The simulation of bat-oriented auditory processing using the experimental data of echolocating signals

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There are various approaches to understanding the echolocation phenomenon of bats. A part of the echolocating process is assessed here by determining what acoustic signal a bat's ears receive during echolocation. It is simplified in an experimental rig to measure the reflections from objects in different dimension and materials which represents a sound discrimination task in bats. It has been assumed in this study that the remarkable echolocating ability of bats, which is not shown in the most other mammalian species, is achieved by their different physical shape of head and ears, and specialised auditory processing of echolocating signals. In human studies, physical characteristics are usually modelled as a head-related transfer function (or HRTF) and gammatone filter banks are widely used to simulate auditory processing in the cochlear. A modified filterbank is used here to represent the auditory processing in bats and combined with the experimental data of object reflections. Bat HRTFs will be used subsequently to determine the acoustic reflections at both ears.

1 Introduction

Bats, especially the suborder *Microchiroptera*, have the remarkable ability to orientate, navigate and capture prey during flight by using echoes. This process is called echolocation. They emit pulses consisting of constant frequency, modulated frequency chirps, or both and listen to returning echoes produced by the object, in the complete darkness. There have been many researchers attempting to unravel and understand their echolocating mechanisms. In order to gain inspiration and make a use from the insight of echolocation in bats for engineering, it is required to simplify and build an appropriate model of the processing they make with understanding of their biological function. This study aims to investigate and understand the advantage that the auditory processing of echolocating signal makes for object. The auditory processing in bats has been modelled and applied to engineering system in a previous study [1] and it has been demonstrated that it is effective on the estimation of the Doppler shift compensation and two-target echo separation. Here we investigate the effect on object differentiation. To perform the study, the air transmission model to define the echoes from the objects and the hearing model of bat were used. First, the echolocating modelling method, suggested in previous study [2] was adopted to characterise the signal returning from the reflecting object. The method consists of separately modelling the emission, echo generation and reception mechanisms as linear, time-invariant systems in each part. Second, a mammalian cochlear processing model [3] was adopted and modified for bat-oriented auditory system. Two different types of echolocating signals were investigated due to the fact that the cochlea is developed differently depending on the type of the signals processed in order to make an efficient auditory processing.

2 Modelling

2.1 Air transmission model

The physical quantities involved in the problem at hand are described in Fig.1. The bat emits an echolocation signal due to which an acoustic pressure disturbance p_{out} is measured at point $\boldsymbol{r}$ at a distance r and azimuth (θ) and elevation (φ) relative to the centre of the bat's head. The disturbance propagates through the air until it is backscattered by the target creating a pressure disturbance p_{echo} back at point $\boldsymbol{r}$. This disturbance travels back towards the bat and reaches its two eardrums after having been diffracted by the pinnae and the head of the bat. We denote the pressure signal reaching the bat's eardrum by p_{ear}.

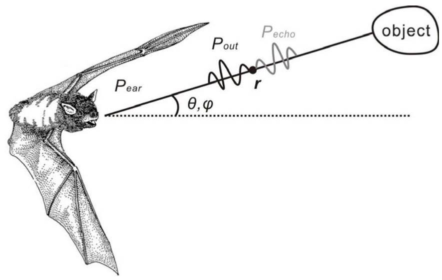

Fig.1 Diagram of echolocating system

Based on the model for the echo generation mechanism described above, one can predict the echolocating signal (p_{echo}) from a particular target that reaches the point before diffraction by the head. It is achieved by convolution of the emitted signal (p_{out}) with the backscattering response of the object ($h_{backscatter}$) at orientation and distance as Eq.(1);

$$p_{echo}(n) = h_{backscatter}(\text{orientation, distance}, n) * p_{out}(n) \quad (1)$$

where n denotes the sample at discrete-time notation. In this study, both constant frequency (CF) and frequency modulated (FM) signals are used to model the outgoing signal. The echo signal is simulated by convolving the outgoing signal with the measured backscattering impulse response from different types of experimental target disks.

2.2 Hearing model

Here we describe the background for the hearing model of bats. Bats use different types of signal to echolocate a target. The signals fall broadly into two categories; constant frequency (CF) and frequency modulated (FM) or a combination of both. By using these signals, bats accomplish echolocating tasks such as detection, discrimination and localisation of the target. Each species of bat emits tonal echolocating signals with different duration, frequency bandwidth and sound pressure level. The particular type of signal used in each species of bat enables effective echolocation for its own processing mechanism. Schnitzler et al. [4] demonstrated that narrowband, shallow FM components seem to be well suited for the detection of echoes from small insects and target movements, whereas broadband, steep FM components seem to be well suited for accurate target localisation by delivering exact time markers. It is generally regarded that broadband echolocating signals carry better spectral information in the target reflection. On the other hand, CF components seem to be suitable for Doppler shift compensation, in combination with CF bats' specialised hearing system. The CF echolocating bats can classify fluttering insects by detecting temporal modulation patterns. Considering the different foraging environments, such as open or closed spaces, and the types of prey that bats echolocate, a diverse adaptation in signal structure has evolved. The auditory system in bats is structured in the same way as that of other mammals. Their ear anatomies basically resemble that of other mammals in form and function. After the echolocating signal returning from the target object reaches the two ears, each ear processes time and frequency analysis in the cochlea. The auditory processing has been simplified and modelled based on bandpass filter banks. The impulse response of the each gammatone filterbank is defined in the time domain as Eq.(2) [3];

$$g(t) = at^{(n-1)} e^{-2\pi bt} \cos(2\pi f_c t + \varphi) \quad t > 0, \qquad (2)$$

Where n is the filter order, b determines the bandwidth of the filter and f_c denotes the centre frequency of the filter. The effective rectangular bandwidth (ERB) is a psychoacoustic measure of the width of the auditory filter at each point along the cochlea, and can be defined as Eq.(3) [4];

$$ERB = \frac{f_c}{EarQ} + \min BW \qquad (3)$$

where $EarQ$ is the asymptotic filter quality at large frequencies and **min**BW is the minimum bandwidth for low frequencies channels. Glasberg and Moore [5] have recommended human data on the equivalent rectangular bandwidth of the auditory filter with the Eq.(2) with $EarQ$=9.26449 and **min**BW=24.7. These values has been adopted or changed for the modification of auditory filterbanks for both FM and CF bat. It is to provide a simple and bio-inspired auditory model of bats rather than a delicate and accurate model which represents their biology. First, FM bats are regarded as having the general pattern of auditory filter banks as other mammals. Therefore, $EarQ$ factor is varied as 10, 20 and 30 for FM signals as the ability of auditory system is determined by the sharpness of the tuning curves of single neurons. The **min**BW is set to the same value as in Glasberg and Moore's equation [5]. The modified gammatone filterbanks for the EarQ value of 10 is shown in Fig.2 (a). The equivalent rectangular widths used for FM bat's cochlea modelling with different $EarQ$ values are shown in Fig.2 (b). The bandwidth becomes more narrowly tuned as the $EarQ$ values increases. Second, the CF bats are thought to carry specialised frequency analysis in the *acoustic fovea* in the cochlea where the neurons are specifically tuned to a narrow frequency range of returning echoes. In this study, the narrowband filters are modelled separately for CF signal analysis around the carrier frequency. Therefore we aim to investigate how advantageous this mechanism may be to process narrowly tuned analysis in object differentiation. For both cases, the bandwidth b is fixed as 1.019 times the ERB as recommended by a previous study [6].

2.2.1 Gammatone filterbank processing

The gammotone filterbanks were modelled within the frequency range from 5 kHz to 35 kHz. Each bandpass filterbank produce subsequent demodulation of each channel. However the output of a linear filterbank does not represent a particularly good activity in cochlea. The inner hair cells compress and rectify the motion of the basilar membrane and hence half-wave rectification is applied to generate the envelope of the decomposed signal. Again, the rectifier generates new frequency components, some of which are unwanted by that particular channel. Thus the low pass filters at 1000 Hz are chosen to remove these unwanted components from the resulting signal. Finally square root compression is used to fit the output signal within a narrow electrical dynamic range.

(a)

(b)

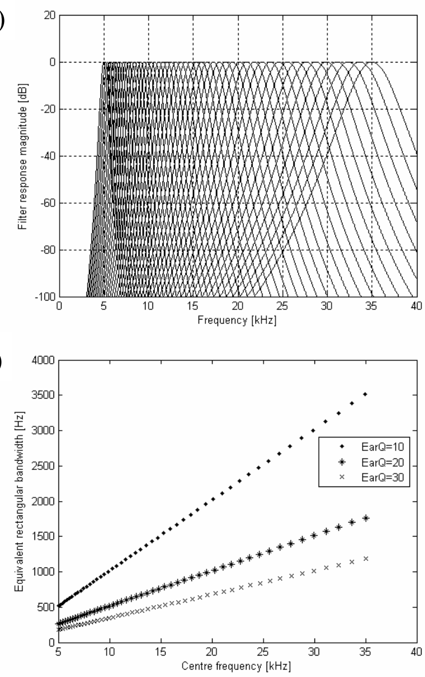

Fig.2 (a) Modified gammatone filter banks based on Glasberg and Moore parameters (1990), $EarQ$=10 (b) Equivalent rectangular bandwidth (ERB)

2.2.2 Acoustic fovea modelling

The narrowband filters are designed to reconstruct the processing in the acoustic fovea of the cochlear of CF bats. For the 20 kHz carrier frequency of the echolocating signal which has been used in this study, the acoustic fovea has been assumed to be located from 18 kHz to 22 kHz based on data from *Pteronotus parnellii* [7]. The filter quality factor was specifically changed for the narrowband analysis. Previous studies reveal that the Q_{10dB}, which centre frequency divided by bandwidth 10 dB from the tip of the bandpass filter, can reach up to 600. We have chosen the $EarQ$ parameter to be fixed as, simple value at 100 but approximately ten times larger than that of human, with each centre frequency within the acoustic fovea. The separation between each center frequency of the narrowband was set as 100 Hz. The filters are also spaced for equal overlapping between neighbouring filters. Hence the model generates 41 narrowband filters and their frequency responses are shown in Fig.3.

For outside the acoustic fovea including adjacent frequencies, the frequency analysis was divided into 5 kHz-17.5 kHz and 22.5 kHz-35 kHz and each part is modeled based on general gammatone filterbanks with an $EarQ$ value of 10.

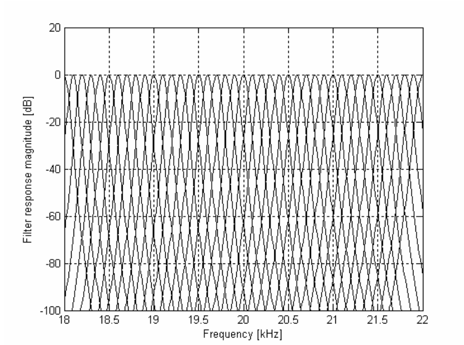

Fig.3 The filterbanks used to model the acoustic fovea of CF bat for narrowband analysis

3 Measurement

3.1 Materials

The backscattering impulse responses of three different sizes of plastic disks and two different thickness of wooden disks were measured in the anechoic chamber. The experimental set-up was as described in the previous paper [8]. Table 1 describes the physical characteristics of the disks used. The distance between the object and the microphone was set to 15 cm. The equalised impulse response which is deconvolved with free field response is used. The equalised impulse response of the large plastic disk is shown in Fig.4. The pulses corresponding to the emitted and reflected signals appear to be within a time separation of less than 1.5 ms.

Material	Category	Diameter [mm]	Thickness [mm]
Plastic	Large	37	20
	Medium	30	7
	Small	15	2
Wood	Thick	64	20
	Thin	64	10

Table 1. Disks specification

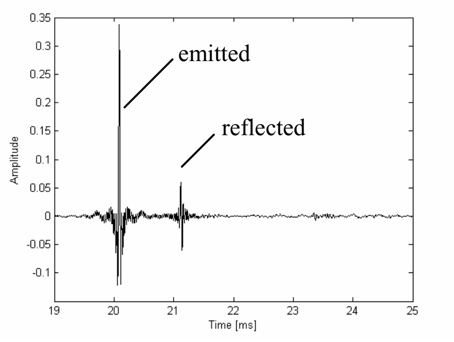

Fig.4 Equalised impulse response of large plastic disk

The reflection part around 21 ms, has a duration of approximately 1 ms and is extracted and used for the simulation.

3.2 Reconstruction of the signal

The signal processing was performed using MATLAB version 7.2. The influence of bat-oriented auditory processing on differentiation between experimental target objects was investigated by reconstructing FM and CF echolocating signals. The reconstruction and signal analysis procedure consists of three parts: simulation of the echolocating signal; auditory pattern spectrogram-like analysis and subtraction of the spectrograms from two different objects [9]. CF signals of 20 kHz sinusoid al waves were generated with durations of 10 ms and FM signals of 10 ms duration were generated with the bandwidth which was set to sweep down from 30 kHz to 10 kHz. Each signal was multiplied by a Hanning window, which has same length as the signal, to remove the undesirable high frequency components at the beginning and end of the signal. The generated signals were convolved with each backscattering impulse response from the disks and auditory processing was performed. The convolved signal which reconstructs the FM echolocating signal for the large plastic disk is shown in Fig.5 (a), while Fig.5 (b) shows the spectrogram of the reconstructed CF signal for the same disk. Finally in this study, the auditory pattern spectrogram-like image was developed as a contour display derived using the image subtraction process from two different objects. The image produced from the same disk is shown in Fig.5 (c). The difference between outputs of the auditory filterbanks for two different objects was calculated and presented as the auditory pattern characteristics for object differentiation. The auditory pattern contour enables us to identify the characteristics of object differences easier than the individual disk auditory images.

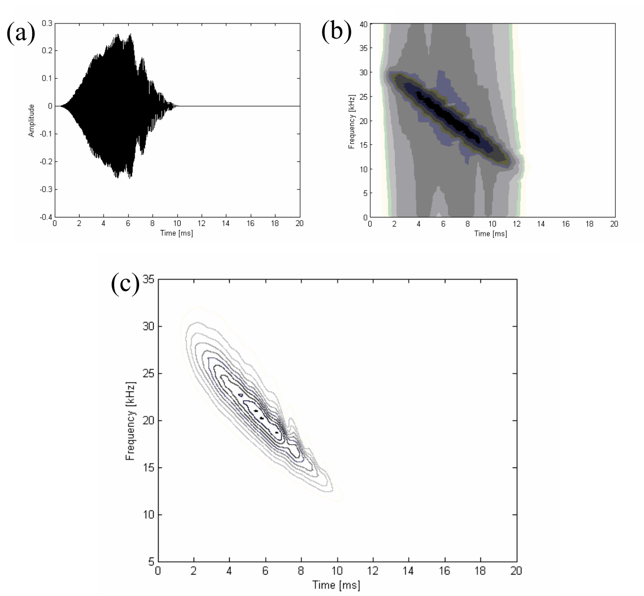

Fig.5 Reconstructed FM reflected signal from the large plastic disk and auditory processing (a) wave (b) spectrogram (c) auditory pattern spectrogram-like image (*EarQ*=10)

4 Results

4.1 FM signal

The effects of using FM signals and auditory processing with various *EarQ* are investigated. The auditory pattern image for large-small plastic disks and thick-thin wooden disks are presented. As shown in Fig.6, the patterns show peaks and notches that become more prominent and precise when a higher value of *EarQ* is applied. Also a higher *EarQ* results in narrower frequency representation in each time segment as expected. These effects are more evident in the large-small plastic disks (different in diameter and thickness) investigation rather than in the thick-thin wooden disks (different in only thickness) pattern. The number of peaks and notches has been decreased in the large-small plastic disks with frequency sharpening effects on the pattern whereas the thick-thin wooden disks mostly showed a sharpening effect only.

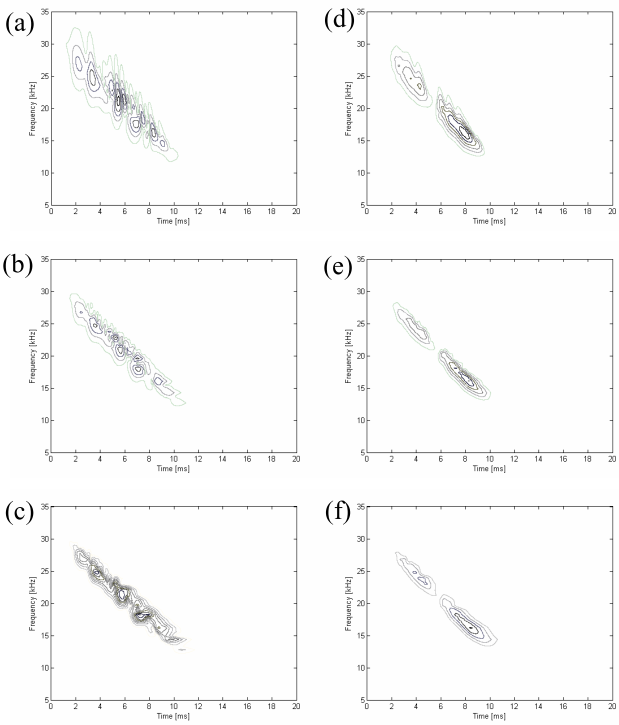

Fig.6 Large-small disk difference in the auditory pattern spectrogram-like image with different asymptotic filter quality (*EarQ*) (a) *EarQ*=10 (b) *EarQ*=20 (c) *EarQ*=30, thick-thin disk difference in the auditory pattern spectrogram-like image with different asymptotic filter quality (*EarQ*) (d) *EarQ*=10 (e) *EarQ*=20 (f) *EarQ*=30

4.2 CF signal

4.2.1 Acoustic fovea effect

Here the effect of the acoustic fovea model implemented on the general gammatone auditory processing was investigated. The spectrogram-like auditory images of the large, medium and small plastic disks were chosen to compare with the image processed with a narrowband foveated cochlear model. Each auditory image is shown in Fig.7. It was shown to have a smaller value of representation as the size of the disk decreases. The foveated model produced higher resolution of frequency components and more sharpened image as expected.

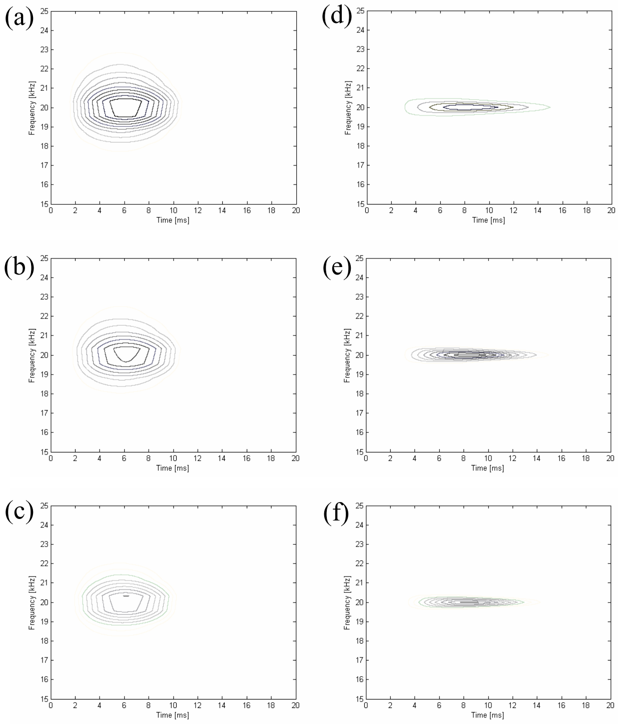

Fig.7 The auditory pattern spectrogram-like images (a)(b)(c) large, medium and small plastic disks with standard gammatone filterbanks (*EarQ*=10), 50 filters of 5 kHz-35 kHz and (d)(e)(f) same disks with modified gammatone filterbanks (*EarQ*=10), 20 filters each in 5 kHz-17.5 kHz , 22.5 kHz-35 kHz and modified by narrowband filters of 18 kHz-22 kHz

4.2.2 Comparison with FM signal

The effect of the foveated cochlear model on the object differentiation was investigated by comparing the result from the same large plastic disk with the FM signal as shown in Fig.8. Whereas the result from the FM signal showed peak and notch representation in the pattern difference image, the CF signal was shown to have no prominent feature although the foveated model was applied. The CF signal seems to have less benefit for object characterisation from this study. This supports previous studies where the CF signal does the role on Doppler shift compensation whereas the FM signal supports improved frequency information.

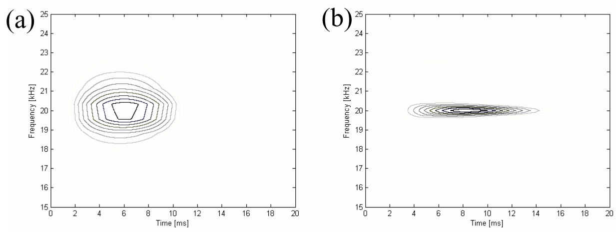

Fig.8 Large-small disk difference in the auditory pattern spectrogram-like image (a) standard gammatone with *EarQ*=10 (b) foveated model

5 Conclusion

Based on the acoustic model for the echo generation mechanism, we have simulated bat-oriented auditory processing of echolocating signals in terms of object differentiation. The bat-oriented gammatone auditory filterbanks were designed based on the standard mammalian cochlear model and modified for both FM and CF signals. As a result the difference between the outputs from the cochlear processing of two objects produced more prominent and narrower peaks and notches for the FM signal with higher asymptotic filter quality factor. The effect has been emphasized by the targets which are different in both diameter and thickness, rather than those which are same in diameter and different in thickness. On the other hand, the auditory image resulting from CF signal which was processed through the model of an acoustic fovea has not presented the characteristics in difference prominently although the processing in the acoustic fovea helped to produce higher frequency resolution and sharpened image. The result indicates that FM signal is more suitable for object characterisation than the CF signal. It also proves that the specialised processing of CF signal in the acoustic fovea supports other function of echolocation, i.e. the Doppler shift compensation, than object characterisation and discrimination.

For extended study, the advanced modelling of the bat's auditory system and the application of head-related transfer functions between the air-transmission model and the hearing model will provide a better insight, and expand the echolocating task to sound localisation using binaural signals.

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