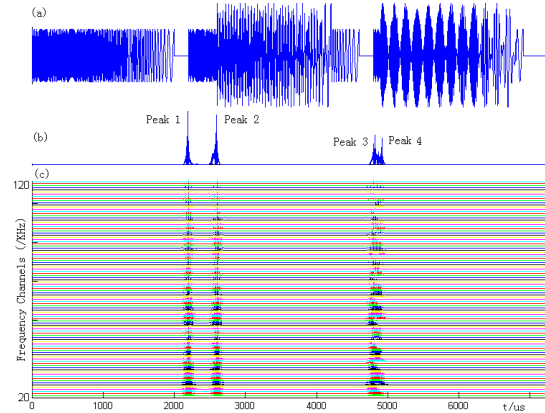


Figure 8. Correlation results (c) and the coincidence cell output (b)

V. ECHOLOCATION BIONICS AND THE SIGNAL PROCESSING MODEL

An overview of bats' echolocation system was introduced including adaptive waveform design for the emission and the data flow along the auditory pathway. The signal processing method was discussed in detail. A simplified model for bats' auditory system was constructed based on the discussion. The model was used to process the echoes from four scattering points. Simulation results indicate that two highly overlapped echoes from closely located scattering points can easily be separated. The range discrimination is better than 17mm for high signal-to-noise ratio. This model can be used to process LFM (Linear Frequency Modulation) signal to get high-resolution range profiles of the targets for recognition and classification. Another advantage of this model is its robustness which is very important for reliability of the system. At present the disadvantage of this model is the complexity. Because the model uses multichannel parallel computation, large amount of resources should be applied for realization of the model. The algorithm structure should be

designed carefully and some blocks should be multiplexed for optimization.

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