

## Sound Radiation Patterns in the Frequency Domain of Cries from a Vespertilionid Bat\*

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Accepted August 28, 1979

**Summary.** Ultrasonic cries from an immobilized vespertilionid bat *Myotis daubentoni*, were recorded simultaneously in front of the bat (on-axis), and at various off-axis angles. The differences between the on-axis and off-axis spectra were computed and related to the theory of directional emission from a baffled rigid-piston radiator. This theory implies zero radiation at a specific frequency for a given piston diameter and off-axis angle (Fig. 1). The bat's difference spectra showed notches of ca. 25 dB with properties as the zeros of the piston theory (Fig. 7). The structure of off-axis cries was found to be qualitatively predictable from the on-axis cries, using the piston theory (Fig. 4). The difference spectra had a complex, oscillatory fine-structure that could not be accounted for by the basic piston theory.

### Introduction

Physical models describing sound radiation patterns are available for some bat-families emitting sound through the nostrils (Megadermidae, Rhinolophidae) and for one mouth-emitting genus, *Pteronotus*. For vespertilionid bats, however, the factors governing the radiation pattern are not known to the extent that such patterns can be estimated from knowledge of the cry properties and anatomical measures.

Most vespertilionid bats employ for echolocation a mouth-emitted cry in the 20 to 120 kHz range, that typically has a downwards frequency sweep of an octave, e.g. from 50 to 25 kHz, often with harmonics, and lasting for a few ms. The cross-section of the heads of these bats is a few wavelengths wide at the higher frequencies and about one wavelength at the

lower frequencies. Since the head acts as an acoustic baffle, with a forward directing effect related to the ratio of baffle-size to wavelength, this indicates that the sound radiation pattern will vary during the cry, being relatively narrow at the high frequencies and wider at the low frequencies. This indeed has been found experimentally in the one species for which a complete pattern has been obtained (Shimozawa et al., 1974). However, since vespertilionid cry properties vary from species to species, and within the same specimen in response to orientation requirements, the radiation patterns will vary accordingly. In the absence of a theoretical understanding of the radiation physics, no means are available for a priori evaluation of this variation, apart from the above crude generalization.

Strother and Mogus (1970) successfully applied the theory of sound radiation from a rigid, vibrating, circular piston in an infinite baffle (Morse, 1948) to describe the radiation pattern of *Pteronotus*, but found the theory inappropriate in predicting half-power beamwidth in *Eptesicus fuscus* (fam. Vespertilionidae).

The rigid piston model states that

$$I_{\theta}/I_0 = 1/(2J_1(x)/x)^2, \\ x = (2\pi/\lambda) \cdot A \cdot \sin \theta. \quad (\text{Eq. 1})$$

Where  $I_{\theta}$ : intensity at an angle with the normal to the piston surface;  $I_0$ : intensity due to an isotropic source;  $J_1(x)$ : first order Besselfunction;  $\lambda$ : wavelength;  $A$ : radius of piston.

While the halfpower point is a standard engineering convention used to characterize lobe-widths, it is worth noting that there is nothing qualitatively unique about this point; a 6 or 20 dB limit might serve equally well. However, when the consequences of the model are derived for a frequency of about

\* Supported by grants from the Danish Science Research Council for Natural Sciences

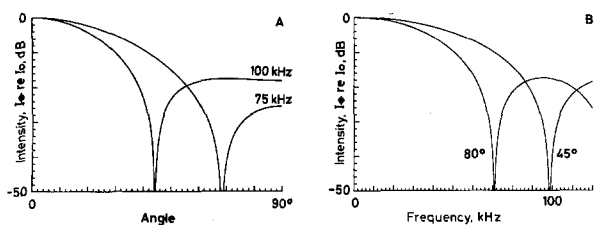


Fig. 1. A Distribution in angle of intensity from a 0.6 cm piston at 75 and 100 kHz (Eq. 1). B Distribution in frequency of intensity from a 0.6 cm piston at 45 and 80 deg. (Eq. 1)

2.4 times that used in determining the halfpower point, the Besselfunction-term  $J_1(x)$  of Eq. 1 approaches zero, implying that for a given frequency and piston diameter, a direction can be found at which no energy is radiated (cf. Fig. 1 A). Likewise, given direction and piston diameter, a frequency can be found at which no energy is present (Fig. 1 B).

The dominating features of the functions are the zeros. If the piston model is indeed applicable to bats, such zeros (notches or minima) in the radiation pattern are predicted, and being of a qualitative nature, they might be easier to determine experimentally than the purely quantitative half-power point. Consequently, the questions of this investigation are: can minima be found in the radiation pattern of vespertilionid bats, and if so, do they have properties that are predictable from the piston model?

The acoustic analogy between a circular, rigid, vibrating piston in an infinite baffle (wall) and an echolocating bat is evidently a weak one. Particularly disturbing is the bat's lack of a structure serving as an infinite or at least, large baffle; also, the transient nature of bat-pulses is a potential problem. To evaluate the robustness of the basic model with respect to violations of its conditions, some simple experiments will be reported.

## Material and Methods

All measurements were made in a 100 m<sup>3</sup> anechoic room with a reflection coefficient of less than 0.1 in the 500 to 100,000 Hz range.

### Model Experiments

A sound source with piston-like properties was obtained by constructing an electrostatic speaker with fixed dielectric according to the Kuhl, Shodder and Schröder (1954) principle (KSS-source). The membrane (diameter: 6.5 cm) was clamped to a metal backplate, following the design of Machmerth et al. (1975). The diameter of the housing was 10 cm. The speaker assembly could be mounted in a circular hard-board baffle, 55 cm in diameter.

To produce directional patterns, the speaker was mounted on a B & K 3922 turntable, synchronized to a B & K 2305 level

recorder. The speaker was driven either with a sinewave source (B & K 2010), or with a synthetic bat-pulse with 20 ms duration, 2.5 to 5 kHz sweep, triangular waveform, square envelope, start and stop at zero level. When sinewaves were emitted at fixed off-axis angles, a reference microphone (B & K 4125) was placed on the axis, keeping the sound pressure level constant with a compressor circuit. The off-axis level was recorded on the level recorder, using a similar microphone. When pulses were measured, the output level was not controlled. Instead, both the on-axis and the off-axis level were recorded on tape and analyzed off-line by a digital method, described below.

### Bat Experiments

The bat, weighing 11 g, was a female *Myotis daubentoni*, fed on mealworms. Its mouth width at the gape-angle was 8 mm. A surgical procedure, essentially that of Shimozawa et al. (1974) was used to fix a 1.8 cm by 1.2 mm piece of stainless steel tubing on the skull, using cyano-acrylic as an adhesive. Minimal amount of adhesive was used in order to retain the shape of the head as much as possible to the preoperation situation. After two days of recovery, the bat was fixed by the pin in a pin-vice in the center of an array of microphones. The bat was supported by a floating vinyl ball (diameter: 9 cm). The microphones (3 × B & K 4138<sup>1/8</sup> inch condenser microphones) were placed at a distance of 25 cm from the bat, with the diaphragms parallel to the sound path. The rostral axis of the bat was found by an aiming device that established the plane normal to a line connecting the eyes. In the vertical plane, the palate was lined up with the plane of the microphone diaphragms. One microphone was positioned on the axis serving as a reference, the other two formed pairs at off-axis angles (43 and 89 deg., or 67 and 291 deg. respectively). Since exact positioning of the bat in the acoustic center proved to be very time consuming, the actual bearings were calculated after recording the pulses, using time of arrival difference information in the microphone signals. The accuracy was better than 4 deg. Corrections for the resulting non-equidistance of the microphones were entered into the sound pressure calculations. No obstacles, except for microphones with their associated preamplifiers (B & K 2 × 2619, 1 × 2618) were in front of the array, which was supported from the ceiling by a steel rod behind the bat. The bat would either emit sound spontaneously or was induced to do so by a light touch.

The microphone-signals were amplified (B & K 2606, 2010, 2425) and recorded together with a digital time signal on a Pentelek 110A 7-track tape recorder, operated at 60 ips. (152 cm/s). Absolute calibration was by a B & K 4230 sound level calibrator and a B & K 4142 electrostatic actuator. The response of the total system was governed entirely by the microphones with a 3 dB cut-off at 110 kHz. The overall accuracy was known within 3 dB.

### Analyzing Methods

The recorded signals were played back at reduced speed from a Racal Store-7 instrumentation recorder and into a Nova-1200 minicomputer via an 8-bit A/D converter, using a sampling rate and low pass filtering corresponding in true time to 640 kHz and 200 kHz respectively. The different channels were digitized one at a time, using the digital timing signal for synchrony. Based on S/N ratio, 17 pulses were selected from the 43/89 deg. series, and 16 pulses from the 67/291 deg. series.

To prepare time/frequency/amplitude-plots, the pulses were sectioned in 67 overlapping parts by a Gauss-window function (ex-

ponent=6) and the spectrum of each section calculated by a FFT-routine. The spectra were then organized in a matrix and plotted as intensity versus time, one line for each frequency. In this way a format related to the classical sonagram is obtained. To find the spectral differences between on- and off-axis recordings, a square window with the entire pulse was transformed (single frame method), while special routines took into account the successive changes in amplitude level in the recording and analyzing chain. This allowed for computation of absolute differences between spectra.

Since the single frame spectra, especially at frequencies above 40 kHz had a complicated fine structure, the difference spectra appeared "noisy". To emphasize the median trend, digital smoothing ("take 7, keep 4, running average") was performed on the difference spectra. The noise spectra were processed by the same routine.

**Results**

*Model Experiments*

Polar plots of the KSS-source at fixed frequencies are seen in Fig. 2. For technical reasons the diameter of the membrane was chosen to be about 10 times the likely cross-section of the mouth of a myotid bat, requiring a similar increase of wavelengths and signal durations to make comparisons valid. Directionality increases with frequency; notches are evident at the two highest frequencies. The quantitative findings for this source with and without a baffle are summarized in Table 1. Deviation from the predictions of the piston model increases with wavelength; this effect is reduced when the baffle is employed, but then oscillations in the radiation pattern are introduced at the lowest frequencies, obscuring the 3 dB beamwidth at 2 kHz. At this frequency, the radius of the baffle is approximately twice the wavelength. The amplitudes of the secondary lobes at 8 and 16 kHz (no baffle) are -24 and -19 dB respectively. The predicted value for the amplitude of secondary lobes is -18 dB.

When the output of the KSS-source is measured at fixed, off-axis angles against frequency using sine waves, the characteristic notch occurs. The actual notch-frequency is lower than predicted by Eq. 1, the effect increasing with wavelength and decreasing when the baffle is used. At 45 deg. without baffle, the notch is found at 8.3 kHz, while according to the piston model 9.1 kHz is expected.

When the KSS-source is excited by a transient pulse with bat cry properties, and the difference between the on-axis and off-axis spectra is derived by the FFT-method, essentially the same relationship is found as for sine wave excitation (Fig. 3). However, the notch-amplitude is reduced to about 30 dB in the transient analysis. Outside the notch, results from

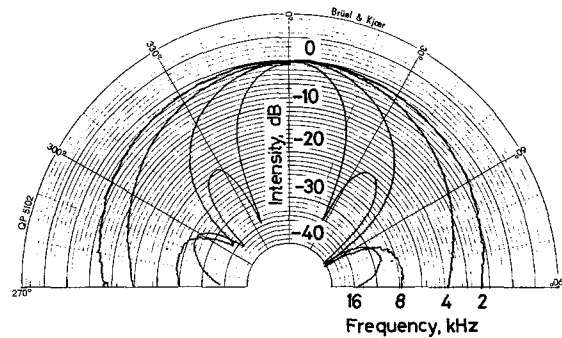


Fig. 2. Distribution in angle of intensity from the 6.5 cm KSS-source at 2, 4, 8 and 16 kHz. Turntable method

Table 1. Directional properties of the KSS-source

Frequency, kHz	3 dB beamwidth, deg.				Notch-angle, deg.	
	2	4	8	16	8	16
Piston theory	—	43	20	10	54	24
KSS-source with baffle	—	35	20	10	58	26
KSS-source without bfl.	52	31	19	10	60	26

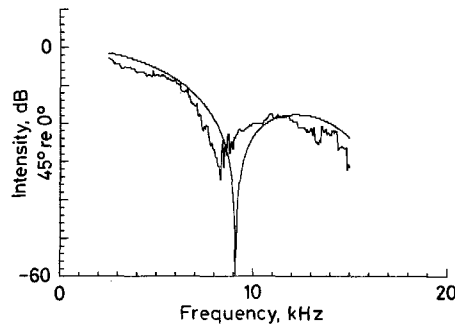


Fig. 3. Distribution in frequency of intensity from the 6.5 cm KSS-source at 45 deg., compared with ideal piston (smooth curve). Single frame method, 256-line spectrum

the sine wave method and the pulse method agree within 2 dB.

*Bat Experiments*

The time/frequency/intensity plot in Fig. 4A shows the detailed structure typical for the cries recorded from the bat. The cry consists of 4 or 5 harmonic bands of decreasing amplitude, the first harmonic sweeping from 45 to 20 kHz in about 3 ms. Energy is present at all frequencies from 20 to well above 120 kHz. In Fig. 4B the same cry recorded at 43 deg. is shown. Note the reduced intensity of the 3rd harmonic in the middle of the cry at about 100 kHz

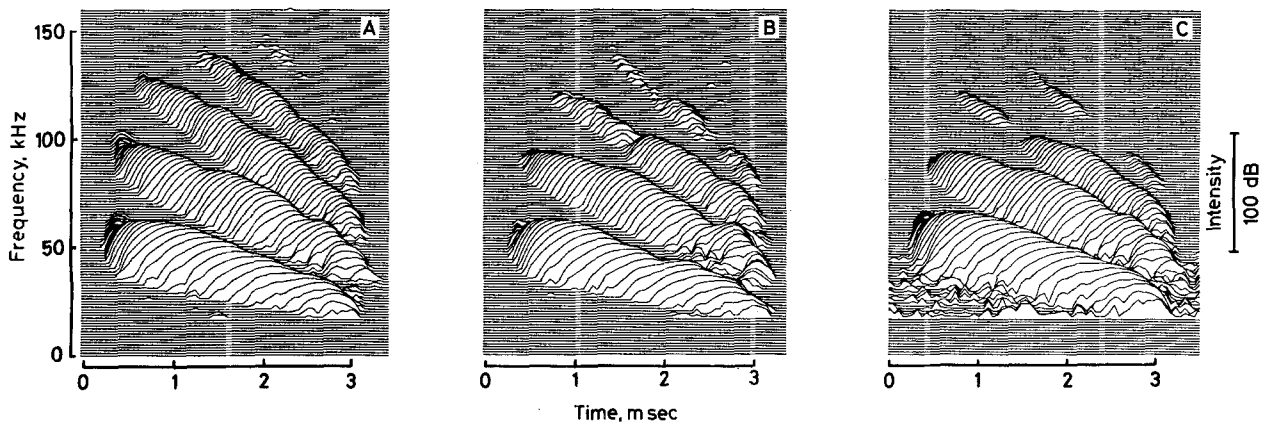


Fig. 4A-C. FFT-sonogram of cry of *Myotis daubentoni*. Noise below a fixed limit has been suppressed, as has energy below 18 kHz. A On-axis signal. B 43 deg. signal. C Computed 43 deg. signal, based on on-axis signal and the theory of angular radiation from a piston of 0.6 cm in diameter 128-line spectra

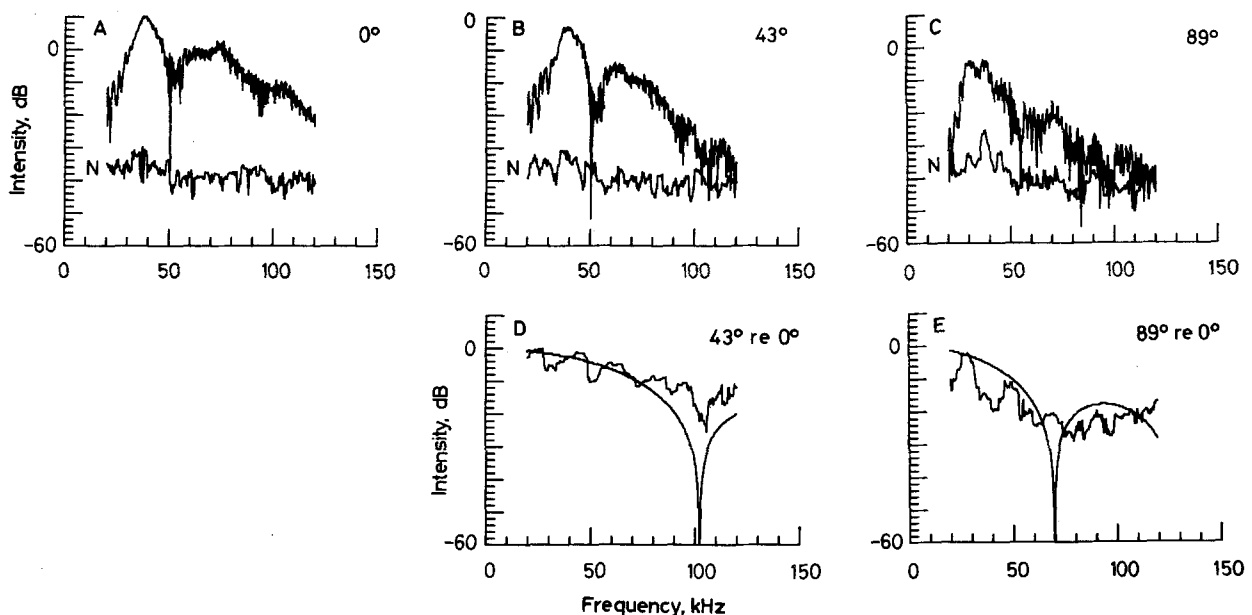


Fig. 5. A-C FFT-spectra of a *Myotis daubentoni* cry recorded on-axis and at 43 and 89 deg. Frequencies below 20 and above 120 kHz have been omitted. Included are the smoothed noise spectra (N). All intensities are given relative to the same reference. D Difference between on-axis and 43 deg. spectrum, compared with ideal piston (smooth curve) of 0.6 cm in diameter. E Difference between on-axis and 89 deg. spectrum, compared with ideal piston of 0.6 cm in diameter. 256-line spectra

and later in the 4th harmonic at the same frequency. Figure 4C is a plot of the prediction by the piston model for 45 deg., using the zero deg. data from Fig. 4A and an assumed "membrane" diameter of 0.6 cm (taken from Fig. 7). As in Fig. 4B, the harmonic bands passing 100 kHz are suppressed, resulting in a qualitative resemblance between Fig. 4B and 4C.

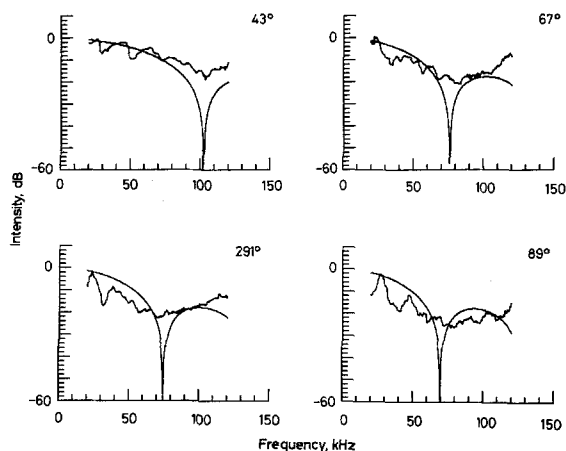
In Fig. 5 spectra generated by the single frame method are shown. On-axis signal energy is 20 to 40 dB above the noise level in the 20 to 120 kHz range (Fig. 5A). From 50 kHz and upwards, the spectrum shows a complicated fine-structure caused by interference between overlapping harmonics. Fig. 5B and 5C show the spectra of the same cry recorded at 43 deg. and 89 deg. respectively. The overall level

at these angles is reduced and approaches noise level at the highest frequencies. Figure 5D and 5E graph the difference between the reference spectrum and the two off-axis spectra. Notches are seen at 105 and 80 kHz respectively. The difference spectra show oscillations with amplitudes of 5 to 10 dB. Data from time sectioning analysis reveal the same oscillatory patterns in the off-axis recordings.

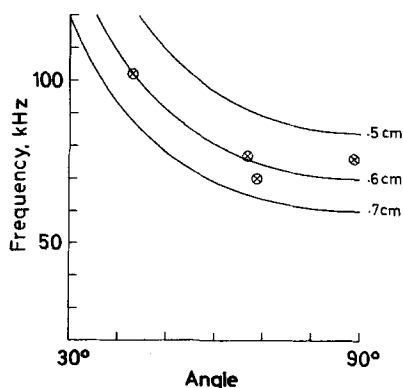
The oscillations to some extent obscure the trend of the difference spectra and create ambiguities for identification of possible notches. In Table 2 are included the number of difference spectra for which notches were readable, and their mean notch frequency. The frequency of notches vary from cry to cry at any angle, but are generally correlated with

**Table 2.** Data on directionality in cries of *Myotis daubentonii*

Angle, deg. →	43	67	89	291
Number of cries analyzed	17	16	17	16
Number of cries with notch detected	17	13	13	9
Mean amplitude of notch, dB	21	25	28	25
S.D., dB	4	2	3	4
Mean frequency at notch, kHz	102	77	76	70
S.D., kHz	3	7	4	9
Mean deviation from 0.6 cm piston model, dB	2.5	3.1	6.7	6.6
Max. deviation from 0.6 cm piston model, dB	9	9	14	13

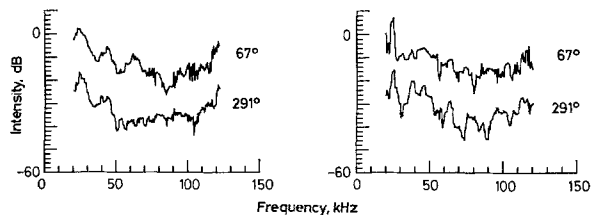


**Fig. 6.** Average difference spectra of all cries analyzed, compared with ideal piston (smooth curve) of 0.6 cm in diameter. 256-line spectra



**Fig. 7.** Variation of notch-frequency with angle and frequency for 3 differently sized pistons. Crosses represent the bat's mean values of notch frequencies (data from Table 2). The point at 291 deg. has been plotted as  $360 - 291 = 69$  deg.

a high frequency at one angle corresponding to a high frequency at the other angle. The magnitude of this variation is indicated by the standard deviation (S.D.) of the mean (Table 2). Mean values for the entire frequency range were produced by averaging



**Fig. 8.** Difference spectra of two cries from bilaterally almost symmetrical recordings. The 291 deg. curves have been displaced  $-20$  dB. 256-line spectra

all spectra from each angle. All average spectra show a single, although shallow depression (Fig. 6). The minor discrepancies between the figures of mean notch frequency in Table 2 and those indicated in Fig. 6, are due to differences in the methods for analysis. The average spectra show that levels at frequencies below minimum are less than expected from the piston model, the discrepancy increasing with angle. At frequencies above minimum, levels are generally too high. The mean deviation for frequencies between 20 kHz and the  $-20$  dB limit on the ideal piston functions is given in Table 2. The figures measure the area between the average and the theoretical functions.

In Fig. 7 is shown the frequency of notch versus angle for 3 diameters of a radiating piston. The point at 291 deg. (left) deviates considerably from that at 67 deg. (right). This is caused by a number of spectra of the type of Fig. 8B. Within the same recording sessions other cries (Fig. 8C and D) show reasonable symmetry between right and left.

**Discussion**

The measurements on the KSS-source showed first that directionality qualitatively, and in most respects also quantitatively, conforms with the rigid piston model (cf. Fig. 2). Secondly, omission of the baffle increases directionality and decreases the notch-frequency, the effect being most pronounced at low frequencies, but otherwise has only negligible influence on the radiation pattern. In the format used, the KSS-source reacts to the removal of the baffle as if membrane diameter increases with wavelength (the increase being 11% at 4 kHz). Finally, transient broad band pulses with bat cry properties are radiated according to their spectral components in the same manner as are constant tones.

Consequently, neither the absence of an infinite baffle, nor the use of broad band FM-pulses invalidates a priori the piston theory as a candidate for the model describing bat radiation patterns.

The merits and shortcomings of the piston-model

in predicting spectrum dependent radiation patterns in the cries of the bat can be inferred from Figs. 4 to 8 and from Table 2. Figure 7 shows that all average notch frequencies are close to values predicted by the model for a diameter of the radiating surface of 0.6 cm. The averaged spectra of Fig. 6 are not suggestive of notches in the radiation patterns. However, most single difference spectra exhibit more pronounced notches (Fig. 5), but since the frequency of the notch changes from cry to cry, the notch of the average will degenerate into shallow depressions. Consequently, the concept of notches or minima with piston model properties appears to be justified by the bulk of data. This is demonstrated by the ability of the model to predict the structure of off-axis cries (Fig. 4C).

Obvious shortcomings are as follows: 1. The notches of single cries are too shallow. 2. The average level of the difference spectra appears to be too low at frequencies below the notch and too high above. 3. Large amplitude oscillations in the difference spectra occur below the notch frequency.

The first observation is not surprising. The limited dynamic range of the combined instrumentation limits the analyzable amplitude, as indicated by the noise-levels in Fig. 5. An additional source of noise was echoes from the on-axis microphone, which was found (by cross-correlation between on- and off-axis signals) to produce echoes of  $-22$  dB relative to the directly received signals. This level is dominated by energy of the first harmonic component; the echo is likely to be lower at the higher frequencies containing the notches, but still notch-amplitudes of more than 30 dB will be masked. The mean notch amplitudes of Table 2 are therefore considered to be noise-limited.

The observation that off-axis radiation below the notch is generally more attenuated than expected may be caused in part by the bat's lack of baffle, as indicated by the findings on the source (Table 1). However, the effect is considerably larger in the bat case (see Fig. 6 and the "error" figures in Table 2). – The "surplus"-energy above the notch is likely to be caused by system noise (cf. Fig. 5), and is thus of a trivial nature.

The oscillations in the difference spectra below the notch frequency merit particular attention because of their large amplitude. Time-sectioning technique showed these oscillations to be traceable to the off-axis recordings, thereby eliminating effects of interfering, overlapping harmonics as causal factors. Echo-interference is equally unlikely, due to the low amplitude of the echoes, and instrumental artifacts based on gross saturation of the recording medium can be ruled out on several lines of evidence. Similar

oscillations were found in the experiments on the artificial source only when the radius of baffle was approaching the emitted wavelength. Possibly, the oscillations in the bat's difference spectra can be explained by complicated shaped structures like the ears acting as a limited baffle. At any rate, the oscillations in the radiation patterns are real phenomena, and they are not predictable by the basic piston model.

When evaluating the similarity between the computed and the recorded cry given in Fig. 4B and C, it should be recognized that there is an element of tautology in the computing procedure because the notch frequency of Fig. 4C is part of the data forming Fig. 7, from which the equivalent diameter of the radiating surface is derived. This emphasizes the problem of an independent measure of the acoustically effective size of the mouth-opening. The physical measure of the gape-width is 30% larger than the effective cross-section suggested by Fig. 7. Since the effective cross-section is related to the degree of opening of the mouth, it is likely to vary from cry to cry and even within a cry (Shimozawa et al., 1974). The magnitude of the standard deviation of the notch frequencies given in Table 2 may be explained by variable cross-sections of the emitting surface. Whatever the nature of the mechanism, the same variability is responsible for converting the notches of the individual difference spectra into shallow depressions in the mean functions, shown in Fig. 6A–D.

The occasional right/left asymmetry demonstrated in Fig. 8 is less likely to be caused by changing gape-width, but suggests the presence of additional variable factors influencing the radiation pattern.

The oscillatory nature of the difference spectra makes comparisons with previous reports on bat sound radiation problematic. When such reports are sufficiently detailed (Shimozawa et al., 1974), oscillations in the radiation patterns are again apparent. When the difference function of Fig. 5C is smoothed graphically, the  $-6$  dB point occurs fairly close to the 55 kHz at which Shimozawa et al. reported a half-amplitude beamwidth of 38 deg. for *Myotis grisescens*. Also, notches in the directional patterns of this bat are evident at the higher frequencies, indicating an effective radiating cross-section of 6 mm. Thus, the radiation patterns from the two myotid species are not demonstrably different from each other.

For the somewhat larger *Eptesicus fuscus*, Simmons (1969) found higher directionality (half-amplitude beamwidth of 23 deg. at 30 kHz). According to the piston model, this indicates the radiating cross-section of *Eptesicus* to be roughly 3 times that of the two myotid species. This figure is definitely too large. Strother and Mogus (1970) in fact rejected the basic piston model on this discrepancy. Two findings in

the present paper may be relevant in this context: The observation of an apparent increase in the radiated cross-section for the KSS-source at low frequencies when a baffle is lacking (Figs. 2 and 3), and the oscillatory nature of the difference spectra, provided this turns out to be a general feature of vespertilionid sound emission. However, whether the rejection can be maintained in regard to the more robust notch-frequency criterion remains unanswered until more detailed data on *Eptesicus* are available.

In conclusion, the piston model seems to be useful in predicting notch-behaviour in the cry of vespertilionid bats, but unsuitable for computing half-power beamwidths. Its main value may be to serve as a standard, to which actual data can be related, and by which the various parameters can be transformed to render crude comparisons possible between data obtained in different formats. For more demanding use, the nature of the gross deviations found from

the basic model should be understood and taken into account.

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