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THRESHOLDS OF PERCEPTION OF MIXED MODULATION*

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This paper is concerned with the determination of perception thresholds of mixed modulation (*MM*) for chosen physical parameters of a signal. Besides a tonal modulating signal, also an irregular modulating signal in the form of a very narrow noise band with a definite mid-band frequency was applied in the course of research.

It was stated that the perception of modulated signals is governed by two mechanisms: the time mechanism and the spectral mechanism, which do not depend on the type of modulation. These mechanisms become evident at definite values of the modulation frequency, which, as we know, conditions the rate of amplitude and frequency changes of the modulated signal.

We have to do with the time mechanism at slow changes of physical parameters of this signal (low modulating frequency). Whereas, when the changes of these parameters are quick (high modulating frequency) the spectral mechanism takes place.

The hypothesis concerning the existance of such perception mechanisms was confirmed by obtained experimental results.

1. Introduction

The problem of perception of sound amplitude and frequency changes has been widely discussed in literature — from the point of view of psychoacoustic investigations [1, 3, 5, 6, 10–12] and neurophysiologic studies [8, 9]. Two main hypothesis' concerning the perception of amplitude-frequency changes of a signal can be distinguished. One of them was presented by Zwicker [11] and Maiwald [6, 7]. It assumes that amplitude and frequency changes are registered by one and the same perception mechanism. Whereas, the second hypothesis presented by Coninx [1], assumes that two independent perception mechanisms of these changes exist, i.e. a separate perception mechanism of amplitude changes and separate perception mechanism of frequency changes.

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A solution to this problem was sought in various experiments, which concerned thresholds of amplitude and frequency modulation perception [10, 12], difference limens of loudness and pitch [3], monaural phase perception [4], etc. These experiments have contributed significantly to a fuller description of the discussed problem. However, they did not confirm the justness of one out of the two presented hypothesis'.

An unconventional approach to the mentioned above problem was presented in papers [1, 2, 5–7, 11], which concern the perception of simultaneous amplitude and frequency changes with modulation (so-called mixed modulation, *MM*). The perception of amplitude and frequency changes in the case of the first hypothesis, which accepts the existance of a single, common mechanism, should proceed in a similar manner.

This means that the perception of frequency changes at mixed modulation should depend on coexisting amplitude changes. Whereas, in the case of the second hypothesis, which accepts the existance of two independent mechanisms, the perception of amplitude changes in the conditions of mixed modulation should be independent from coexisting frequency changes.

ZWICKER'S paper [11] is on of the first, which postulates the existance of one perception mechanism of amplitude and frequency changes of a singal. It analyses the sensation created by amplitude (*AM*), frequency (*FM*) and mixed (*MM*) modulation of an octave noise band (1–2 kHz), partially masked by a noise contained in band 2–10.5 kHz. It results from this paper that amplitude modulated signals can be evaluated as equal to frequency modulated signals, if adequate modulation indices (i.e. m and β) strictly satisfy definite relations. Investigations on the possibility of equalizing senstations created by mixed modulation and frequency modulation have proved that for a *MM* signal two effects, dependent on the phase difference between signals which modulate amplitude and frequency, can occur. Consistant phases of these signals cause a "deepening" (addition) of modulation effects, expressed by an increased deviation of the *FM* signal. As for opposite phases of these signals, the intensification of the modulation effect is observed only at lower frequencies ($f_m < 100$ Hz) and for values of the amplitude modulation factor exceeding 20–30%, while for the modulating frequency equal to $f_m = 50$ Hz and for $m \leqslant 20\%$, the modulation effect is attenuated.

MAIWALD'S paper [6] deals with a similar problem. Instead of a modulated noise octave, as in paper [11], a simple tone with amplitude and frequency modulated at the same time was applied. This research has led to results similar to those obtained in paper [11]. It should be noticed that mentioned above papers [6, 11] deal with relatively slow amplitude and frequency changes of the signal (ZWICKER — $f_m = 3$ and 10 Hz; MAIWALD — $f_m = 4$ Hz), and high values of deviation and amplitude modulation factor in comparison with threshold values.

Results of papers presented above have contributed to the formation of a functional perception model of modulated signals. According to this model, one mechanism governs the perception process of small amplitude and frequency changes. On the basis of this model, supplemented with MAIWALD'S more recent studies [7], the perception threshold of amplitude modulation can be calculated, as well as loudness difference limens, if the spectrum of the acoustic signal is known.

The problem of perception of *MM* signals and *MM* signals partially masked with a noise band, for consistant and opposite phases of amplitude and frequency modulating signals, has been analysed in CONINX'S paper [1]. These studies have led to the normalization of curves of just noticeable amplitude and frequency modulation in relation to threshold values. The cooperation of both types of modulation can be evaluated from these curves. Coninx gives the relationship between the threshold of amplitude modulation and coexisting frequency modulation at the absence of other signals for only one case. On the basis of this relationship it can be stated that a case of consistant phases of modulating signals, at definite experimental conditions (i.e. carrier frequency 8 kHz and modulating frequency 5 Hz), the coexistance of two types of modulation causes the "summation" (in the sense of mutual aid) of sensations created by both types of modulation. In the case of opposite phases between modulating signals, the cooperation of these types of modulation do not influence the values of thresholds so significantly. Values of thresholds are approximately independent from the coexisting modulation with sub-threshold value. A final conclusion can be drawn from research performed by CONINX — two independent perception mechanism of amplitude and frequency changes exist. According to CONINX, the cooperation between amplitude and frequency changes, which was proved on the basis of asymmetric shapes of curves of just noticeable modulations, can be explained not on the basis of one perception mechanism of amplitude and frequency changes, but on the basis of a mutual influence of amplitude on the pitch, and of frequency on the loudness of a signal. This problem has been also considered in detail in paper [3]. In another paper [2] CONINX tried to explain differences in the perception of *MM* signals with consistent and opposite phases between modulating signals, by converting amplitude and frequency changes into loudness and pitch changes, respectively.

Also the paper of HARTMANN and HNATH [5] is an important work in this domain. It deals with the perception of modulated signals; *AM*, *FM* and *MM*, and includes the masking effect. This paper was aimed at the determination of the individual components of a signal spectrum on values of the threshold of modulation perception. The dependence of the threshold of mixed modulation perception on the quotient of frequency and amplitude modulation indices for a case of consistent and opposite phases between signals modulating amplitude and frequency is especially important in this work.

This paper has led to the extension of the perception model of modulated signals, which was developed by GOLDSTEIN [4], and to the determination of its two boundary cases. These are: non-summation model, according to which the modulation is percepted on the basis of the dominating spectrum component; and the envelope fluctuation model, according to which the modulation takes place due to the perception of fluctuations of physical parameters of a modulated signal. On the basis of the discovered relationship between adequate modulation indices on the threshold of mixed modulation perception, HARTMANN and HNATH could support ZWICKER'S hypothesis [12], which assumes the existance of one mechanism responsible for the perception of amplitude and frequency modulation.

2. Time and spectral structure of *MM* signals

Let us consider a tonal signal with angular frequency ω_o in the following form

$$a(t) = A(t)\cos\omega_0 t, \tag{1}$$

with amplitude and frequency modulated by another tonal signal

$$b(t) = B\cos\omega_m t. \tag{2}$$

The time structure of this signal can be written as

$$a(t) = A_0[1+m\cos(\omega_m t+\varphi)]\cos[\omega_0 t+\beta\sin(\omega_m t+\psi)] \tag{3}$$

where m and β denote amplitude and frequency modulation indices, respectively, and $\varphi-\psi$ is the phase shift between signals, which modulate amplitude and frequency. Making use of a simple trigonometric transformation and assuming that $m, \beta \ll 1$ it can be easily proved that

$$\begin{aligned} a(t) \approx A_0\cos\omega_0 t &+ (A_0/2)(m\cos\varphi-\beta\cos\psi)\cos(\omega_0-\omega_m)t \\ &+ (A_0/2)(m\cos\varphi+\beta\cos\psi)\cos(\omega_0+\omega_m)t \\ &+ (A_0/2)(m\sin\varphi-\beta\sin\psi)\sin(\omega_0-\omega_m)t \\ &- (A_0/2)(m\sin\varphi+\beta\sin\psi)\sin(\omega_0+\omega_m)t. \end{aligned} \tag{4}$$

As it results from equation (4), the spectrum of an amplitude and frequency modulated signal consists of three fundamental components — the central one represents the carrier signal, while the sidebands are results of modulation. It should be noticed that amplitude values of sidebands depend on the mutual phase shift of signals, which modulate amplitude and frequency. When this shift equals $\varphi = \psi = 0$, then amplitude of the bands are proportional to $m-\beta$ for the lower and to $m+\beta$ for the higher band (Fig. 1).

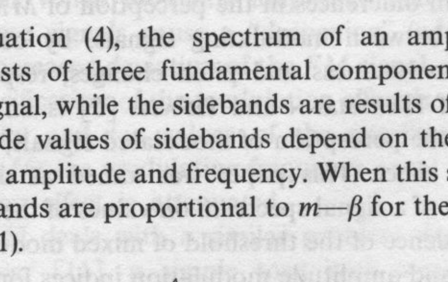

Fig. 1. Spectrum of signal simultanously amplitude and frequency modulated by a sinusoidal signal (see relationship (4)

The determination of the spectrum of a tone with amplitude and frequency modulated by a random signal is a more complicated problem than in the case of a tone modulated by a sinusoidal signal. The random modulating signal was accepted as the result of a stationary ergodic process with a normal distribution, in order to determine the spectrum of such a tone. Then its autocorrelation function, *rms* value and correlation function for the modulated signal could be derived. Additionally, the power spectral density of the modulated signal could be determined on the basis of the WIENER–CHIŃCZYN theorem.

This new method of determination of modulated signals is inconvenient in practice, because (in a case of correlated signals which modulate amplitude and frequency) the probability distribution of the product of the random signal and its integral has to be found. Moreover, this method does not give a direct measure of modulation, which has to be defined for measuring purposes.

Therefore, in this paper certain simplifying assumptions concerning the random modulating signal were made in order to determine the spectrum of a tone modulated by a random signal. Namely, the modulating signal (in this case a very narrow noise band) can be approximated by a tone with its frequency equal to the mid-band frequency and the amplitude equal to the rms of the noise band. And so,

$$n(t) = \sqrt{\sigma^2}\cos\omega_m t,$$

where σ is the variance of the noise band. When an assumption is made, that the phase shift $\varphi - \psi$ between the amplitude and frequency modulating signal is equal to zero, then the time and spectral form of the modulated signal can be noted in an analogic manner as in the case of a signal modulated by a tone, i.e.

$$a(t) = A_0(1 + m_{\mathrm{ef}}\cos\omega_m t)\cos(\omega_0 t + \beta_{\mathrm{ef}}\sin\omega_m t) \tag{5}$$

and

$$a(t) \approx A_0\cos\omega_0 t + (A_0/2)(m_{\mathrm{ef}} - \beta_{\mathrm{ef}})\cos(\omega_0 - \omega_m)t + (A_0/2)(m_{\mathrm{ef}} + \beta_{\mathrm{ef}})\cos(\omega_0 + \omega_m)t. \tag{6}$$

Quantities

$$m_{\mathrm{ef}} = (\sqrt{\sigma^2}/A_0)k; \qquad \beta_{\mathrm{ef}} = \Delta\omega_{\mathrm{ef}}/\omega_m = (\sqrt{\sigma^2}/A_0)k' \tag{7}$$

denote the *rms* index of amplitude modulation factor and the *rms* index of frequency modulation, respectively. They are the measures of modulation. It results from equation (6) that the spectrum of a tone with the amplitude and frequency modulated by a noise band is similar to the spectrum of a tone modulated by a sinusoidal signal, however, sidebands appear instead of spectral components. An identical result can be achieved under an assumption that the modulating noise band consists of a finite amount of components with adequate amplitude and frequencies, which are within this band. The obtained above form of a spectrum of a tone amplitude and frequency modulated by a random signal has been confirmed by results of an experimental analysis of modulated signals, which were audio monitored during the course of investigations.

3. Aim of research

As it results from paragraph 1, the problem of mixed modulation has been undertaken in many research contexts. First works on mixed modulation concerned the evaluation of signals modulated with the application of such values of modulation indices, which considerably exceeded thresholds of their perception. Only CONINX (carrier frequency 8 kHz, modulating frequency 5 Hz) [1] and HARTMANN (carrier frequency 1 kHz and modulating frequency 25 Hz) have determined thresholds of perception of mixed modulation with a varying percentage share of amplitude and frequency modulation. Signals used in papers [1, 5] are relatively simple, regular sinusoidal signals, which differ from occuring in practice signals, which determine amplitude and frequency changes (e.g. in speech or music).

Research performed here was aimed at the determination of thresholds of perception of changes occurring in an amplitude and frequency modulated (*MM*) signal in two cases. In the first case a regular signal (sinusoidal) was the modulating signal, while in the second case — an irregular signal (random), which was applied in such investigations for the first time. The application of a random modulating signal allowed a closer approximation of reality (i.e. sounds of speech and music, which are characterized by irregular changes of amplitude and frequency) by experimental conditions. Moreover, a comparison could be done between changes of thresholds of perception in both cases, i.e. regular and irregular changes of physical parameters of an MM signal.

4. Apparatus and research methods

A generator with the amplitude and frequency of the output signal controlled by external voltage, was the main element of the apparatus applied in the determination of thresholds of perception of simultaneous amplitude and frequency changes of a modulated signal. In dependence on the type of experiment, either a tone generator or a white noise generator with a filtering system were used as the source of voltage.

Simultaneous amplitude and frequency changes were archieved as a result of mixed modulation (*MM*) of a tone by a sinusoidal or random signal. Regular or irregular changes of physical parameters of the modulated signal were obtained. Measurements of threshold values for a case of a tone-tone modulation were performed for a signal with frequency equal to: 4, 64, 400 Hz. These values of modulation frequency to a certain extent represent three characteristic regions of perception of modulated signals. Namely: the "follow up" region, where the organ of hearing keeps up with the observation of loudness maxima and minima, and the pitch of a signal; the roughness region, where changes of physical parameters occur so quickly that the ear is not able to register them and sufficiently slowly for sidebands of the spectrum to belong to the same critical band; region of separation of sidebands, where sidebands of the spectrum are outside the critical band, which corresponds to the carrier signal.

Measurements for a case of an irregular modulating signal were performed for a signal with the carrier frequency equal to 1000 Hz and for three bands of modulating noise with the width of 1.5% mid-band frequencies equal to 4, 64, 400 Hz.

In the course of all experiments the signal was presented monaurally through *SN* 60 earphone. The intensity level of a signal was constant and equal to 75 dB, and the phase shift between signals modulating amplitude and frequency was equal to zero.

Measurements were carried out on the basis of a modified tuning method. According to this method, the listener with the application of a special controller set such a value of amplitude modulation factor or its deviation, which was evaluated as threshold. This was done in two series: ascending, from very small subthreshold changes of m or β values to just noticeable values; and descending, from very high supra threshold values of m or β, at which the modulation was clearly audible to the moment at which the signal did not change at all, according to the listener. Data obtained in ten ascending tests and ten descending tests were statistically tested with the test of goodness of fit, test of rank sum, F-Snedecor test at the significance level of $\alpha = 0.05$, in order to determine whether results from both series are from one population. Positive results of these tests have supported this hypothesis.

Two listeners with audiologically normal hearing participated in the experiment.

5. Results of measurements and their analysis

Thresholds of perception of amplitude modulation and frequency modulation were determined seperately in the first part of investigations in order to compare them with data from literature and to verify applied methods. Experiments were performed for a regular and irregular modulating signal. Obtained results are presented in Figs. 2a and 2b — for listener *EO* and *AS*, respectively. These figures also show experimental results achieved by ZWICKER [12] for comparative reasons. Figs. 2a, b prove obtained results to be quantitatively and qualitatively consistant with data from literature.

Thresholds of perception of amplitude and frequency modulation differ strongly at low modulating frequencies ($f_{\text{mod}} \leqslant 70$ Hz), while above this frequency they accept approximately identical values. This happens due to the monoaural phase effect (worked out by GOLDSTEIN [4]). A significant decrease of threshold values, accompanying an increase of the modulating frequency above 70 Hz is observed, because the spectrum of the modulated signal exceeds the width of one critical band. In such a case the amplitude and frequency modulation are percepted as identical phenomena and the phase effect disappears. As it has been mentioned previously also thresholds of perception of amplitude and frequency modulation obtained with irregular modulating signals have been determined separately. Research results are shown in Figs. 2a and 2b.

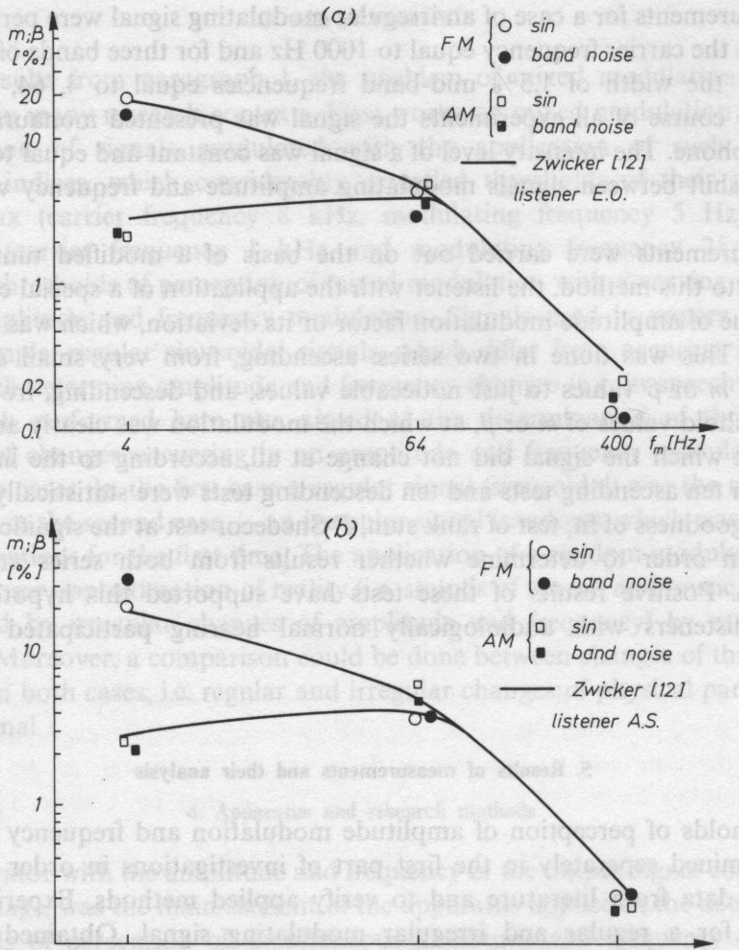

Fig. 2. Thresholds of perception of amplitude (*AM*) and frequency (*FM* modulation for a regular (sinusoidal) and irregular (random) modulating signal in terms of modulating frequency, a — for listener *EO*, b — for listener *AS*

Research was concerned mainly with the determination of thresholds of perception of mixed modulation. To this end, at an adequately chosen subthreshold value of the amplitude modulation factor, the listener himself increased the signal deviation to the moment when he percepted (observed) just noticeable changes of the signal (ascending series), or decreased its value to the moment when he percepted a pure sound (descending series). Subthreshold values of the amplitude modulation factor were equal to

$$0.2\,m_t;\ 0.4\,m_t;\ 0.6\,m_t;\ 0.8\,m_t;\ 1\,m_t$$

(i.e. expressed as a fraction of the threshold value m_t, which has been determined in the first part of research). Figs, 3, 4 and 5 present changes of thresholds of perception

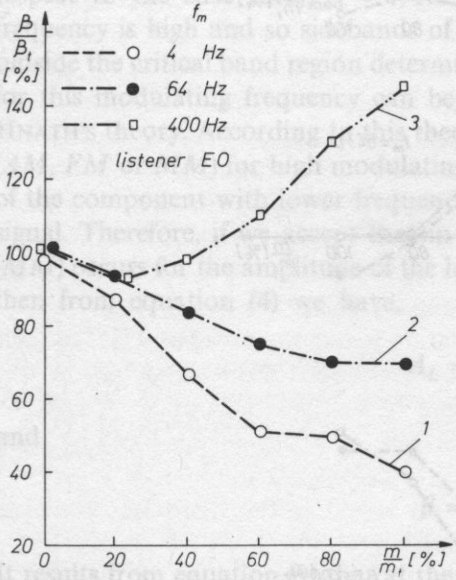

Fig. 3. Thresholds of perception of amplitude–frequency modulation of a tonal signal for listener *EO*, for a regular modulating signal with the following frequencies: 4, 64, 400 Hz

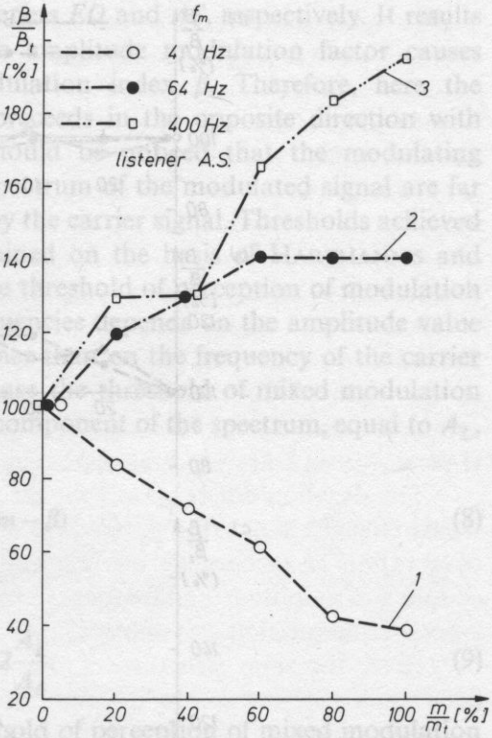

Fig. 4. Thresholds of perception of amplitude-frequency modulation of a tonal signal for listener *AS* for a regular modulating signal with the following frequencies: 4, 64, 400 Hz

of mixed modulation (amplitude-frequency) for regular (Figs. 3, 4) and irregular (Figs. 5) amplitude and frequency changes of the modulated signal. The following quantities are marked on the respective coordinate axes of these diagrams: adequats frequency β and amplitude m modulation indices, normalized with respect to threshold values (β_t, m_t), which were determined in the first part of investigations. Curves marked 1 in Figs. 3 and 4 represent changes of thresholds for a regular modulating signal with frequency $f_m = 4$ Hz, for listeners *EO* and *AS*, respectively. It results from these diagrams that an increase of the amplitude modulation factor m from 0 to the threshold value (i.e. when $m/m_t = 100\%$) for $f_m = 4$ Hz, causes a significant decrease of the frequency modulation index.

Hence, we can infer that in the range of low modulating frequencies, i.e. in the region in which the ear can "follow" the changes of values of signal parameters in time, a coupling is observed in the sense of summation (aid) of sensations produces by both types of modulation under consideration. Or in other words — subthreshold changes of amplitude and subthreshold changes of frequency, which are produced simultaneously in a sinusoidal signal (in the conditions of mixed modulation *MM*),

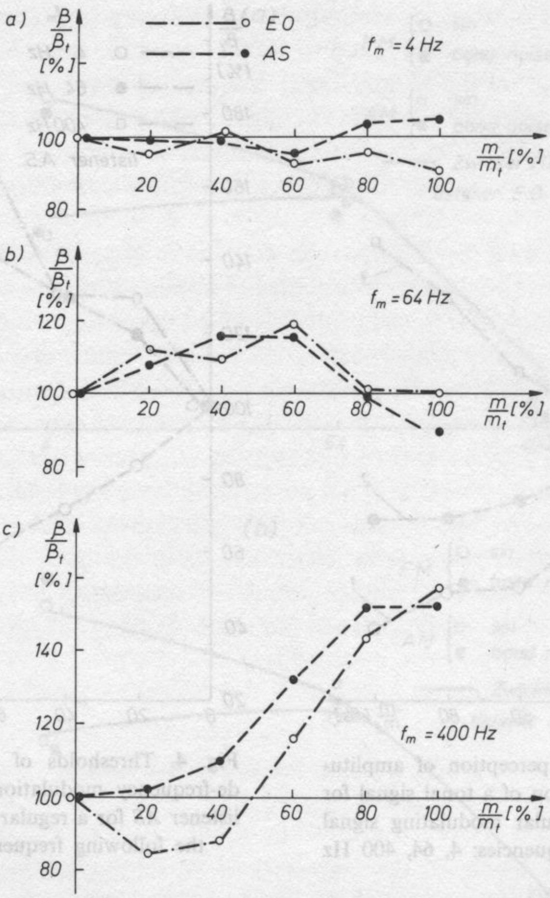

Fig. 5. Thresholds of perception of amplitude-frequency modulation of a tonal signal for listeners *EO* and *AS* for a random modulating signal with mid-band frequency equal to: a — 4 Hz, b — 64 Hz, c — 400 Hz, and width 1.5%

are percepted by listeners for definite values of *m* and *β*. Similar relations have been observed by Coninx [1] for threshold values, and Zwicker [10] for above threshold values.

Such an effect of summation of sensations, created by simultaneous *AM* and *FM* modulation, has not been observed in the case of an irregular modulating signal, i.e. for irregular amplitude and frequency changes of the tone (see Fig. 5a). In this case the *MM* threshold does not depend on occuring changes of the amplitude of the signal, which are determined by the value of the amplitude modulation factor. The divergence of *MM* thresholds for a regular (sinusoidal) and irregular (random) modulating signal is rather surprising, because threshold values determined from separate investigations of amplitude and frequency modulation, were very similar for both types of the modulation signal, i.e. regular and irregular (see Figs. 2a and 2b). Curves marked 3 in Figs. 3 and 4 represent thresholds of mixed modulation for modulating frequency $f_{mod} = 400$ Hz, for listeners *EO* and *AS*, respectively. It results from these figures that an increase of the amplitude modulation factor causes a distinct increase of the frequency modulation index β. Therefore, here the cooperation of both types of modulation preceeds in the opposite direction with respect to the case for $f_{\mathrm{mod}} = 4$ Hz. It should be noticed that the modulating frequency is high and so sidebands of the spectrum of the modulated signal are far outside the critical band region determined by the carrier signal. Thresholds achieved for this modulating frequency can be explained on the basis of HARTMANN'S and HNATH'S theory. According to this theory the threshold of perception of modulation (*AM*, *FM* or *MM*) for high modulating frequencies depends on the amplitude value of the component with lower frequency, rather than on the frequency of the carrier signal. Therefore, if we accept that in our case the threshold of mixed modulation (*MM*) occurs for the amplitude of the lower component of the spectrum, equal to A_L, then from equation (4) we have,

$$A_L = \frac{A_0}{2}(m-\beta) \tag{8}$$

and

$$\beta = m - 2\frac{A_L}{A_0}. \tag{9}$$

It results from equation (9) that at the threshold of perception of mixed modulation the frequency modulation index is in linear dependence with the amplitude modulation factor *m*. Such a relationship is presented approximately by curves marked 3 in Figs. 3 and 4.

A similar situation takes place for an irregular modulating signal. Results of investigations for this case are shown in Fig. 5b. Also here the frequency modulation index increases linearly with an increase of the amplitude modulation factor in a certain interval. This proves that the irregular character of rapidly changing physical parameters of the signal does not influence perception significantly. Curves marked 2 in Figs. 3 and 4 represent thresholds of perception of mixed modulation for listeners *EO* and *AS*, respectively, when a sinusoidal signal with frequency $f_{\mathrm{mod}} = 64$ Hz is the modulating signal. It results from these figures that results obtained for both listeners differ in quality. For listener *AS* (Fig. 4) an approximately linear increase of the frequency modulating index β accompanies the increase of the amplitude modulation factor *m*, while for listener *EO* (Fig. 3) the β value decreases with an increase of *m*. Therefore, a cooperation of both types of modulation in the sense of their mutual aid, very much like for the modulation frequency of 4 Hz, was stated for listener *EO*, while in the case of listener *AS*, the cooperation has a reverse direction, like for modulating frequency $f_{\mathrm{mod}} = 400$ Hz.

Fig. 5c presents thresholds analogic to those in Figs, 3, 4 (curves marked 2), but in this case a narrow noise band with mid-band frequency equal to 64 Hz is the modulating signal. We can see that an initial increase of the amplitude modulation factor causes a small rise of the frequency modulation index, what suggests a case analogic to that for $f_{\mathrm{mod}} = 400$ Hz, i.e. mutual weakening of sensations created by both types of modulation. However, a further increase of the amplitude modulation factor causes a decrease of β to its initial value, i.e. like for $f_{\mathrm{mod}} = 4$ Hz. Presented above results of experiments point to a rather complex mechanism of perception of MM modulated signals. The spectral structurs, or in other words — the component with frequency lower than the carrier frequency of the signal, is the factor, which determines the perceptivity of changes in a case of regular amplitude and frequency changes of the signal occuring very quickly (high value of f_{mod}). This means that the component with higher frequency does not influence the perception process at the threshold of perception, although its amplitude is by $A_0\beta$ higher than the amplitude of the lower component. Thus, the component with higher frequency undergoes complete masking by the carrier signal at high modulating frequencies, what HARTMANN and HNATH postulated in their theory [5].

The situation differs greatly for the modulating frequency equal to 4 Hz. In such a case changes of physical parameters occur slowly enough for the ear to "follow" the observation of successiove minima and maxima of loudness and pitch. A positive coupling of amplitude and frequency changes occurs — sensations produced by both types of modulation are summed.

Here, the time structure of the modulated signal is the main factor which determines the perception of MM modulation.

The presented above two methods (mechanisms) of perception of modulated signals, have been isolated considering only the value of the modulating frequency. As it has been mentioned above, the time mechanism functions when changes of physical parameters of a signal are relatively slow; while the spectral mechanism functions when these changes are relatively fast. It is possible that these are two independent mechanisms, which can occur seperately, or simultaneously as a certain combination, especially for modulating frequencies from the range of so-called roughness. The transition of the time mechanism into the spectral mechanism is undoubtedly a continuous process, individual for different listeners and dependent on values of modulation frequencies. Data presented in Figs. 3 and 4 (curves marked 2) confirm this. It results from them that for modulating frequency $f_{\mathrm{mod}} = 64$ Hz, the spectral mechanism prevails for listener AS, while for listener EO the time mechanism dominates.

Relationships between adequate modulation indices, which were observed for mentioned values of modulating frequencies, prove that the perception of one type of modulation is not independent from the coexisting second type of modulation.

Research performed does not give a final answer to the question, in which frequency ranges these mechanisms (spectral and time) occur. It is initial research, which tries to explain the method of perception of signals varying in time. A rather arbitrary choice of modulating signals, which was done on the basis of perception ranges of modulated signals widely mentioned in literature, limits investigations to only a part of phenomena accompanying the perception of these kinds of signals.

Therefore, research seems worth continuing, especially in the domain of signals modulated by irregular signals, which as we know constitute a great part of sounds met in practice.

References

[1] E. Coninx, *The detection of combined differences in frequency and intensity,* Acustica, **39**, 3, 138–150 (1977).

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

[3] A. Czajkowska, *Generalized difference thresholds and valuation of simultaneous changes of intensity and frequency of a tone,* Arch. Akustyki, **16**, 3, 257–266 (1981) (in Polish).

[4] L. J. Goldstein, *Auditory spectral filtering and monaural phase perception,* JASA, **41**, 2, 458–479 (1967).

[5] W. M. Hartmann, G. H. Hnath, *Detection of mixed modulation,* Acustica, **50**, 5, 297–312 (1982).

[6] D. Maiwald, *Ein Funktionsschema des Gehörs zur Beschreibung der Erkennbarkeit kleiner Frequenz und Amplitudenanderungen,* Acustica, **18**, 2, 81–92 (1967).

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

[8] A. R. Moller, *Coding of amplitude and frequency modulated sounds in the cochlear nucleus,* Acustica, **31**, 6, 292–299 (1974).

[9] A. R. Moller, *Frequency selectivity of single auditory—nerve fibres in response to broadband noise stimuli,* JASA, **62**, 1, 135–142 (1977).

[10] E. Ozimek, A. Sęk, *Perception of irregular changes of sinusoidal signals* (paper sent to Acustica).

[11] E. Zwicker, *Direct comparison between the sensation produced by frequency modulation and amplitude modulation,* JASA, **34**, 8, 1425–1430 (1962).

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

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