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DIFFERENCE LIMES FOR THE SWITCHING PHASES AS A FUNCTION OF FREQUENCY AND DURATION OF THE TONE PULSES

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The discriminating ability of the ear for the switching-on and switching-off phase of the non-stationary tone pulses with a rectangular envelope curve was investigated. The difference limens for the switching-on and switching-off phase of the tone pulses of frequencies 250 Hz, 1000 Hz and 4000 Hz, the sound pressure level of 65 dB and the duration in the extent 4 ms—128 ms were determined experimentally.

The experimental results indicate that the difference limens for the switching phases of non-stationary tone pulses reach a higher value when the pulses are longer. For a given exist no significant differences in the difference limens for the switching-on and switching-off phases. The obtained results agree with the changes of the spectrum of the corresponding pulses.

ДИФФЕРЕНЦИАЛЬНЫЙ ПОРОГ СЛЫШИМОСТИ ДЛЯ ФАЗ ВКЛЮЧЕНИЯ И ВЫКЛЮЧЕНИЯ КАК ФУНКЦИЯ ЧАСТОТЫ И ДЛИТЕЛЬНОСТИ ЗВУКОВЫХ ИМПУЛЬСОВ

Исследуется разрешающая способность уха для фаз включения и выключения нестационарных звуковых импульсов с прямоугольной огибающей. Экспериментальным путём определены дифференциальные пороги слышимости для фаз включения и выключения звуковых импульсов с частотой 250 гц, 1000 гц и 4000 гц, при уровне звукового давления 65 дб и длительности 4—128 мсек.

Экспериментальные результаты свидетельствуют о том, что дифференциальные пороги слышимости для фаз включения и выключения нестационарных звуковых импульсов достигают более высокого значения в том случае, когда импульсы являются более длительными. Для данной комбинации физических параметров импульсов нет существенной разницы в дифференциальных порогах слышимости для фаз включения и выключения. Полученные результаты согласуются с изменениями в спектрах соответствующих импульсов.

I. INTRODUCTION

An important sensorial organ transmitting an information perceived in the environment is the ear. From the information-theoretical point of view it is

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therefore necessary to obtain more information on the communicative function of the ear. The physical carrier of the auditorial information are the acoustic signals. From the physical point of view the acoustic signals are defined by the values of their physical parameters, for example by the frequency, duration, sound pressure level (SPL), shape of the envelope curve or by the switching phases. From the sensorial standpoint the signals are described by the sensorial parameters, for example the pitch, duration, loudness, timbre.

An information can be transmitted only by means of discriminable signals and consequently the discriminating ability of the ear plays an important role as far as its communicative function is concerned. The discrimination of the tone signals takes place on the basis of the differences in the sensorial parameters by which they are characterized. The sensorial measure of the discrimination of the signals is the difference limen (*DL*) for a certain parameter. In general the *DL* is defined as the minimal perceivable difference of the physical parameter (of the acoustical signal) [1].

A complete characterization of the hearing as a sensorial communicative channel requires the determination of the number of the discriminable signals with regard to all sensorial quantities. This task however is very pretentious due to several reasons and therefore it will be necessary to carry out many more sensory-acoustic experiments. The relatively early works of an experimental character dealt with the determination of the *DL*s for the following physical parameters: frequency, duration and intensity — of course in their various combinations. Recently, however, it has been shown that for the *DL* also other physical parameters may be of importance, for example the switching phase, the envelope shape, etc. [2, 3], therefore also the *DL*s for further parameters become topical.

In the experiments performed in the years 1970—1973 the effect of the initial phase on the perception of short tone pulses with an integral number of periods and a rectangular envelope was investigated [4—7]. The obtained results show that the initial phase affects the pitch of the tone pulses and that its change results in a perceptional discrimination of the non-stationary tonal signals. In addition it was also possible to interpret these results theoretically [8] on the basis of the changes in the spectra of the corresponding pulses.

In the experiments with the pulses characterized by an integral number of periods (i.e. with pulses at which the initial phase determines also the final phase), however, it was impossible to get information on how the differences in the particular phases of switching affect the discrimination of pulses, i.e. the differences at the phase of switching-on (initial phase) and the phase of switching-off (final phase) of the pulse and also how the problem appears when the other parameters of the pulses change. The solution of these problems allowed the construction of an electronic switch by means of which it is possible to select independently the phase of switching-on and -off the pulse with a rectangular envelope [9] or in other words

to use a switch capable to transmit the pulses with a non-integral number of periods.

II. EXPERIMENT

The aim of the research work into the discrimination ability of the ear with regard to the switching phases was to determine the functional dependence of the difference limen for the switching-on phase ($DL\varphi$) and switching-off phase ($DL\Psi$) on the frequency and duration of the tone pulses with a rectangular envelope.

The experiments were done on four audiometrically examined subjects with a normal hearing who participated also in earlier experiments (two men and two women, 20—30 years of age). The applied pulses had frequencies of 250 Hz, 1000 Hz and 4000 Hz. The duration of the pulses was in the extent of 4 ms—120 ms (it fulfilled the condition $\tau = 2^n$ ms, where n is a natural number). On the frequency 250 Hz no measurement with the pulse duration of 4 ms was made. The *SPL* of pulses, i.e. the *SPL* of the stationary signals, from which the signals were cut out, was 65 dB.

II. 1. *The measuring method*

The $DL\varphi$ and $DL\psi$ were measured by the sensorial-physical method of constant stimuli, frequently used in the present.

The subject sitting in a sound-insulated room received a couple of tone pulses through the earphone. The first — standard — pulse had the zero phase both when switching-on and -off. The switching-on phase (when measuring the $DL\varphi$) or the switching-off phase (when measuring the $DL\psi$) of the second -comparative — pulse was changed by selected intervals of the switching angles (integral multiplies of 5° determined on the basis of preliminary measurements). The task of the subject was to estimate as to whether the received couple of pulses was equal (positive response) or non-equal (negative response). Therefore, there existed two categories of responses only. The subject was not obliged to deal with the question how the pulses differ, if they are non-equal (e.g. in the pitch, timbre etc.). To questions of this character the subject responded incidentally after several series of measurements.

II. 2. *Notes on the statistical evaluation of the results*

The relationship between the sensorial and signal parameters of the acoustic signals has a statistical character and subsequently the *DL*s too have a statistical character. The concrete definition of *DL* is formulated in connection with the method by which it is determined.

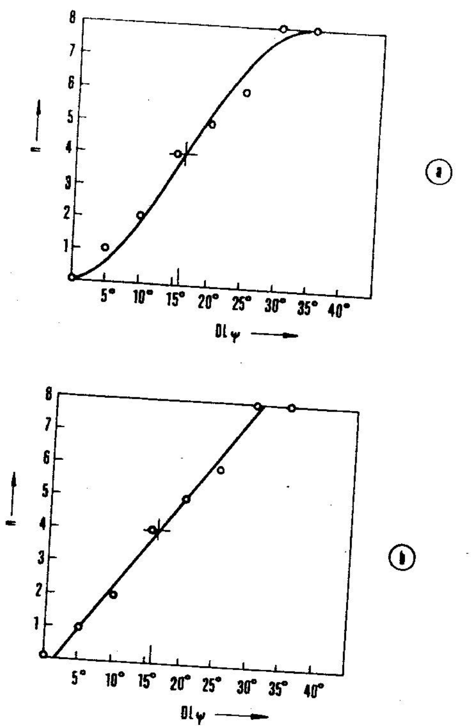

Fig. 1. Experimental points of one series of measurements a) approximated by the integral curve of normal distribution; b) approximated by the straight line.

The results obtained in the particular series of our measurements can be represented by a series of points as can be seen in Fig. 1. At particular values of the switching-off phases (plotted on the abscissa) there was (in the ordinate direction) plotted the number of the negative responses of the subject. Thus in the direction of the ordinate there was plotted the empirical probability indicating that a concrete comparative pulse coupled with a standard one is perceived as a nonequal one.

With respect to the high reliability of the experimental apparatus it can be claimed that the physical parameters, especially the phases of the switching and the frequency of the tone pulses are accurate and thus the assumption can be made that the values of the abscissa in the figures of the type of Fig. 1 are accurately determined; the responses of the subjects succumb to the normal distribution. The set of points in Fig. 1 thus determines the empirical curve of the normal distribution.

As far as regards the mathematical-statistical processing of the experimental results the *DL* is represented by that point of the abscissa which corresponds to the 0.5 probability of the ordinate.

In the *DL*-computations we have approximated the normal distribution curve in its integral shape by a straight line [10] using the least square method. The point in which this straight line intersects the 0.5 probability level is identical with the point in which this probability level intersects the corresponding integral curve of the normal distribution [11]. This property was used in the evaluation of the results. Through application of this procedure the DL_i for each subject was determined. Then for each set of the physical parameters the *DL* was computed as the average value of DL_i. In addition to this average value we further introduce in the results the standard deviation

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(DL_i - DL)^2}{n-1}}$$

as a measure of the dispersion of the measured values.

II. 3. *Apparatus*

The block diagram of the measuring apparatus is shown in Fig. 2. The signal from the tone generator TG (Brüel-Kjaer 1022) was brought to the phasing units

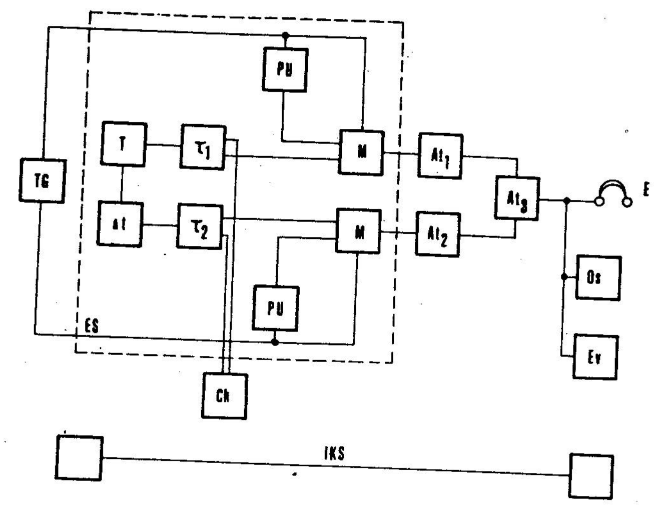

Fig. 2. Block diagram of the used apparatus.

PU and to the modulating units M of the electronic switch ES. The electronic switch passed on the couples of pulses with a rectangular envelope. The timing unit T allowed the selection of the pulse repetition frequency as well as the automatic or manual control of the device and moreover controlled the linkage units, i.e. the lagging unit Δt and the timing units τ_1, τ_2. These units then formed rectangular pulses of the needed duration and of the interstimulating interval. The output signal from the timing units was brought to the modulating units controlled by the pilot pulses of the phasing units. The phasing units allowed an independent jump-by-jump adjustment of the initial and final phases within the selected intervals. From the outputs of the modulating units the signal was supplied to the attenuators At_1, At_2, At_3 (RTF Xa 716) by which the *SPL* of pulses could be adjusted to the required value. The signal brought to the earphone E (Beyer DT 48) was continuously checked by the oscilloscope Os (Tesla BM 462) and the electronic voltmeter EV (Brüel-Kjaer 2402). The duration of the pulses was checked by the chronometer Ch (Radiometer MSM 1a). Between the subject and the experimenter there was installed an intercommunication system IKS both optical and acoustic enabling the subject to give the responses to the experimenter and allowing the understanding between the experimenter and the subject.

The apparatus — except the earphone — was installed in an operating room in front of a sound insulated box with the subject sitting in it.

II. 4. *Results*

The dependence of the *DL*s for the switching phases on the frequency and duration of the pulses was investigated under conditions that can be formally expressed as follows:

$$DL\varphi = F_1(f, \tau); \quad DL\psi = F_2(f, \tau), \; SPL = \text{const.} = 65 \text{ dB} \qquad (1)$$
$$\varphi_0 = \psi_0 = \text{const.} = 0°$$

a) $f = 250$ Hz, $\tau = 2^n$ ms, where the integral number $n \in \langle 3,7 \rangle$
b) $f = 1000$ Hz, $\tau = 2^n$ ms, where the integral number $n \in \langle 2,7 \rangle$
c) $f = 4000$ Hz, $\tau = 2^n$ ms, where the integral number $n \in \langle 2,7 \rangle$

where φ_0 is the phase of switching-on, and ψ_0 is the phase of switching-off of the standard pulse.

The results of the experiment are tabulated in Table 1 and plotted in Fig. 3. From the curves in Fig. 3 representing the empirically obtained functional dependences of the type (1) it can be concluded that both $DL\varphi$ and $DL\psi$ have, at the frequency of 250 Hz and the interval of a duration of 8—64 ms, values in the range 15°—19° and in this range of duration no significant functional dependence on the pulse duration was found. An expressive increase of both the $DL\varphi$ and the $DL\psi$ has been registered only at the duration of 128 ms. At the frequency of 1000 Hz

Table 1

Difference limens for the switching-on and the switching-off phase in degrees as a function of frequency and duration of pulses (*SPL*=65 dB)

frequency Hz		duration ms					
		4	8	16	32	64	128
250	$DL\varphi$		16.96	18.6	17.65	19.11	27.87
	SD		1.35	1.58	2.74	3.32	6.62
	$DL\psi$		15.12	15.36	18.21	17.91	26.55
	SD		0.59	1.18	3.51	3.24	5.5
1000	$DL\varphi$	16.68	16.91	15.2	15.87	27.06	44.66
	SD	3.58	1.59	0.87	0.74	6.33	3.31
	$DL\psi$	17.45	18.01	15.03	15.54	27.1	46.56
	SD	0.7	1.67	0.53	2.98	7.2	2.76
4000	$DL\varphi$	20.64	16.46	20.71	28.67	35.12	48.77
	SD	5.28	3.29	4.97	7.02	10.81	4.79
	$DL\psi$	19.64	15.52	20.45	24.75	36.14	47.9
	SD	7.52	3.27	7.16	5.66	10.05	7.42

significantly higher values of $DL\varphi$ and $DL\psi$ were registered already at the duration of 64 ms and both *DL*s have the lovest values (less than 16°) at the durations of 16 and 32 ms. At the frequency of 4000 Hz the $DL\varphi$ and $DL\psi$ had minimum values at the duration 8 ms and then gradually these values increased.

The results of measurements show that the given frequency and pulse duration no significant differences exist between $DL\varphi$ and $DL\psi$. The discriminating ability of the ear with regard to the switching phases as a function of the pulse duration is however dependent on the frequency (compare Fig. 3). From a definite duration on, which is the shorter the higher the frequency of the tested pulses is the discriminating ability of the ear with regard to the switching phases becomes gradually lower (i.e. the $DL\varphi$ and $DL\psi$ increase). The tendency of the $DL\varphi$ and $DL\psi$ to increase with the increasing pulse duration is in agreement with the tendency of the corresponding spectra of the tone pulses.

III. DISCUSSION

The fundamental knowledge obtained from the measurements, i.e. that the $DL\varphi$ and $DL\psi$ increase with the prolonged duration of tested pulses, is not surprising. From the spectral analysis of the non-stationary tone pulses it follows that at a given difference in the switching phases of two tone pulses with the prolongation of

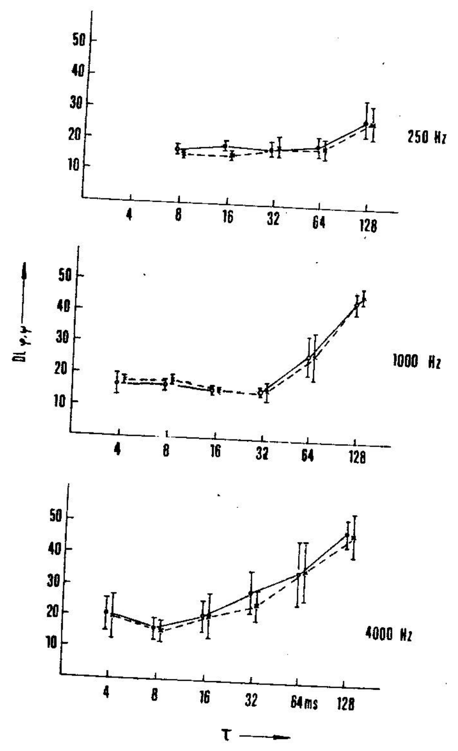

Fig. 3. Difference limens for the switching-on phase (full line) and switching-off phase (dashed line) as a function of the duration of pulses of the given frequencies. The vertical bars indicate ± 1 *SD* of *DL*.

their duration, the pictures of the spectral densities of amplitudes show an approaching tendency or in other words the longer the sinusoidal pulses are, the less their spectra differ — at a given difference in the switching phase. A relevant difference in the spectra of the relatively longer pulses can thus be reached — keeping their other parameters unchanged — only by increasing the difference of the switching phase. This statement referring to the mathematical-physical aspect of the problem thus — as expected — results in higher $DL\varphi$ and $DL\psi$ as function of the pulse duration.

In Sect. II.4 it has been stated that at a given combination of the pulse physical parameters, i.e. the frequency, duration and *SPL*, there exist no significant differences between the *DL* for the switching-on and switching-off phases of the pulse. A comparison of this experimental result with the computations of some

spectral densities of amplitudes confirms a good agreement between the obtained results of the measurements and the spectra of the corresponding pulses [11].

Similarly as in the experiments with pulses with an integral number of periods [8], the subject answered also in these measurements the question "how could you discriminate the pulses when they are not equal" independently of one another, by stating that the second pulse of the couple was somewhat higher in pitch and sharper or harder, respectively. From this it can be concluded that the physical parameter of the switching phase affects the sensorial parameters pitch and timbre of the pulses.

The results obtained in the research work into the functional dependence and the sensorial-physical interpretation of them contribute at the same time to the elucidation of the differences in the measurements of the *DL*s for the frequency as measured by Cardozo [12] and Chistovich [13]. Cardozo was the first who observed the fact that the *DL* for frequency has the lowest value when the pulses begin with the zero initial phase and consequently he used such pulses in his experiments. His measurements are identical with the measurements of Chistovich in that both applied pulses with a rectangular envelope and an integral number of periods. In the experiments of Chistovich, however, the initial phase of pulses was accidental. The *DL* for frequency measured by Chistovich have higher values than those measured by Cardozo. This fact with regard to our results within a relatively long interval of duration may lead to different results obtained by the mentioned authors.

IV. CONCLUSIONS

1. The difference limens for the switching phases of nonstationary tone pulses increase with the prolongation of their duration, this increase being the faster the higher the pulse frequency is.

2. For a given combination of the physical parameters of the pulses no significant differences exist in the *DL* for the switching-on and the switching-off phases, this being in agreement with the spectral density of amplitudes of the corresponding pulses.

3. The pulses differing by the switching phases may be discriminable by their pitch and timbre.

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