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THRESHOLDS OF PERCEPTION OF IRREGULAR SIGNAL FREQUENCY CHANGES

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In the literature, the problem of the perception of signal frequency changes has been considered mainly with reference to regular changes, obtained in the process of frequency modulation of a tone by a tone. There are, however, no publications on the thresholds of the perception of irregular frequency changes.

This fact was an encouragement to undertake investigations with the essential purpose of determining the thresholds of the perception of irregular frequency changes for a signal with constant amplitude and a decaying signal with an exponential envelope, depending on: the carrier freguency of the signal, its intensity level and the duration of the decaying signal. The courses of the perception thresholds of irregular frequency changes obtained here are much more general than the data published previously on the subject in the literature.

The investigation results obtained permit better knowledge of the mechanism of the so-called dynamic perception of signals, i.e. the perception of signals with parameters varying in time, whose natural counterpart in practice are the sounds of speech and music.

1. Introduction

The previous investigations carried out in the field of research on the perception of signal frequency changes have been concerned mainly with the determination of the thresholds of the perception of these changes for cases of frequency modulation (FM) [2–6, 8, 21–23] or the evaluation of similarity of modulated signals [5, 14]. The results of these investigations permitted e.g. the determination of the dependence of the threshold frequency deviation Δf (or the quotient $\Delta f/f_m$) on the carrier frequency.

These investigations were developed by HARTMANN [8] and FETH [4], who presented the thresholds of the perception of the frequency modulation of a simple tone by various signals, including rectangular, triangular, trapezoidal and sinusoidal ones.

The results of the previous investigations show that in the process of the perception of modulated signals, the phases of the lateral spectral components of their spectra are of deciding significance only when they are within one critical band. In this range, it is interesting to note ZWICKER's conception [22], according to which the perception of modulated signals can be based on the working principle of the "rectangular filter". This conception was discussed in a large number of papers [2, 3, 5–7, 13]. FETH [3] and CONINX [2] questioned to some extent its validity, while GOLDSTEIN [5], MAIWALD [13] and HARTMANN [6, 7] complemented it, replacing the rectangular filter by a trapezoidal one, which improved distinctly the agreement between these conceptions and then results of experimental research. In this respect, it is particularly interesting to note the investigations carried out by HARTMANN [6, 7], who, after performing a series of experiments, found that the perception of signals modulated by tones depends only on the spectral component with frequency lower than that of the carrier, since the component with the higher frequency is then completely masked.

It is also intersting to mention that some papers in this range of research indicate the existence of some additional effects related to frequency modulation, such as e.g. roughness, studied in detail in paper [11], and the so-called trill effect, considered in papers [15, 20].

A separate group of investigations consists of research on the perception of frequency changes constant in time, occurring between two steady states. The experimental investigations in this rrange [1, 16, 17] indicated that the time parameters of the signal exert a deciding influence on the threshold of the perception of frequency changes of this type. In this case, the durations of the steady states of signals play a particular role. So far, however, it has not been determined sufficiently well to what extent the threshold of the perception of these frequency changes is determined by steady states, and to what extent, by the continuous change in the frequency of the signal.

All the papers mentioned so far were concerned with frequency changes occurring in a signal with constant amplitude.

In the literature, apart from papers [1, 2, 9, 18, 19], there are in fact no more specifically documented data on the perception of frequency changes accompanied by given changes in the intensity level of the signal. In this range, interesting results were introduced in paper by CONINX [2] and HARTMANN [9], dealing with the perception of simultaneous changes in the amplitude and frequency of the signal, and moreover, these changes have the character of frequency and amplitude modulation by the same process. The problem of frequency modulation of a signal with amplitude varying in time was also the object of considerations in paper [18], as a result of which the thresholds of the perception of the frequency changes in a signal decaying exponentially were determined. These investigations found the existence of the dependence of the threshold deviation on the intensity level of the signal and on its carrier and modulating frequencies. In paper [19], in contrast to continuous frequency changes, the perception of jump frequency changes, occurring in a decaying signal, was investigated. Apart from the determination of the thresholds of the perception of a single jump frequency change, depending on its time parameters (i.e. its duration and the time defining its localisation in the signal), investigations were also performed to estabilish the effect of one of the frequency changes on the threshold of the perception of the second change. As a result of these investigations, it was found that in the case of two jump frequency changes, one can speak of the existence of the specific phenomenon of masking, consisting in the increase in the threshold of the perception of the second frequency change, in the case when the value of the first is above the threshold [19]. It should be noted that all the papers mentioned above are concerned with frequency changes of which it can be said that they have a determined character, expressible in analytical form.

A distinct extension and generalization of the problems mentioned above is the question of the determination of the perception thresholds of irregular frequency changes with character close to random, which has no counterpart in the literature. It is significant that this question is related directly to the perception of processes occurring in reality (e.g. natural sounds of speech and music), for which one of the more important characteristics is the stochastic character of amplitude and frequency in time.

The problem of the perception of irregular frequency changes occurring in signals with amplitudes constant and decaying exponentially with time, is the object of the present considerations. The essential purpose of the paper is tc determine the thresholds of the perception of these changes, depending on the carrier frequency of the signal, changes in its intensity level and the duration of the signal.

Within the range of the investigations performed, irregular frequency changes were obtained by way of frequency modulation of a tone by particular bands of white noise. In the process of the perception of the signals thus modulated, the essential role is played by their spectral structure, which will be discussed in greater detail in section 2.

2. Spectral structure of a signal with frequency modulated by band noise

In the case of the frequency modulation of a tone by another, one can, as is known, determine in a relatively simple way, on the basis of Bessel functions, the spectrum of the modulated signal [10, 12]. In addition for a signal of this type, its basic parameters are defined unambiguously, such as the carrier and modulating frequencies and the deviation range. A much more complex matter is the problem of the determination of the spectrum of a tone with frequency modulated by a random signal, which in the case considered was a band of white noise with the power N, defined by the formula

$$G_x(\omega) = \begin{cases} G_x & \text{for } -\omega_g < \omega < \omega_g, \\ 0 & \text{for other } \omega, \end{cases} \tag{1}$$

and the Gaussian probability distribution

$$p(x) = \frac{1}{N\sqrt{2\pi}} \exp\left(-\frac{x^2}{2N}\right). \tag{2}$$

This complexity results from the lack of an analytical expression describing the form of the modulating signal, which is assigned to the class of random signals.

It can be assumed that the random process considered is a stationary ergodic process with the autocorrelation function $R_x(\tau)$ and the variance σ_x^2. The instantaneous frequency $\omega(t)$ of the modulated signal can be expressed, in general, as

$$\omega(t) = \omega_0 + kx(t) = \frac{d\Phi(t)}{dt}, \tag{3}$$

where $x(t)$ is some sample function of the random process, and $\Phi(t)$ is the instantaneous phase of the modulated signal.

In the case considered, the frequency deviation (or the phase deviation) cannot be determined for the modulated signal as the maximum shift in this quantity, as it is done in the case of determined modulating processes. A quantity called the effective frequency deviation $\Delta\omega_{ef}$, which is proportional to the effective (mean square) value σ_x of the modulating signal, is used as the measure of the degree of modulation by random (noise-like) processes, i.e.

$$\Delta\omega_{ef} = k\sigma_x. \tag{4}$$

In order to determine the spectrum of the modulated signal, first its autocorrelation function should be defined. The phase of the very process $\Phi(t)$ can now be considered. Integration of expression (3) gives

$$\Phi = \omega_0 t + k\int_0^t x(t')\,dt' = \omega_0 t + \theta(t). \tag{5}$$

The function $\theta(t)$ also has the Gaussian probability distribution, since it has been formed by integrating the process $x(t)$. The spectral density of the function

$\theta(t)$ can be written in the form

$$G_\theta(\omega) = k^2 \frac{G_x(\omega)}{\omega^2}. \tag{6}$$

Knowledge of phase (5) of the modulated signal and of the probability distribution of the function $\theta(t)$ permits to calculate the autocorrelation function $R(\tau)$ of the modulated signal by statistical averaging. This gives as a result

$$R(\tau) = \frac{1}{2} A^2 \cos\omega_0\tau \exp\{-[R_\theta(0) - R_\theta(\tau)]\}, \tag{7}$$

where $R_\theta(\tau)$ is the autocorrelation function of the function $\theta(t)$. By using now the Wiener-Chinczyn theorem, the spectrum of the modulated signal $G(\omega)$ can be represented in the following way:

$$G(\omega) = \frac{1}{2} A^2 \exp[-R_\theta(0)] \int_{-\infty}^{\infty} \exp[R_\theta(\tau)] \big[\exp[i(\omega+\omega_0)\tau] + \exp[i(\omega-\omega_0)\tau]\big] d\tau. \tag{8}$$

By considering the modulation by a noise band (defined by dependence (1)), which occurs when $R_\theta(0) \ll 1$, the expression $\exp[R_\theta(\tau)]$ can be given in the form of a series, taking into account only the first two of its terms. In addition, using dependence (6), it can finally be written that

$$G(\omega) = \frac{A^2}{4}\left[\delta(\omega-\omega_0) + k^2\frac{G_x(\omega-\omega_0)}{(\omega-\omega_0^2)^2} + \delta(\omega+\omega_0) + k^2\frac{G_x(\omega+\omega_0)}{(\omega+\omega_0)^2}\right]. \tag{9}$$

The final dependence (9) describes the spectrum of a sinusoidal signal with the pulsation ω_0, frequency-modulated by a band noise, determined by relation (1).

It follows from this formula that the spectrum of the modulated signal contains a sinusoidal carrier signal, represented in this case by the function $\delta(\omega \pm \omega_0)$, while the components with the form $G_x(\omega \pm \omega_0)/(\omega \pm \omega_0)^2$ express the fuzziness of the spectrum, related to the process of frequency modulation

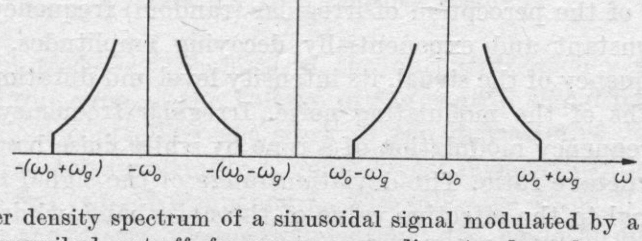

Fig. 1. The power density spectrum of a sinusoidal signal modulated by a noise band with a prescribed cut-off frequency, according to dependence (9)

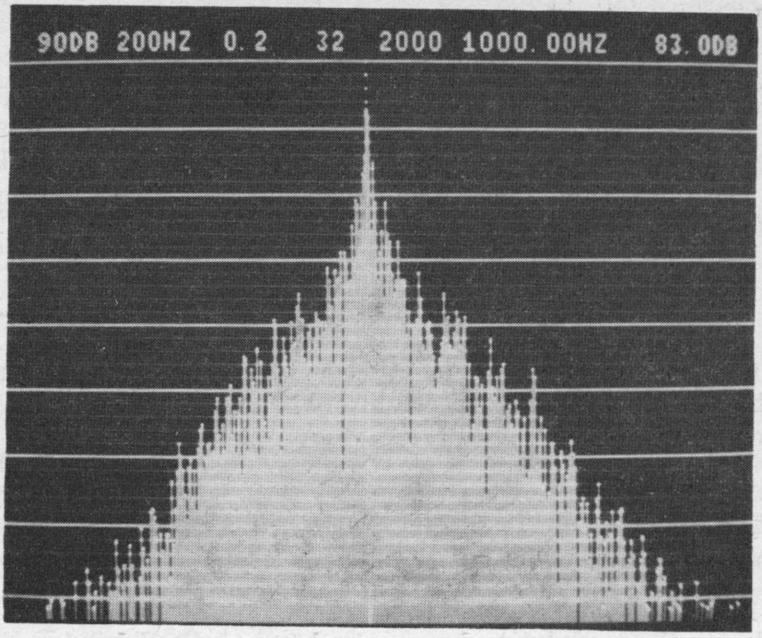

Fig. 2. The power density spectrum of a sinusoidal signal $f_c = 1$ kHz modulated by a noise band with the cut-off frequency $f_g = 63$ Hz, obtained by means of a BK 2033 narrow-band analyser

Fig. 1 shows schematically the theoretical relation (9). In turn, Fig. 2 shows, for comparison with theoretical considerations, the spectrum of a sinusoidal signal with the frequency $f_c = 1$ kHz, modulated by a noise band with the frequency $f_g = 63$ Hz, obtained by means of a BK 2033 narrow-band analyser.

3. Purpose and range of the investigations, the equipment and method of the measurement

3.1. Purpose and range of the investigations

The essential purpose of the investigations undertaken was to determine the thresholds of the perception of irregular (random) frequency changes for a signal with constant and exponentially decaying amplitudes, depending on: the carrier frequency of the signal, its intensity level and duration, for the different bandwidths of the modulating noise. Irregular frequency changes were obtained by frequency modulation of a tone by white noise bands with widths varying in an octave ratio. The deviation range of the signal thus modulated was proportional to the effective value of the noise band, while the bandwidth defined the range of modulating frequencies.

The investigations included:

– change in the carrier frequency f_c in an octave ratio, over the range 125–4000 Hz;

– change in the bandwidth of modulating noise, defined by the cut-off frequency f_g of the band, over the range 31–1000 Hz;

– change in the intensity level of the modulated signal, over the range 55–85 dB (with jumps every 10 dB);

– change in the duration T of the decaying signal, over the range 125 ms–1.5 s.

3.2. Equipment and method of the measurement

Fig. 3. shows a schematic diagram of the equipment set-up used to investigate the thresholds of the perception of irregular (random) frequency changes. An essential part of this set-up was the voltage-controlled simple tone generator

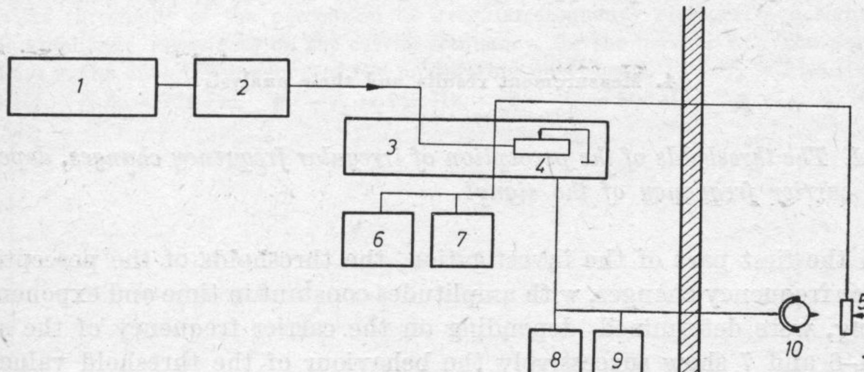

Fig. 3. A schematic diagram of the measurement system: *1* – white noise generator, *2* – low-pass filter, *3* – voltage-controlled generator, *4, 5* – potentiometers, *6* – digital voltmeter, *7* – plotter voltmeter, *8* – digital voltmeter, *9* – frequency meter, *10* – headphones, *11, 12* – signalling boards

3, which permitted any changes in the output frequency to be obtained, in the direct proportion to the voltage of the control signal fed to the control input. The signal controlling the work of the generator *3* was white noise generated by the noise generator *1*, undergoing previous filtration by a low-pass filter *2*, with the cut-off frequency f_g. The effective value of the noise band, responsible for the effective value of deviation, Δf_{ef}, could be adjusted independently by means of the potentiometers *4* and *5*, linked in parallel, at the disposal of the experimentator and observer. Additional elements of this set-up consisted of a system of meters for the control of both the modulating and output signals. The whole of the equipment was complete with SN-60 *10* measurement headphones and the signalling boards of the experimentator *11* and the observer (12).

Measurements of the thresholds of the perception of irregular frequency changes were carried out on the basis of a method which was some modiffication of the limits method. This method consisted in the determination by the listener, by means of the potentiometer *5*, of the just perceptible value of the frequency deviation occurring in a modulated signal, which was regarded as the threshold value of the effective deviation. It should be pointed out that an essential influence on the accuracy of the determination of the threshold deviation value was exerted by the accuracy of the determination of the effective value of the modulating noise band intensity, to which particular attention was paid during the measurements. Two listeners with audiologically normal hearing, over the frequency range applied, took part in the investigations.

4. Measurement results and their analysis

4.1. The thresholds of the perception of irregular frequency changes, depending on the carrier frequency of the signal

In the first part of the investigation, the thresholds of the perception of irregular frequency changes, with amplitudes constant in time and exponentially decaying, were determined, depending on the carrier frequency of the signal. Figs. 4–6 and 7 show successively the behaviour of the threshold values Δf_{ef} obtained over this range for the listeners EO and AS.

The parameter of these thresholds is the cut-off frequency f_g of the modulating noise band. In keeping with the results shown in Figs 4–7, an increase in the carrier frequency of the signal, over the range 125–1000 Hz, causes only a slight change in the value of Δf_{ef}. In turn, any further increase in this frequency, above 1000 Hz, causes a distinct increase in the threshold deviation. The results given by Figs 4–7 also indicate that changes in the threshold deviation Δf_{ef} do not depend unambiguously on the modulating noise bandwidth, or, alternatively, on the cut-off frequency f_g of this band, but that they constitute some scatter of results. This fact is justified by the results of the investigations of the threshold deviation in the case of modulation of a tone by another, according to which the lowest threshold of the perception of the deviation occurs at low modulating frequencies, of the order of a few Hz. This signifies that in the case of modulation by a noise band, the value of the threshold deviation is determined above all by the components lying in the low frequency range,

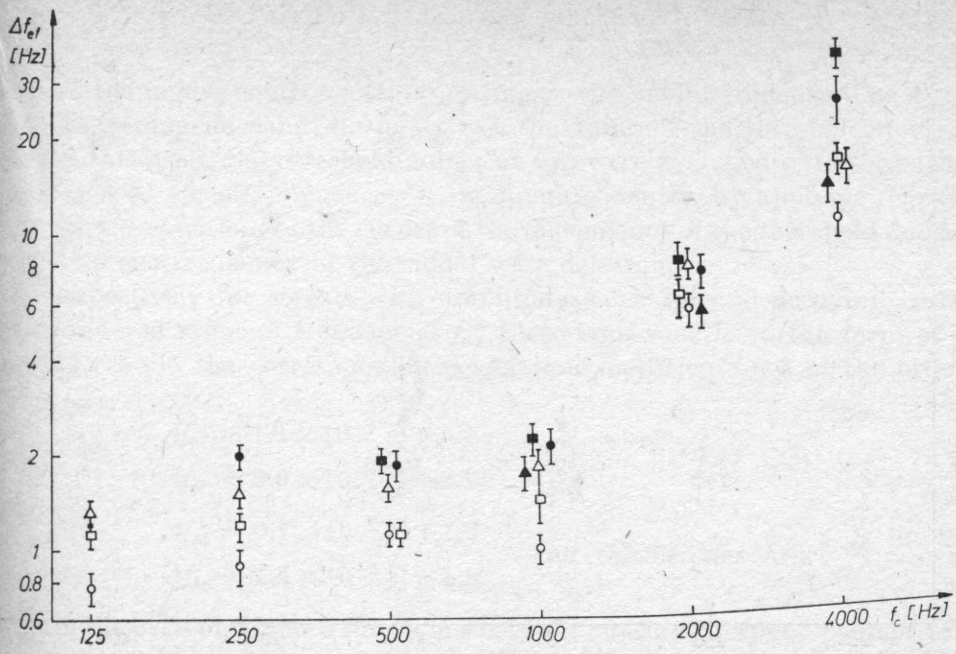

Fig. 4. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on the carrier frequency, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ f_g – 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

Fig. 5. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on the carrier frequency, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g – 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

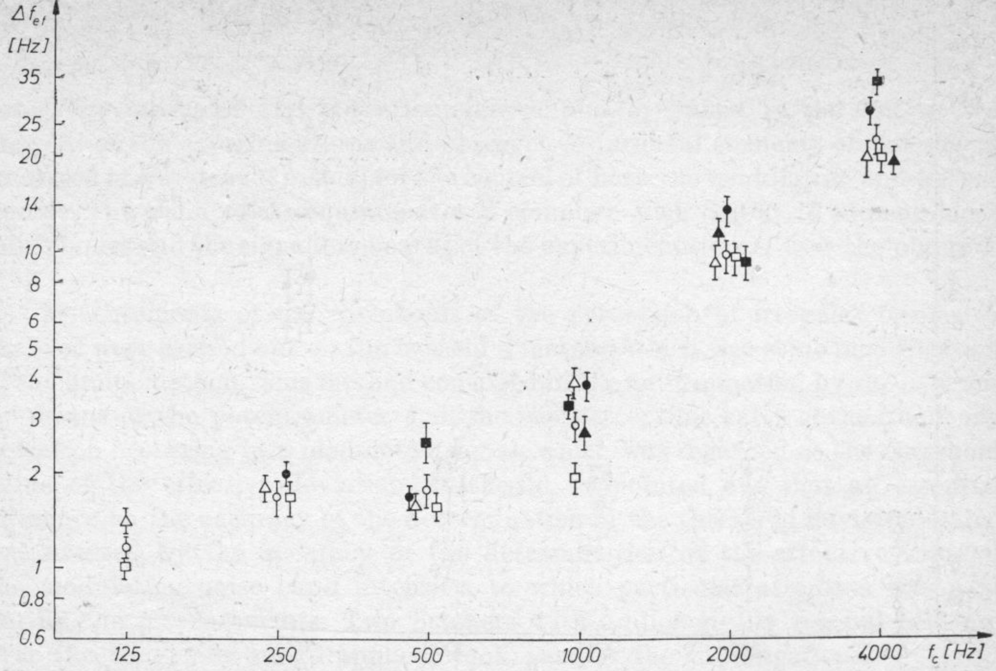

Fig. 6. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on the carrier frequency, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

Fig. 7. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on the carrier frequency, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

whereas the higher components, appearing in the modulating signal as a result of a broadening its band, do not affect the value of the threshold deviation.

On this basis, the threshold values of Δf_{ef} were averaged over the range of the measured cut-off frequencies f_g, and, subsequently, by applying regression analysis, the equations of the curves of the dependence of the threshold deviation on the carrier frequency of the signal were determined.

Respectively for signals with amplitudes constant and decaying in time, for considered range of frequencies f_c, these equations have the form of (10) and (11), while the corresponding correlation coefficients are of the order of 95%:

$$\begin{aligned} \Delta f_{ef} &= 1.1 \times 10^{-6} f_c^2 + 1.4 \\ \Delta f_{ef} &= 2.0 \times 10^{-6} f_c^2 + 2.1 \end{aligned} \quad \text{(for the listener EO);} \qquad (10)$$

$$\begin{aligned} \Delta f_{ef} &= 0.7 \times 10^{-6} f_c^2 + 1.6 \\ \Delta f_{ef} &= 1.5 \times 10^{-6} f_c^2 + 1.9 \end{aligned} \quad \text{(for the listener AS).} \qquad (11)$$

On the basis of the data shown in Figs 4–7 and the corresponding expressions (10) and (11), it can be stated that the threshold value of the deviation perception is proportional to the squared carrier frequency of the signal.

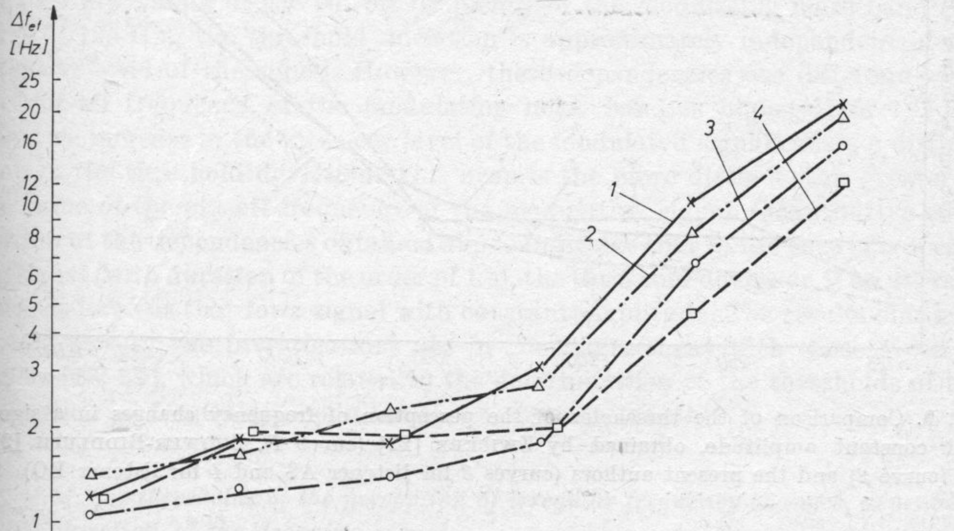

Fig. 8. Comparison of the thresholds of the perception of irregular frequency changes for the cases of a decaying signal (curves *1* and *2*) and one with constant amplitude (curves *3* and *4*). x ——— listener EO (*1*), decaying amplitude; △ – · · – listener AS (*2*), decaying amplitude; □ – · – listener AS (*3*), constant amplitude; ○ – – – – listener EO (*4*), constant amplitude

Fig. 8 shows a comparison of the courses of the thresholds obtained for a signal with constant amplitude (curves 3 and 4) and for a signal with amplitude decaying exponentially in time (curves 1 and 2). As can be seen in this figure, the thresholds of the perception of irregular frequency changes occurring in the decaying signal are distinctly higher than the analogous thresholds obtained in the case of irregular changes occurring in a signal with constant amplitude.

Irrespective of the facts established above, the investigation results obtained for a signal with constant amplitude were compared with the values of the perception thresholds of regular frequency changes occurring in the case of modulation of a tone by another, which were presented in papers [21, 22]. This comparison is shown in Fig. 9.

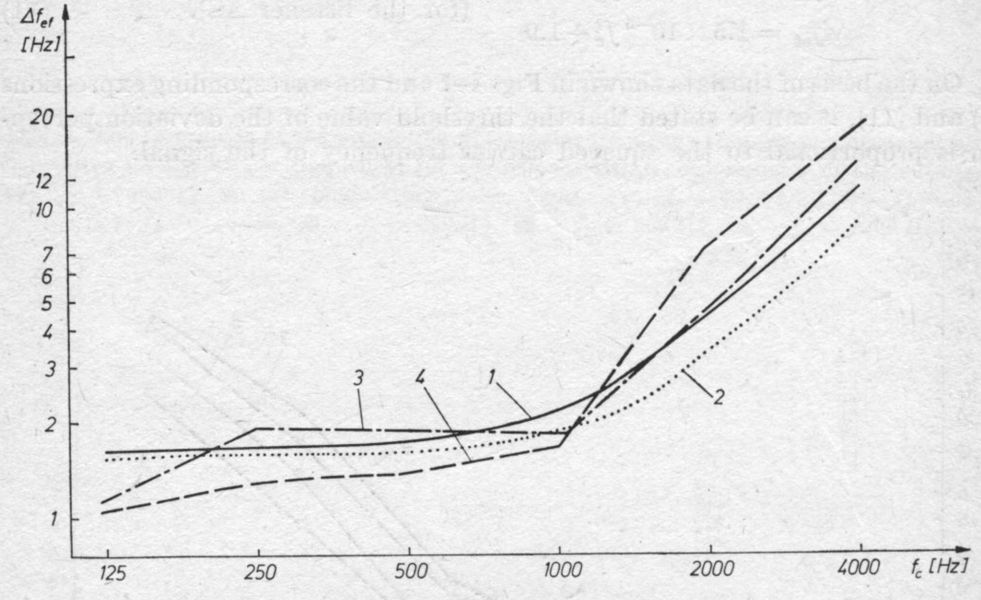

Fig. 9. Comparison of the thresholds of the perception of frequency changes in a signal with constant amplitude, obtained by ZWICKER [22] (curve *1*), SHOWER-BIDDLUPH [21] (curve *2*) and the present authors (curves *3* for listener AS and *4* for listener EO)

The unified threshold values, expressed in units of effective deviation as defined by the following formula, were plotted on the axis of ordinates of the figure:

$$\Delta f_{\mathrm{ef}} = \frac{\Delta f_{\max}}{\sqrt{2}}, \tag{12}$$

whereas the values of the carrier frequency of the signal were plotted on the axis of abscissae.

It follows from comparison of the curves given in Fig. 9. that both in the case of frequency modulation of a tone by another (curves 1 and 2) and the modulation of a tone by a noise band (curves 3 and 4), there are analogous dependencies of the threshold deviation on the carrier frequency of the signal.

4.2. The thresholds of the perception of irregular frequency changes, depending on the intensity level of the signal

In the second part of the investigations, the thresholds of the perception of irregular signal frequency changes were determined, depending on the intensity level. This signal, with the constant carrier frequency $f_c = 1000$ Hz, was modulated by white noise bands with the cut–off frequencies $f_g = 31.5$ Hz, 63 Hz, 125 Hz, 250 Hz and 500 Hz. The intensity level of the modulated signal varied over the ranges of 55 dB, 65 dB, 75 dB and 85 dB. The investigation results obtained for a signal with constant amplitude and a decaying one are shown successively in Figs 10–13. The parameter of these dependencies is the cut-off frequency of the modulating noise band. It follows from Figs 10–13 that for low values of the cut-off frequency of the modulating noise band (i.e. for $f_g < 125$ Hz), the threshold deviation is approximately independent of the intensity level of the signal. However, these dependencies are different when the cut-off frequency of the modulating noise band is higher than 125 Hz. Then, an increase in the intensity level of the modulated signal causes a distinct drop in the threshold deviation. This drop is the more distinct, the greater is the value of the cut-off frequency of the modulating signal. Quantitative comparison of the dependencies obtained above indicates that in the case of a decaying signal (with duration of the order of 1 s), the threshold deviation is on average twice as large as that for a signal with constant amplitude. The results obtained in this part of the investigations are in good agreement with those given in papers [18, 22], which are related to the determination of the thresholds of the perception of frequency modulation of a tone by another.

4.3. The thresholds of the perception of irregular frequency changes, depending on the duration of the decaying signal

In the third part of the investigations, the dependence of the threshold deviation on the duration of the decaying signal, which was successively 125, 250, 500, 1000 and 1500 ms, was determined. The following parameters were assumed as constant: the intensity level of the signal, $L = 75$ dB, and its carrier frequency $f_c = 1000$ Hz. Just as in the previous cases, also in this part of the investigations, the parameter of the measured threshold values was the

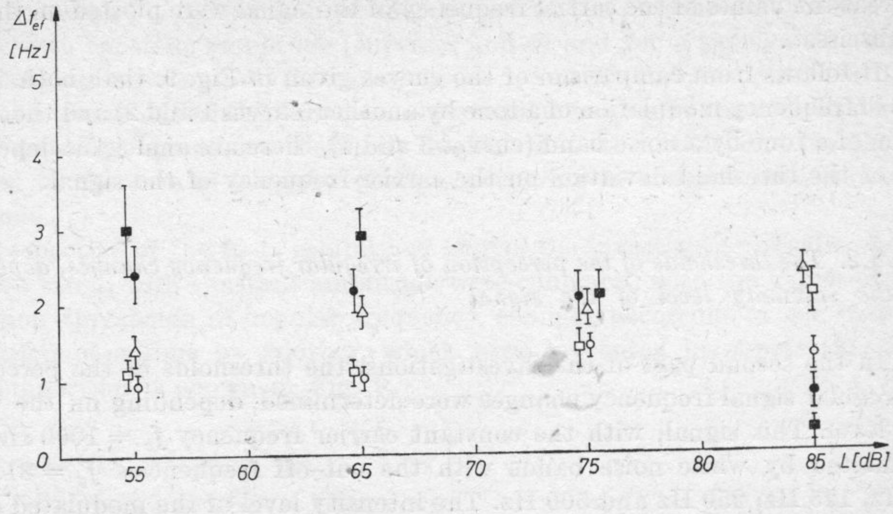

Fig. 10. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on its intensity level, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – $f_g = 31.5$ Hz, □ – $f_g = 63$ Hz, △ – $f_g = 125$ Hz, ● – $f_g = 250$ Hz, ■ – $f_g = 500$ Hz

Fig. 11. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on its intensity level, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – $f_g = 31.5$ Hz, □ – $f_g = 63$ Hz, △ – $f_g = 125$ Hz, ● – $f_g = 250$ Hz, ■ – $f_g = 500$ Hz

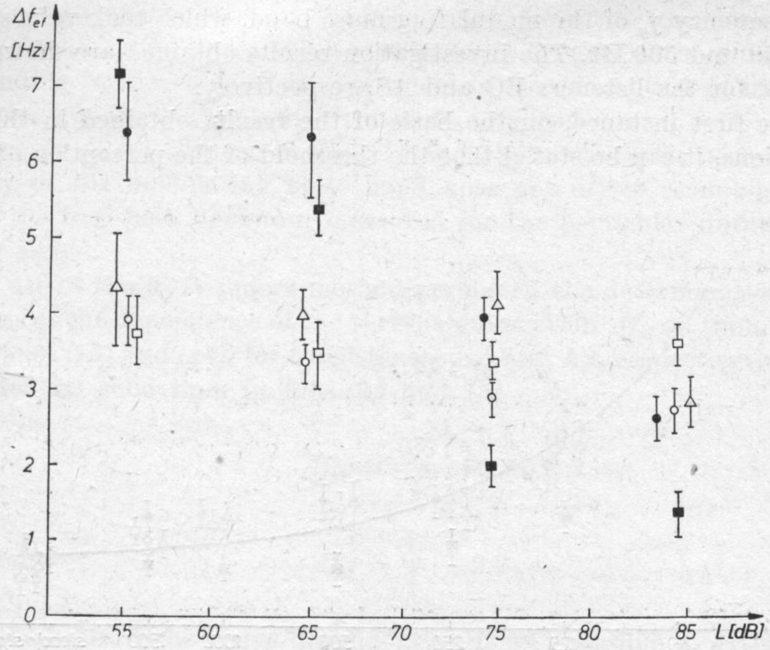

Fig. 12. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its intensity level, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz

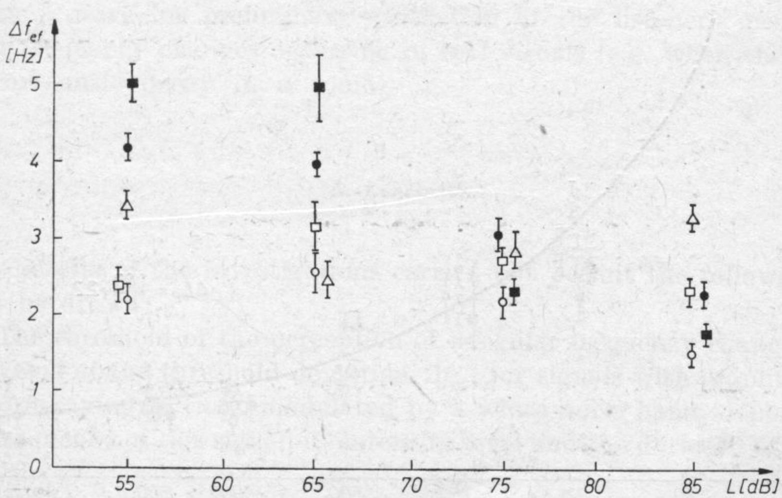

Fig. 13. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its intensity level, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f = 250 Hz, ■ – f_g = 500 Hz

cut-off frequency f_g of the modulating noise band, which took values of 31, 5, 63, 125, 350 and 500 Hz. The investigation results obtained are shown in Figs. 14 and 15, for the listeners EO and AS, respectively.

In the first instance, on the basis of the results obtained in this part of investigations, it can be stated that the threshold of the perception of irregular

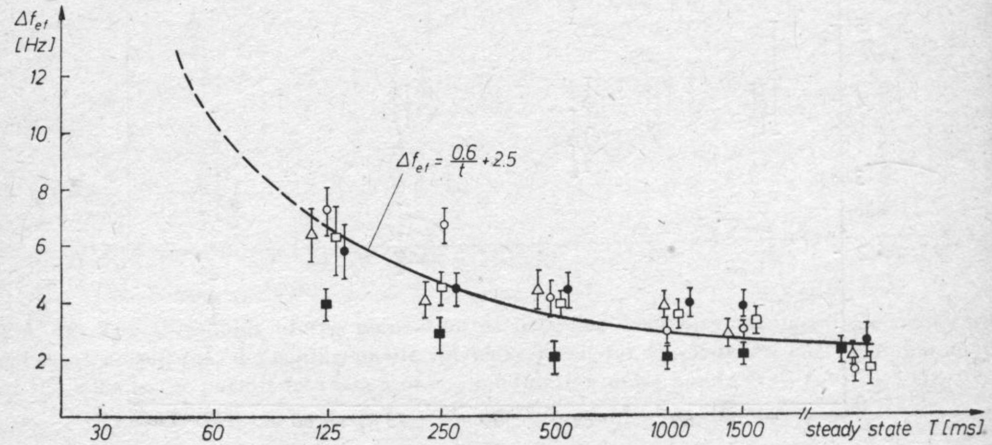

Fig. 14. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its duration, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz

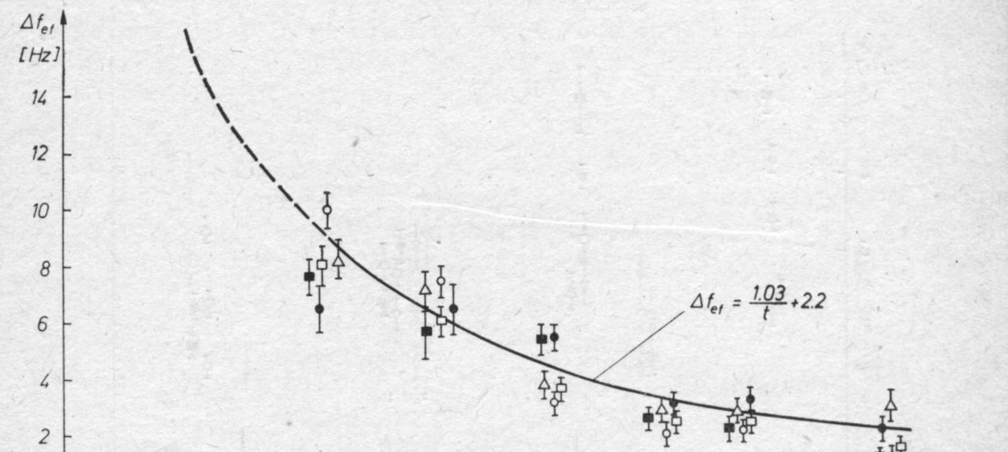

Fig. 15. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its duration, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz

frequency changes decreases in the inverse proportion to the duration of the decaying signal. In the limits, it tends to a constant value of the order of 2–3 Hz corresponding to the value of the threshold of the perception of irregular frequency changes for a signal with constant amplitude.

Moreover, it can be seen in Figs. 14 and 15 that an increase in the cut-off frequency of the modulating noise band does not affect unambiguously the value of the threshold deviation measured for the particular durations of the decaying signal.

The use of the least-square method permitted the determination of analytical forms of the dependence of the threshold deviation Δf_{ef} on time, defined by dependencies (13) and (14), for the listeners EO and AS, respectively, which are represented by solid lines in Figs. 14 and 15.

$$\Delta f_{ef} = \frac{0.6}{t} + 2.5, \tag{13}$$

$$\Delta f_{ef} = \frac{1}{t} + 2.2. \tag{14}$$

On the basis of the above dependencies, it was possible to extrapolate the values of the threshold deviation to durations much shorter than 125 ms (see Figs 14 and 15), corresponding approximately to the times of transient transitions occurring in the natural sounds of speech and music. As is known, these transitions are accompanied by large sound frequency changes with a very irregular character. It seems that these thresholds can, after their experimental verification, serve for preliminary evaluation of the listener's perception of irregular frequency changes occurring in real signals (e.g. when the sounds of speech or music decay in a room).

5. Conclusions

The results of the investigations carried out permit the following conclusions to be drawn:

1. The threshold of the perception of irregular frequency changes, defined by the value of the threshold deviation Δf_{ef}, for signals with amplitudes constant and decaying in time, modulated by a white noise band, depends on the carrier frequency of this signal, its intensity level and the duration of the decaying signal.

2. The threshold value of the frequency deviation Δf_{ef} is proportional to the squared carrier frequency f_c of the modulated signal for considered range of frequencies f_c. This dependence can be expressed analytically as $\Delta f_{ef} = Af_c^2 + B$, where the coefficients A and B take specific values for a given listener.

3. For higher cut-off frequencies of the modulating noise band (i.e. for $f_g > 125$ Hz), the value of the threshold deviation decreases as the intensity level of the decaying signal increases, whereas for $f_g < 125$ Hz it is approximately independent of the intensity level of the signal.

4. The thresholds of the perception of irregular frequency changes for a signal with constant amplitude are lower than the analogous thresholds obtained in the case of a decaying signal, for frequencies higher than 500 Hz.

5. The threshold of the perception of irregular frequency changes for the decaying signal is in the inverse proportion to its duration. In the limit, it tends to a value of 2–3 Hz, corresponding to the threshold value of the perception of irregular frequency changes for a signal with constant amplitude.

In conclusion, it should be pointed out that the thresholds of the perception of irregular frequency changes obtained here are much more general than those published so far in the literature, since they are related to signals for which frequency changes in time have approximately a random character, i.e. they belong to a broad class of signals encountered in practice.

References

[1] P. T. Bready, A. S. House, K. N. Stevens, *Perception of sounds characterized by a rapidly resonant frequency*, J. Acoust. Soc. Am., **33**, 10, 1357–1362 (1961).

[2] F. Coninx, *The perception of combined frequency and amplitude modulation with clearly audible modulation depths*, Acoustica, **39**, 3, 151–154 (1977).

[3] L. Feth, *Combinations of amplitude and frequency differences in auditory discrimination*, Acustica, **26**, 2, 67–77 (1972).

[4] L. Feth, R. Wolf, R. Bilgar, *Frequency modulation and the difference limen for frequency*, J. Acoust. Soc. Am., **45**, 6, 1430–1437 (1969).

[5] L. J. Goldstein, *Auditory spectral filtering and monaural phase perception*, J. Acoust. Soc. Am., **41**, 2, 458–479 (1967).

[6] W. M. Hartmann, *Detection of frequency modulation at large modulation frequencies* J. Acoust. Soc. Am., Suppl. 1, **63**, 66 (1978).

[7] W. M. Hartmann, *Detection of amplitude modulation*, J. Acoust. Soc. Am., Suppl. 1, **65**, 59 (1979).

[8] W. M. Hartmann, M. A. Klein, *Theory of frequency modulation for low modulation frequencies*, J. Acoust. Soc. Am., **67**, 3, 935–946 (1980).

[9] W. M. Hartmann, *Perception of mixed modulation*, Acustica, **50**, 5, 297–312 (1982).

[10] A. Hund, *Frequency modulation*, Mc Graw-Hill Book Company, Inc., New York and London, 1942.

[11] S. Kemp, *Roughness of frequency-modulated tones*, Acustica, **50**, 2, 126–133 (1982).

[12] L. Knoch, T. Ekiert, *Modulation and detection* (in Polish), WKiŁ, Warsaw, 1979.

[13] D. Maiwald, *Die Berechnung von Modulationsschwellen mit Hilfe eines Funktionsschemas*, Acustica, **18**, 4, 193–207 (1967).

[14] R. C. Mathes, R. L. Miller, *Phase effects in monaural phase perception*, J. Acoust. Soc. Am., **19**, 5, 780–797 (1947).

[15] G. Miller, G. Heise, *Trill threshold,* J. Acoust. Soc. Am., **22**, 5, 637–638 (1950).

[16] I. V. Nabělek, A. K. Nabělek, I. J. Hirsh, *Pitch of tone bursts changing frequency,* J. Acoust. Soc. Am., **48**, 2, 536–553 (1970).

[17] I. V. Nabělek, A. K. Nabělek, I. J. Hirsh, *Pitch of sound with continuous or discontinuous change of frequency,* J. Acoust. Soc. Am., **53**, 5, 1305 (1973).

[18] E. Ozimek, *Perception of amplitude and frequency modulation for decaying sounds,* Proc. of the III Congress of FASE, Gottingen, 223–226, 1982.

[19] E. Ozimek, A. Sęk, *Thresholds of perception of jump frequency changes for a decaying signals,* Archives of Acoustics, 2 (1985).

[20] J. Shonle, K. Horan, *Trill threshold revisited,* J. Acoust. Soc. Am., **59**, 2, 469-471 (1976).

[21] E. G. Shower, R. Biddluph, *Differential pitch sensitivity of the ear,* J. Acoust. Soc. Am., **3**, 2, 275–278 (1931).

[22] E. Zwicker, *Die Grenzen der Hörbarkeit der Amplitudemodulation, und Frequensmodulation eines Tones,* Acustica, **2**, 3, 125–133 (1952).

[23] E. Zwicker, R. Feldtkeller, *Das Ohr als Nahrichtenempfänger,* S. Heinel Verlag, Stuttgart, 1967.

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