NONLINEAR BEHAVIOR AT THRESHOLD DETERMINED IN THE AUDITORY CANAL AND ON THE AUDITORY NERVE

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In order to study mechanical nonlinearities in the mammalian hearing organ over a broad range of frequencies, we have both used and adapted the Kiang-Moxon threshold tuning curve paradigm (Liberman, 1978) to measure distortion products $2f_1-f_2$ (the CDT) and f_2-f_1 (the DT) and to measure two manifestations of two tone suppression.

The data presented here was primarily recorded from the auditory nerves of over twenty cats. Both the physiological techniques and the computer controlled audio and electrical instrumentation are discussed fully in Allen (1983). Most of the data presented here will be threshold curves defined such that the curve is the locus of points in frequency-amplitude space where the amplitude was adjusted until the neural unit under study generated one action potential more during a 50 ms interval with the signal on than the spontaneous rate during the immediately preceding 50 ms interval.

DISTORTION PRODUCTS

Using the Kiang-Moxon paradigm we measured the frequency threshold curve (FTC) for the neural units that we encountered on the auditory nerve. Given the FTC and, hence, the CF, we then input a tone pip comprised of two frequencies, f_1 and f_2, such that either $2f_1-f_2$ or, alternatively, f_2-f_1 was equal to the CF. Again we used the Kiang-Moxon paradigm to find the locus of points in the frequency amplitude (f_1,A_1) plane such that the unit responded with one more spike during the driven interval than during the silent interval. This locus of points defines a distortion threshold curve (DTC). For all of the data curves presented here the amplitudes of f_1 and f_2 are equal $(A_1=A_2=A)$.

Effectively our procedure is to calibrate an auditory neuron (by measuring its FTC) and then to use this "calibrated" neuron to control the level of the primary frequencies. In Fig. 1 we show four FTC's superimposed on the units' $2f_1-f_2$ DTC's. The amplitude of the distortion product is equal to the FTC threshold at CF. Note that for frequencies less than the point of intersection of the DTC with the FTC both the distortion product and f_1 drive the unit. Hence this point of intersection (marked with a triangle in Fig. 1) is the last point in the DTC's in Figs. 2 and 3. Since the unit's threshold at CF is the amplitude of the distortion product (and the sensitivity of the detector) in the Figs. 2 and 3, the DTC will be normalized to the threshold at CF.

Fig. 2(a) shows cubic spline fits to all of the $2f_1-f_2$ DTC's for one cat. Although the individual curves in this figure can not be resolved, it is apparent that the non-monotonic behavior as seen in Fig. 1 is commonplace. It is further evident that at high CF's, the detectable distortion products can be generated at lower amplitude of the primaries.

As is seen in Fig. 2(b), if the DTC's are replotted versus log f_2/f_1, the slopes are found (non-monotonicities aside) to range from 50-70 dB/octave (of f_2/f_1), with a mean across animals of about 55 dB/octave (of f_2/f_1). For the CDT, the data spread is least using log $(f_2/f1)$ as the dependent variable. For the DT (f_2-f_1) f_1 seems to be an appropriate variable (Fig. 3).

In Fig. 3 we show a plot of the dependence of several f_2-f_1 DTC's upon frequency for one animal. As before the frequency of the distortion product equals the CF of the neural unit and the amplitude of the DT is equal to the threshold of the unit at CF. In this figure all responses have been normalized by the CF threshold. It is clear from Figs. 3 and 2(a) that the f_2-f_1 DTC is much less frequency dependent than the $2f_1-f_2$ DTC. Also we found a much larger variability

R. Klinke et al. (eds.), *HEARING — Physiological Bases and Psychophysics*

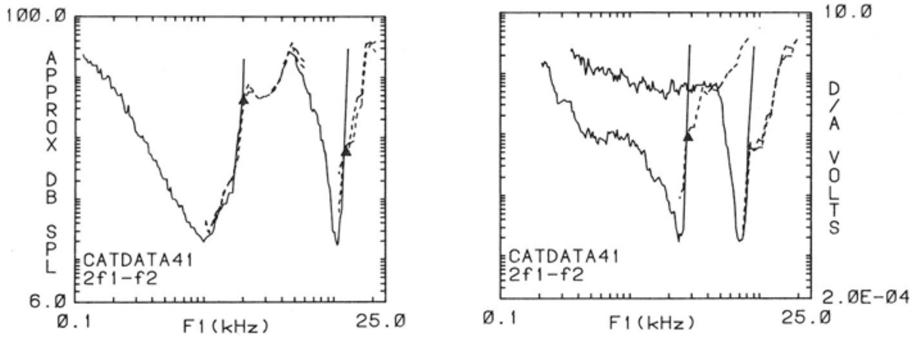


Fig. 1. *This figure shows some FTC's (solid lines) for Cat 41 with raw distortion product data (the DTC's, the dashed lines) for the respective units. With two units two passes at the DTC are shown. Also on some of the DTC's there is a triangle at the DTC-FTC intersection. Points on the DTC of lower frequency than the intersection point are not considered part of the DTC because the* f_1 *primary rather than the distortion product is driving the unit (10.0 volts to our driver results in an SPL of about 100 dB re 20 μPa at the tympanic membrane)*

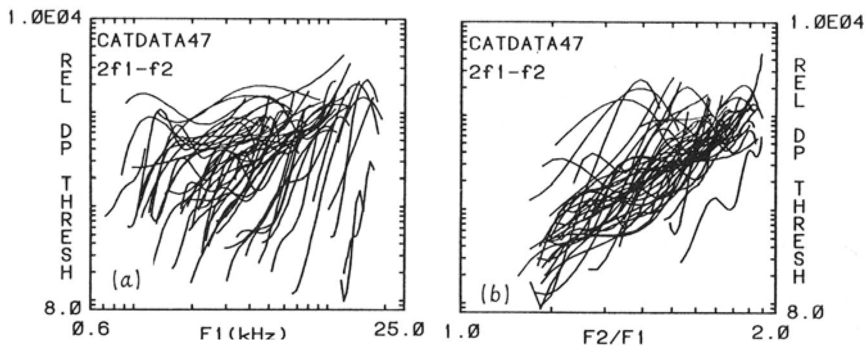
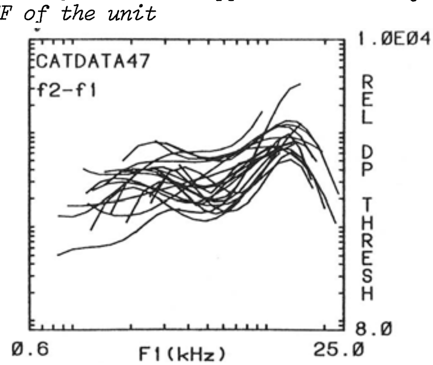


Fig. 2. *In (a) we show a collection of the cubic spline fits to the* $2f_1-f_2$ *DTC's of Cat 47. Cubic spline fits were used to average multiple passes at the DTC. The density of curves is too great to resolve the individual curves in most cases, but the trends in the DTC's with frequency are apparent. In (b) the same data as in (a) is replotted using log* (f_2/f_1) *as the independent variable (note the log scale). Disregarding non-monotonicities, generally the DTC's approximate straight lines of the same slope independent of the CF of the unit*

Fig. 3. *In this figure are the cubic spline fits of the* f_2-f_1 *DTC's of Cat 47. It is evident here that the frequence dependence of the DT is different from that of the CDT*



between cats for the DT, whereas all of our cats with good thresholds showed a fairly similar threshold for the CDT.

While we were measuring the DTC we also made ear canal pressure measurements in several animals with a calibrated Bruel and Kjaer ½ inch microphone terminating a 2 cm long probe tube. The probe microphone was used to ascertain the level of distortion in the external auditory meatus and in a closed acoustic cavity. In the acoustic cavity the level of the distortion products was always more than 70 dB below the level of the primaries (and near the distortion floor of the driver).