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Published in:
Journal of the Acoustical Society of America

DOI:
10.1121/1.383202

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1979

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Wit, HP., & Ritsma, RJ. (1979). Stimulated acoustic emissions from the human ear. *Journal of the Acoustical Society of America*, *66*(3), 911-913. https://doi.org/10.1121/1.383202

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Stimulated acoustic emissions from the human ear

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(Received 16 April 1979; accepted for publication 13 June 1979)

The influence of stimulus frequency upon the magnitude of stimulated acoustic emissions from within the human ear was studied. Stimuli of higher frequency generate much smaller emissions (responses) than stimuli of lower frequency at the same stimulus level. For low response levels the relation between stimulus level and response level is approximately linear. High response levels rise approximately as the cube root of stimulus level. A tuning curve could be derived by suppressing emissions with a second steady tone.

PACS numbers: 43.63.Hx, 43.63.Kz, 43.63.Rf

INTRODUCTION

Some months ago the existence of stimulated acoustic emissions from within the human auditory system was discovered by Kemp (1978). Repeating the measurements of Kemp with a broadband stimulus we registered tone burstlike echoes in a number of human ears. The frequency of these echoes was about 1.5 kHz. This gave us the idea that echoes would be larger after stimulation with short 1.5-kHz tone bursts instead of an acoustic click. In order to investigate the influence of stimulus frequency upon the magnitude of the response (echo), we measured acoustic emissions after stimulation with short tone bursts having a narrow frequency band. Three different center frequencies chosen: 1.7, 2.8, and 4.2 kHz.

In the "Addendum" of his paper Kemp stated that the emissions could be suppressed by a second steady tone and that derived tuning curves show high selectivity. We can confirm this finding.

MATERIAL AND METHOD

Nine normal hearing subjects (23-to 34-years old) participated in the measurements. Figure 1 shows the acoustic probe that was placed in the subjects external auditory meatus. The measured frequency response of the miniature microphone (ceramic type Knowles K 1671) is given in Fig. 2. With a spectrum analyzer (Ubiquitous UA-6B) three different acoustic stimuli with rather narrow frequency spectra were selected. (bandwidth 600–900 Hz). Stimulus center frequencies were 1.7, 2.8, and 4.2 kHz (see Fig. 3). Stimuli were pres-

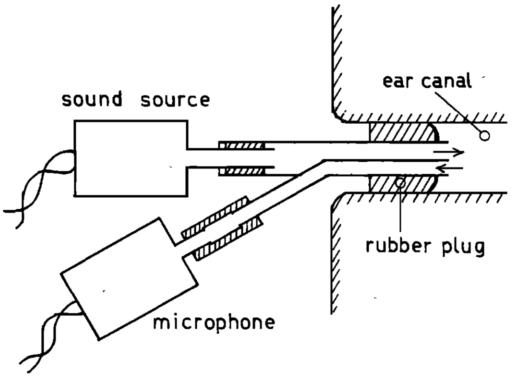

FIG. 1. Acoustic probe placed in subjects ear canal.

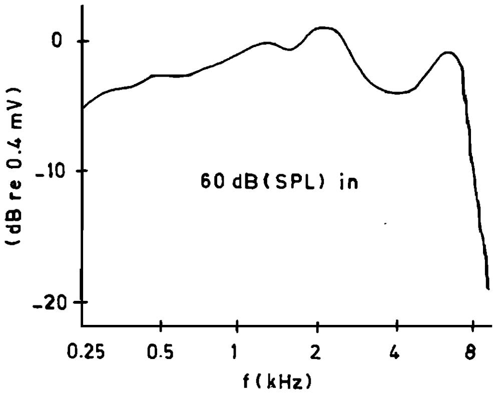

FIG. 2. Frequency response of ceramic miniature microphone.

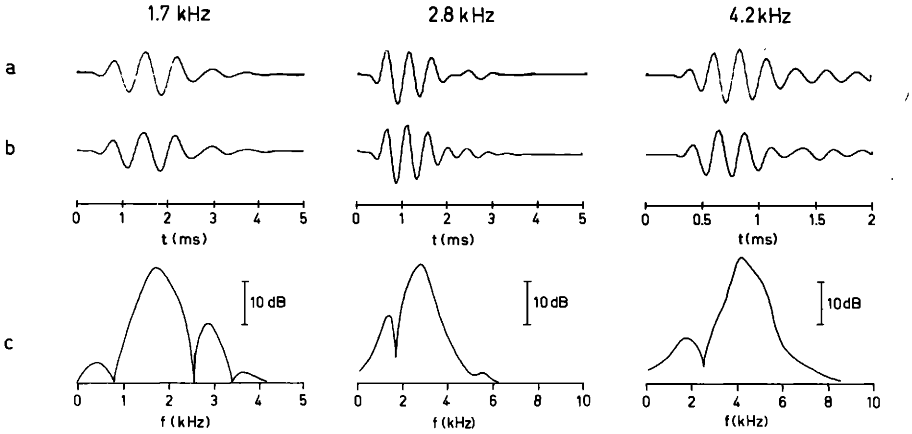

FIG. 3. Transient stimuli with frequency spectra. (a) Acoustic signal with probe in human ear. (b) Acoustic signal with probe in coupler. (c) Frequency spectrum of acoustic signal with probe in coupler.

ented to the subject with a repetition rate of 16/s.

After proper amplification the microphone signal was fed either to a modified Princeton Applied Research type TDH 9 analog signal averager (100 memory points) or to a Datalab type DL 400 digital averager (1024 memory points). High-pass filtering was applied to the amplified microphone signal (cutoff frequency 500 Hz; slope 14 dB/octave).

Responses were measured in a time window from 0- to 5-ms post stimulus time in order to obtain the peak sound pressure level generated in the subjects meatus by the transient stimulus. After that, acoustic activity in the meatus was measured in the time window from 5 to 25 ms with a much higher amplification combined with clipping of the signal in the 0–5-ms interval.

A second steady tone could be mixed with the transient stimuli to derive tuning curves. As the phase of the steady tone was free running with respect to the time base of the averager, this signal gave a negligible contribution to the measured responses.

RESULTS

The nine selected subjects showed acoustic emissions of the type described by Kemp.

Fortunately one subject showed such large responses that a graph could be obtained showing the acoustic stimulus (1.7 kHz) as well as some responses on the same sound pressure level scale (Fig. 4). Responses from the same subject for the three different stimulus frequencies are given in Fig. 5. Among other things this figure shows that stimulation with 4.2 kHz gives responses that are almost identical with the responses to the 1.7-kHz stimulus, apart from the difference in stimulus intensity. In Fig. 6 the average peak sound pressure level of the largest response is given for different stimulus intensities for the three stimulus frequencies (average results from nine subjects). For all subjects this largest response fell within the time interval 9–16 ms (average 12.1 ms) after the onset of stimulation.

The individual results for two subjects are given in Figs. 7(a) and 7(b). These subjects were selected because they were quiet enough during the measurements to make registration of low intensity responses possible.

With the Békésy method (using a motor driven attenuator) hearing thresholds of these two subjects were

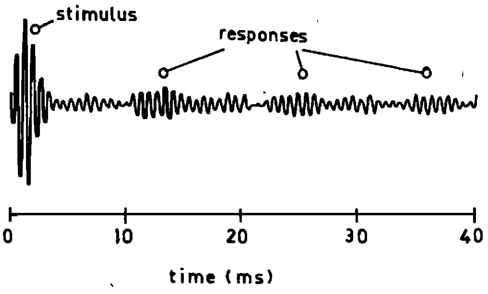

FIG. 4. Stimulus and responses on the same scale.

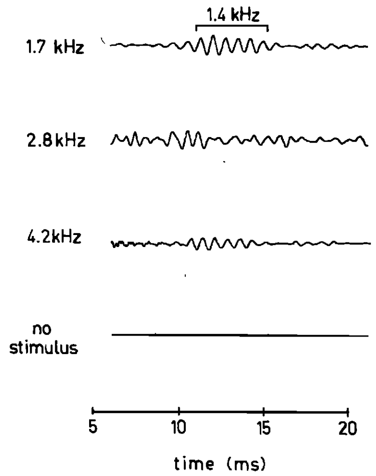

FIG. 5. Responses from one subject to different stimuli. Stimulus level was chosen in such a way that responses had approximately the same magnitude. The lower trace was obtained in the absence of a stimulus. Instrument settings were identical for all traces.

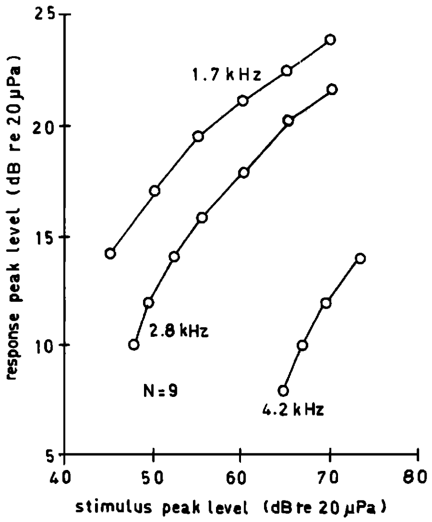

FIG. 6. Relation between stimulus level and response level for different stimuli. Average results from nine subjects.

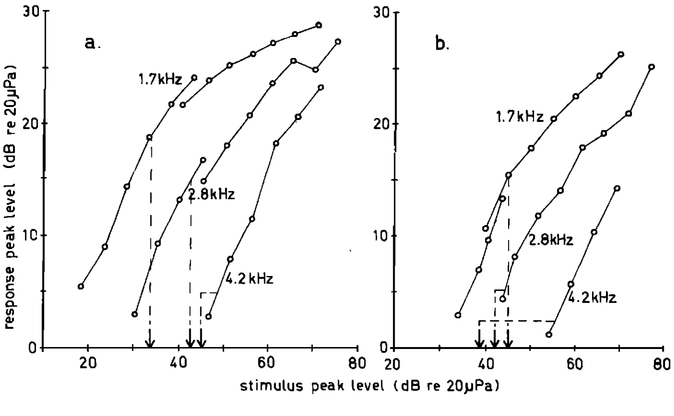

FIG. 7. Relation between stimulus level and response level for different stimuli. Individual results from two subjects. (Connected points are the results from one series of measurements.)

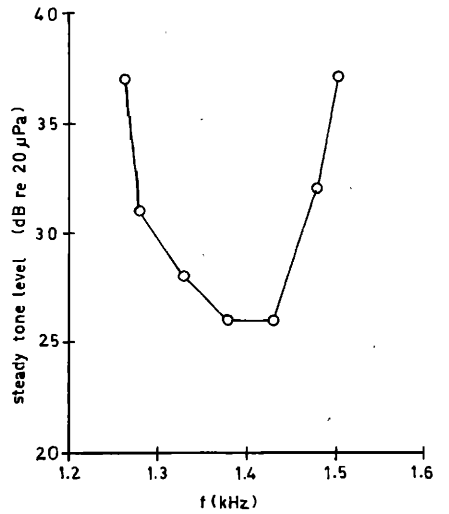

FIG. 8. Tuning curve obtained by suppressing response with a steady tone. Stimulus frequency 1.7 kHz, response frequency 1.4 kHz. Stimulus peak level 39 dB, response peak level 24 dB (re 20 μPa). Vertical scale gives steady tone level that reduces peak sound pressure level of response to 75% of its initial value.

measured for the three different stimuli. These thresholds are indicated by arrows in Fig. 7. The tuning curve from Fig. 8 was measured for the subject giving the largest responses. It was obtained by suppressing the first large response to the 1.7-kHz stimulus (at $t = 12$ ms; see Fig. 4) with a steady tone.

DISCUSSION

As Fig. 6 shows, the 4.2-kHz stimulus gives much smaller responses than the 1.7-kHz stimulus at the same stimulus level: Response magnitude depends on stimulus frequency. The difference in response magnitude is not caused by a difference in sensation level; it remains after expressing stimulus level in dB(SL) instead of dB(SPL)—see Fig. 7. Another interesting result derived from Fig. 7 is the fact that responses are still present below the threshold of audibility of the stimulus.

Kemp's statement that the response level rises approximately as the cube root of the input excitation level holds only for higher response levels. For low response levels the slope of the "input–output" curve (Fig. 7) tends towards unity.

We could confirm suppression of emissions by a second steady tone yielding a tuning curve that shows high selectivity (Fig. 8). Up to this moment the origin of the emissions is not clear to us; possible mechanisms are discussed extensively by Kemp (1978). May the results given above contribute to clarifying this problem.

Kemp, D. T. (1978). "Stimulated acoustic emissions from within the human auditory system," J. Acoust. Soc. Am. 64, 1386–1391.

The Mellin transforms and constant-*Q* spectral analysis

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(Received 15 September 1978; accepted for publication 27 April 1979)

It has been shown recently that constant-*Q* spectral analysis constitutes one means for implementing a Fourier-Mellin transform which is relevant in acoustical signal processing. This letter points out a further connection between constant-*Q* spectral analysis and the Mellin transform: The latter is shown to be the basis for inverting the integral transforms representing both the "short-time" and the "average power spectrum" resulting from any constant-*Q* spectral analysis.

PACS numbers: 43.60.Cg

INTRODUCTION

In a recent paper in this Journal[1] the constant-*Q* spectral analysis was indicated as one means for implementing a "Fourier–Mellin" transform (which has been shown to be a relevant integral transform in signal processing and, in particular, in hearing processes).

The relationship between constant-*Q* spectral analysis and the Mellin transform, however, is considerably deeper than this. It has been shown, in fact, that if a signal undergoes a short-time spectral analysis via a continuous set of constant-*Q* bandpass filters, this processing can be mathematically represented through an integral transform that can be easily inverted (so as to recover the original signal) by means of the Mellin transform.[2]

In this paper the attention is focused on "long-time" (that is averaged or classical) rather than "short-time" constant-*Q* spectral analysis and it will be shown that its mathematical representation also admits an inversion formula based on the Mellin transform.

I. SHORT-TIME AND AVERAGED SPECTRAL ANALYSIS WITH UNIFORM BANDPASS FILTERS

It is well known that the short-time spectral analysis performed through a set of "uniform" bandpass filters can be represented by the following Fourier transform[3]:

$$F_w(\omega,t_0) = \int_{-\infty}^{t_0} f(x)\,w(t_0 - x)\exp(-j\omega x)\,dx\,, \tag{1}$$