ARCHIVES OF ACOUSTICS
19, 1, 37–58 (1994)

AM AND FM DIFFERENCE LIMENS *

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This paper reports two basic experiments aimed at determining difference limens (DLs) for amplitude and frequency modulation as a function of the modulation indices (m, β), modulation frequency and sound pressure level of the modulated signals. Two types of modulator were used. The first one was the sinusoidal signal. In this case the simplest (sine by sine) amplitude and frequency modulation was considered. In the second case the modulator had a constant frequency but its amplitude was randomly changed with mean 0 and standard deviation σ. In a two-alternative forced choice task just noticeable differences of modulation intensity were measured. It was found that AM and FM difference limens increase with the increase of modulation indices of the reference signals. Additionally, it was shown that the difference limens were almost independent of the modulation frequency. They were also independent of the type of modulator used in the investigations.

1. Introduction

Investigations into the perception of amplitude and frequency modulated signals have been extensively described [1–11, 13–25]. One group of papers deals with the thresholds used to detect AM and FM whereas the other group deals with investigations into the intensity of loudness or pitch fluctuation and roughness of the modulated signals.

Modulation thresholds were investigated by ZWICKER [25] who determined AM and FM thresholds with reference to the amplitude and frequency of the carrier signal and to the modulation frequency. This helped to determine three perception ranges of the modulated signals: follow-up, roughness and sidebands separation.

Modulated signals generate different auditory sensations in these areas, what affects the detection threshold of AM and FM. In the case of small modulation frequencies ($f_{mod} < 20$ Hz — follow-up range), changes in the signal amplitude or frequency bring about changes in signal loudness or pitch. When $f_{mod} \in (20-\text{CMF})$ Hz (CMF — critical modulation frequency [20, 21, 25]), the sensation evoked by the modulated signal is called roughness [11, 22, 23]. For modulation frequencies $f_{mod} > \text{CMF}$, what corresponds to the transition of sidebands of modulated signals

* This research was supported by the grants 20071 1901 and 2 0910 01 from the Committee of Scientific Researches (KBN)

spectra beyond the range of one critical band, the auditory sensation is similar to that evoked by a multi-tone. It is worth stressing here that in this situation thresholds for detecting amplitude and frequency modulation expressed as modulation indices (i.e., m and β) reach the same value.

In investigations into supra-threshold changes of amplitude and frequency modulated signals, the main focus has so far been on the evaluation of the intensity of loudness and pitch fluctuation, and the evaluation of the intensity of the roughness of AM and FM signals [4–6, 8, 11, 17–19, 22–24]. Pitch or loudness fluctuation defines changes of these parameters which occur less than 20 times per second (i.e. $f_{mod} \leqslant 20$ Hz). Roughness occurs when modulation frequency is greater than 20 Hz and at the same time does not exceed the critical modulation frequency (CMF) [20, 21, 25] which depends on the carrier frequency [21].

TERHARDT [22, 23] described the dependence of the intensity of loudness fluctuation on the carrier frequency, modulation frequency and sound pressure level. He found out that the intensity of loudness fluctuation and the intensity of roughness are proportional to the square of the AM index. Likewise, GUIARO and GARAVILLA [8] discovered that the roughness of the AM signal is nonlinearly correlated with modulation depth. SCHOENE [19], on the other hand, showed that the intensity of loudness fluctuation is independent of the sound pressure level and modulation frequency in the range up to $f_{mod} \leqslant 10$ Hz. FASTL [4] found out that the intensity of tonal signal fluctuation and that of a noise band is proportional to the logarithm of the AM index.

The determination of AM difference limens has been discussed less extensively. An AM difference limen (AM DLs) denotes a just noticeable difference between two AM signals which differ only with respect to the amplitude modulation index.

One of the first papers dealing with this problem is the one by SCHOENE [19], which pertains to the dependence of AM difference limens on the modulation index of the reference signal. It was shown that the difference limens are linearly correlated with the AM index of the reference signal. Moreover, it was also shown that AM difference limens are independent of modulation frequency in the range up to $f_{mod} \leqslant 10$ Hz. FLEISCHER [5] has shown a linear dependence of AM difference limens on the AM index. It is worth pointing out that both SCHOENE'S [19] and FLEISCHER'S [5] papers are concerned with AM in the case when both carrier and modulating signals were sinusoids.

OZIMEK and SĘK [17] showed AM difference limens of an octave noise band as a function of the selected physical parameters of the carrier signal and modulating signals. They found out that the dependence of the difference limens on the AM index of the reference signal can be characterized by a local maximum [17].

WAKEFIELD and VIEMEISTER'S paper [24] is one of the recent papers which discusses AM difference limens of a broadband noise. These authors showed that the difference limens of AM do not depend on the sound pressure level and modulation frequency. It is worth stressing that the results obtained by FLEISCHER [5], SSCHOENE [19] and OZIMEK and SĘK [17] are fully compatible, what was also observed by WAKEFIELD and VIEMEISTER [24].

The roughness and intensity of pitch fluctuation of frequency modulated signals have been discussed by TERHARDT [22, 23]. In addition to investigations into the roughness of AM signals, he also studied the problem of roughness of a FM signal. Terhardt suggested that, in accordance with Zwicker–Maiwald's model [25, 15], the general principles of the dependence of roughness and intensity of pitch or loudness fluctuation on the parameters of modulated signals should be similar for both types of modulation (i.e. AM and FM). This hypothesis was confirmed by experiments by TERHARDT [8].

KEMP [11] discussed the perception of roughness in FM signals. He evaluated the roughness of a tonal signal frequency modulated by a sinusoid with respect to the physical parameters of both the carrier and modulation signals. Kemp found out that the magnitude of the roughness depends on modulation frequency, carrier frequency and the sound pressure level. Maximal relative roughness occurs for the frequency modulation 40–80 Hz. Relative roughness is nonlinearly correlated with signal deviation. A similar relation observed was between the amplitude modulation index and roughness in the case of AM signals [19].

FM difference limens were discussed by OZIMEK and SĘK [18]. FM DLs denote a just noticeable difference between two FM signals which differ only with respect to frequency deviation. The authors measured FM difference limens of a tonal signal frequency modulated with another tonal signal with respect to modulation frequency, carrier frequency and the sound pressure level. Futhermore, they also discussed the dependence of the DLs on reference signal deviation. It was observed that FM difference limens were approximately independent of the carrier and modulation frequency. They were also independent of the sound pressure level. However, an increase in reference signal deviation caused an approximately nonlinear increase of the difference limens' value. Ozimek and Sęk also measured DLs using random modulators with uniform and Gaussian probability distributions. Similar difference limens were obtained for both types of modulator.

As follows from the above presented overview, most of the papers discussing investigations into the perception of AM and FM signals with supra-threshold modulation intensity concerned the evaluation of the roughness and intensity of loudness and pitch fluctuation. Some other papers were devoted to AM difference limens and only a few discussed the problem of difference limens of frequency modulated signals. It should be stressed that most of the papers concerned with AM and FM detection or discrimination were based on periodic sinusoidal changes of amplitude and frequency. However, different carrier signals, including a white noise [19, 24] or its different bands [17], were used.

In environmental signals, periodic amplitude and frequency changes occur very seldom and are usually of very short duration. Signals such as music, speech or traffic noise are characterized by quasi-random changes in both amplitude and frequency domains. Hence it seems interesting to determine the difference limens of random changes of some physical parameters obtained by amplitude and frequency modulation.

However, random changes of amplitude and frequency can be of two types. In the case, for example amplitude modulation, a random modulation signal causes irregular changes of both modulation depth and modulation frequency. This simultaneous changes of modulation depth and modulation frequency is significant for the evaluation of a signal and can affect the threshold. Therefore a sinusoidal signal whose amplitude was randomly changed was adopted as a random modulator, similarly to SĘK [21]. In the AM case this modulator caused random changes of the AM index whereas in the FM case the modulator caused random change of frequency deviation. A modulator of this type, generated by a computer, was a set of successive equal periods of function sin (ωt) with an amplitude changing randomly from the period to period.

2. Aim of investigations

The main purpose of the investigations was to determine AM and FM difference limens for a sinusoidal carrier signal with respect to modulation frequency, modulation indices, the type of modulator and sound pressure level.

A just noticeable difference between two amplitude or frequency modulated signals which differed with respect to the value of a respective modulation index were determined. One of them, called the reference signal, was characterized by a constant value of the AM index m_r (in AM case) or deviation d_r (in FM case). The second one, called the test signal was characterized by lower values of modulation indices than the reference signal, i.e., $m_t < m_r$ and $d_t < d_r$.

Measurements of AM and FM difference limens were carried out for the modulation frequency $f_{mod} = 2$, 8, 32 and 128 Hz. These values correspond to the perception ranges of the modulated signals mentioned above, i.e., 2 and 8 Hz correspond to the follow-up range, 32 Hz corresponds to the roughness range and 128 Hz corresponds to the sidebands separation range.

Four values of the AM index of the reference signal (m_r) and four values of the deviation of the reference signal (d_r) were used. A sinusoidal carrier frequency $f_c = 1000$ Hz was used. The sound pressure level was $L_c = 35$, 45, 55, 65, 75 and 85 dB SPL. Two types of modulator were used. One of them was a sinusoid and the other a sinusoid with an amplitude randomly changing from period to period. In the case of AM and FM with random modulators it appeared necessary to analyze the temporal and spectral structure of the modulated signals and to define a direct measure of modulation intensity. The problems are discussed in Section 3 of this paper, in the case of both AM and FM.

3. Temporal and spectral structure of modulated signals

Analytical considerations aimed at determining the temporal and spectral structure of modulated signals, where simple tones are both modulation and carrier signals are reduced to simple trigonometric transformations. Let us assume that the carrier signal has the form:

$$a(t)=A_0\cos(\omega_0 t), \tag{1}$$

and the modulation signal has the form:

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

In the case of amplitude modulation, the temporal form of a modulated signal can be described as follows:

$$a_{\mathrm{AM}}(t)=A_0(1+m\sin\omega_m t)\cos\omega_0 t \tag{3}$$

or:

$$a_{\mathrm{AM}}(t) = \frac{A_0 m}{2}\cos(\omega_0-\omega_m)\,t+A_0\cos(\omega_0 t)+\frac{A_0 m}{2}\cos(\omega_0+\omega_m)\,t, \tag{4}$$

where

$$m=\frac{kB}{A_0}, \tag{5}$$

denotes the coefficient of amplitude modulation depth and k is a constant.

In the case of frequency modulation the temporal form of a modulated signal can be expressed as follows:

$$a_{\mathrm{FM}}(t)=A_0\cos(\omega_0 t-\beta\cos(\omega_m t)), \tag{6}$$

where

$$\beta=\frac{\Delta\omega}{\omega_m}=\frac{k_1 B}{\omega_m} \tag{7}$$

is a frequency modulation index, $\Delta\omega$ — frequency deviation and k_1 a constant.

The FM signal can be expressed as follows [12]:

$$a_{\mathrm{FM}}(t)=A_0\sum_{-\infty}^{\infty} J_n(\beta)\cos(\omega_0+n\omega_m)\,t, \tag{8}$$

where $J_n(\beta)$ is a Bessel function of the first kind, n-th order.

The spectra of AM and FM signals consist of discrete components among which the central one is the component which correspond to the carrier signal and all the others are products of modulation. In the case of AM, the spectrum, in addition to the central component, includes two sidebands with equal amplitudes, situated at a distance of $\pm\omega_m$ from the carrier. In the case of FM, in addition to the component which corresponds to the carrier signal, the spectrum consists of a theoretically unlimited number of sidebands. The sidebands are symmetrical with respect to the central component and they are $\pm\omega_m$ separated in the frequency domain. Odd sidebands with frequencies lower than the carrier are phase shifted by π with respect to sidebands with frequencies higher than the carrier frequency. This causes the so-called monaural phase effect (MPE) [20, 21].

The determination of the spectrum of a simple tone amplitude or frequency modulated by a random signal is a more complex issue. If a random modulation signal is a realization of a stationary ergodic process with a normal probability distribution, an autocorrelation function [12] can be determined for a modulated signal. Using the Wiener-Chińczyn theorem, we can determine the power spectral density function of the modulated signal. However, this method when used to determine the spectrum of a modulated signal is troublesome since it does not provide a direct measure of modulation intensity. A clear definition of the intensity of modulation for both AM and FM is necessary for measurement purposes. Therefore, in order to determine the spectrum of a sinusoid amplitude modulated by a random signal, earlier consideration on modulation of the tone-tone type were taken into account. However the random modulator is a sinusoidal signal with a randomly changing amplitude. Thus the temporal and spectral structure of the modulated signal does not change significantly as compared with the tone-tone modulation, provided that the amplitude of the modulation signal B in the expression (2) is a randomly changing parameter. Consequently, the values of amplitudes of the sidebands of the AM or FM signals' spectrum change randomly in accordance with amplitude variations of the modulation signal.

In the simplest case of the tone-tone modulation, the amplitude modulation index m (5) or the frequency modulation index β (7) is the measure of intensity modulation. Modulation indices defined in this way cannot be used directly in the case of a modulation by a random signal because such a signal is characterized by an indefinite value of amplitude. Therefore, in the case of AM, the root-mean-square AM index m_{RMS}, which expresses the ratio of RMS values of the modulator and carrier signals, was adopted as the measure of modulation intensity [12]:

$$m_{\mathrm{RMS}} = k\sqrt{\frac{\sigma_{\mathrm{B}}^2}{A_0^2}}\,. \tag{9}$$

In the case of FM, $\Delta\omega_{\mathrm{RMS}}$ which expresses the root-mean-square value of frequency deviation, was adopted as the measure of modulation intensity [12]:

$$\Delta\omega_{\mathrm{RMS}} = k_1\sigma_{\mathrm{B}}, \tag{10}$$

where σ_{B} denotes an RMS value of a random modulator.

AM difference limens were expressed, as in WAKEFIELD and VIEMEISTER [24] by means of the following expression:

$$\Delta M = 10\,\mathrm{Log}\,(m_r^2 - m_t^2)\ [\mathrm{dB}], \tag{11}$$

where m_r and m_t denote the root-mean-square AM indices for the reference and test signal respectively. The AM index of the reference signal was determined in the same way [5, 24]:

$$M_r = 10\,\mathrm{Log}(m_r^2)\ [\mathrm{dB}], \tag{12}$$

In the FM case difference limens were expressed as differences between the root-mean-square deviations (10) of the reference signal d_r and test signal d_t:

$$\Delta F = d_r - d_t\ [\mathrm{Hz}]. \tag{13}$$

4. Method

The two-alternative forced choice method (2AFC) with Levitt's adaptive procedure [13] was used. The subject listened monaurally to a pair of modulated signals in a random order. One of them was a reference signal with a constant supra-threshold modulation intensity (m_r or d_r) and the other one was a test signal with changing modulation intensity (always smaller than the reference signal, i.e., $m_t < m_r$, $d_t < d_r$). The subject's task was to indicate the signal in which the intensity of amplitude changes (in the case of AM) or intensity of frequency changes (in the case of FM) was greater. The difference in the modulation intensity between the reference signal and the test signal (i.e., $m_r - m_t$ or $d_r - d_t$) was increased by a factor of 1.5 after two successive correct answers or decreased after one incorrect answer. This procedure tracks the point on the psychometric function corresponding to 71% correct. A single measurement of the threshold was completed when 12 reversals were obtained. The threshold value from such a measurement was calculated as an arithmetic mean value of the modulation index at the last eight turnpoints. The results presented in this paper are arithmetic means of ten independent measurements. Three subjects with audiologically normal hearing took part in the investigations.

The signals were numerically generated via a 12-bit D/A converter. Each signal had a 1500 ms duration including raise and decay times of 100 ms each. The inter stimulus interval was 400 ms. The subjects were tested in a sound isolated booth and they used an answering keyboard to give their answers.

5. Results and their analysis

5.1. AM *difference limens*

The dependence of AM difference limens on modulation frequency was the basic one to be determined in this part of the study. The investigations consisted in determining the just noticeable difference between the reference signal, characterized by a constant value of the AM index $m_r = 25$, 50, 75 and 95%, and the test signal in which the AM index m_t was changed in the range from 0 to m_r (i.e. $m_t \leqslant m_r$). The results of these investigations, for the sound pressure level 75 dB SPL, carrier frequency 1000 Hz and for a sinusoidal modulator signal were shown in Fig. 1 for the subjects EO and AS respectively. The AM index of the reference is the parameter of the data.

As can be seen, AM difference limens are very similar for both subjects and they are approximately independent of modulation frequency.

Similar investigations were also carried out for a random modulator, i.e., a sinusoidal signal with an amplitude randomly changing from period to period. In these investigations the same carrier signal was used, i.e., $f_c = 1000$ Hz and $L_c = 75$ dB.

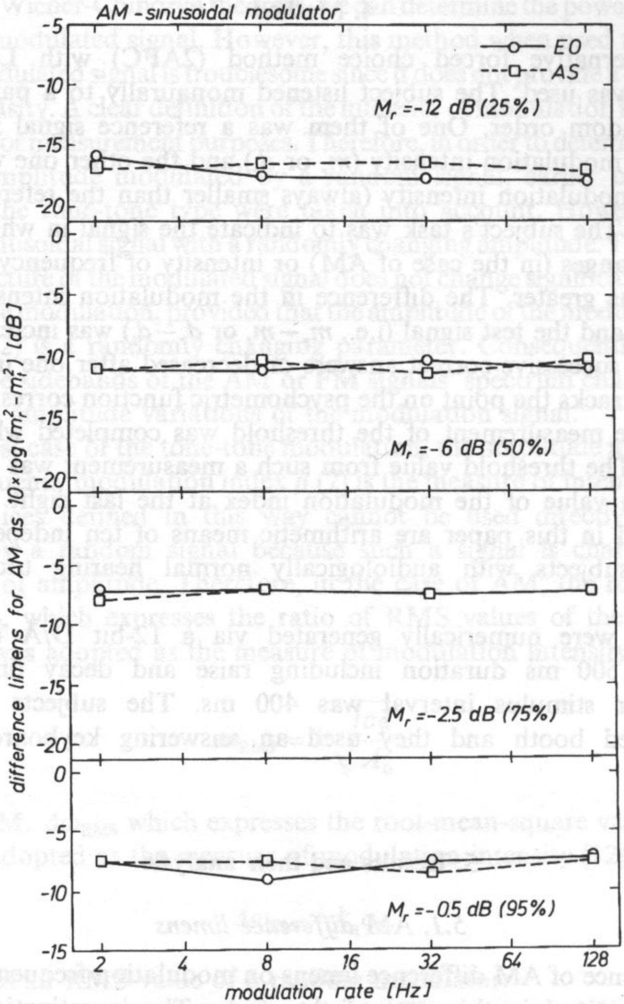

Fig. 1. Dependence of AM difference limens on modulation frequency for a sinusoidal modulator. The AM index is the parameter of the data.

The results were shown in Fig. 2 for the subjects EO and AS. For both subjects AM difference limens for a random modulator are similar and independent of the modulation frequency.

The data obtained for both types of modulator were subjected to analysis of variance ANOVA with the following factors: type of modulator, modulation index of reference signal, subject and frequency modulation. The effect of the modulation index was highly significant [F (3,55) = 622, p < 0k.0001]. The effect of the subject was not significant [F (1,55) = 0.938, p = 0,34]. Also the effects of the modulating frequency and type of modulator were not significant [F (3,55) = 0.494, p = 0.69] and [F (1,55) = 2.47, p = 0.67] respectively.

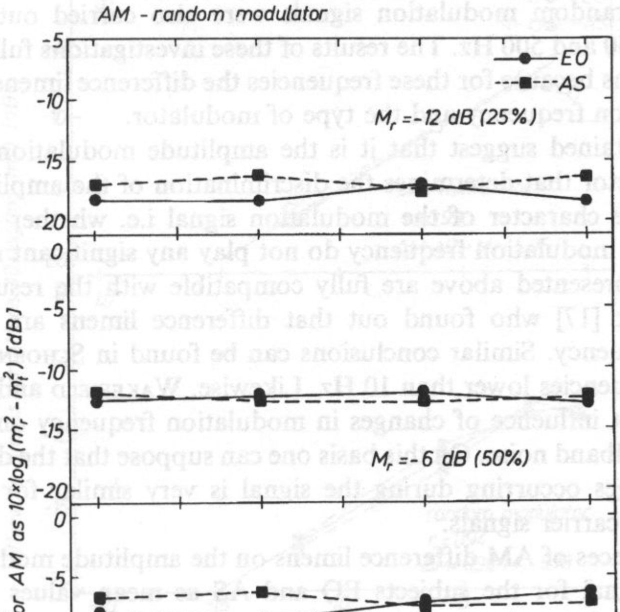

Fig. 2. Dependence of AM difference limens on modulation frequency for a random modulator. The AM index is the parameter of the data.

Generally, it can be stated that the difference limens obtained for sinusoidal and random modulators are very close to each other. This means that discrimination of the amplitude changes does not depend on the type of modulator, i.e., whether it is sinusoidal or random. This helps generalize conclusions drawn from experimental data on the roughness and intensity of amplitude fluctuation for sinusoidal changes and apply them to random changes of amplitude. This is similar to SĘK's [21] conclusion which states that the threshold for detecting amplitude modulation did not depend on the type of modulator. Measurements of AM difference limens for the

sinusoidal and random modulation signals were also carried out for the carrier frequencies of 250 and 500 Hz. The results of these investigations fully confirmed the above conclusions because for these frequencies the difference limens did not depend on the modulation frequency and the type of modulator.

The data obtained suggest that it is the amplitude modulation index which is primarily the factor that determines the discrimination of the amplitude changes in AM signals. The character of the modulation signal i.e. whether it is random or periodic and the modulation frequency do not play any significant role in this case.

The results presented above are fully compatible with the results obtained by OZIMEK and SĘK [17] who found out that difference limens are independent of modulation frequency. Similar conclusions can be found in SCHOENE [19] who used modulation frequencies lower than 10 Hz. Likewise, WAKEFIELD and VIEMEISTER [24] noted the lack ot influence of changes in modulation frequency on AM difference limens of a broadband noise. On this basis one can suppose that the discrimination of amplitude changes occurring during the signal is very similar for many different modulation and carrier signals.

The dependences of AM difference limens on the amplitude modulation index of the reference signal for the subjects EO and AS as mean values for modulation frequencies were shown in Fig. 3a and b, for sinusoidal and random modulators respectively. As can be seen from Fig. 3a, AM difference limens for a sinusoidal modulator and the value $M_r \leqslant -2.5$ dB are a rising function of the AM index of the reference signal. The rising character of this dependence suggests that just noticeable increases in changes of the signal physical parameters are approximately proportional to the existing changes (reference changes) what is fully compatible with Weber's law. The regression analysis conducted for this data showed that in the case of a sinusoidal modulator this dependence can be expressed as:

$$\Delta M = 1.01\ M_r - 5.06, \tag{14}$$

at the correlation coefficient $r = 0.99$.

Similar dependencies were obtained in investigations concerning the valuation of the intensity of loudness and pitch fluctuation and roughness for both types of modulation [11, 22]. It was found that the intensity of roughness and that of loudness and pitch fluctuation are rising (nonlinearly) functions of respective modulation indices.

The dependence of AM difference limens on the AM index of the referrence signal for a random modulator was shown in Fig. 3b. Also in this an case increase in the AM index signal caused an increase in difference limens. This dependence can be approximately expressed as:

$$M = 0.99\ M_r - 5.73. \tag{15}$$

However, for this modulator there were clear differences between the subjects with respect to the difference limens. These differences affected the value of the correlation coefficient which in this case was equal to $r = 0.94$.

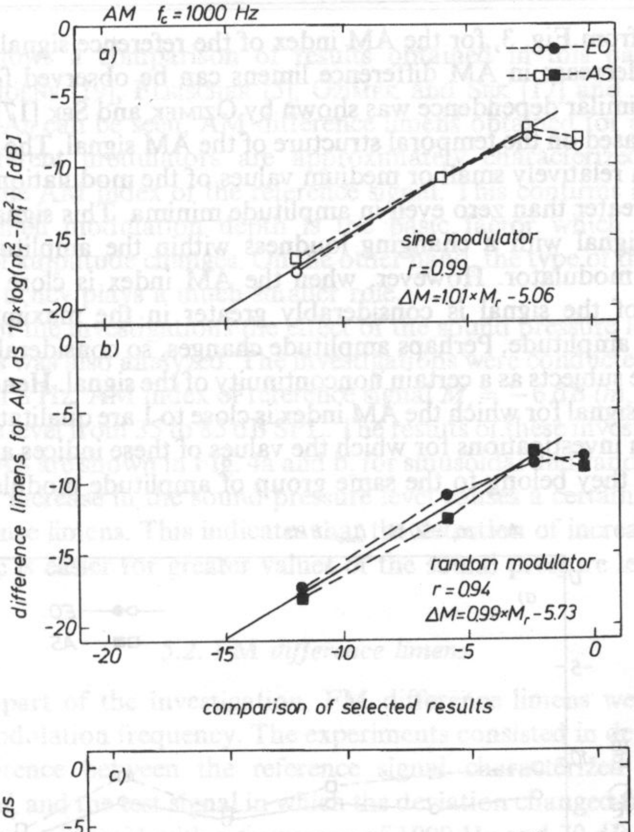

Fig. 3. Dependence of AM difference limens on the AM index of the reference signal for a sinusoidal (a) and random (b) modulator. Solid lines denote the best linear aproximation, c — comparison of averaged results with literature data.

—□— this paper	$r = 0.95$ $\Delta M = 0.83 * M_r - 3.41$
$r = 0.99$ $\Delta M = 1.0 * M_r - 5.84$	---▽--- Fleischer [5]
···○··· Ozimek & Sęk [17]	$r = 0.98$ $\Delta M = 0.99 * M_r - 5.88$
$r = 0.99$ $\Delta M = 1.04 * M_r - 4.6$	---◇--- Wakefield & Viemeister [24]
···△··· Schoene [19]	$r = 0.95$ $\Delta M = 0.9 * M_r - 5.70$

As follows from Fig. 3, for the AM index of the reference signal M_r greater than -2.5 dB, the decrease in AM difference limens can be observed for both types of modulator. A similar dependence was shown by OZIMEK and SĘK [17]. They also tried to interpret it based on the temporal structure of the AM signal. The amplitude of the AM signal with relatively small or medium values of the modulation depth is always substantially greater than zero even in amplitude minima. This signal is perceived as a continuous signal with a changing loudness within the amplitude maxima and minima of the modulator. However, when the AM index is close to 1, the sound pressure level of the signal is considerably greater in the maximum than in the minimum of its amplitude. Perhaps amplitude changes, so considerably different, are perceived by the subjects as a certain noncontinuity of the signal. Hence investigations of a modulated signal for which the AM index is close to 1 are qualitatively different in perception from investigations for which the values of these indices are small, in spite of the fact that they belong to the same group of amplitude modulated signals.

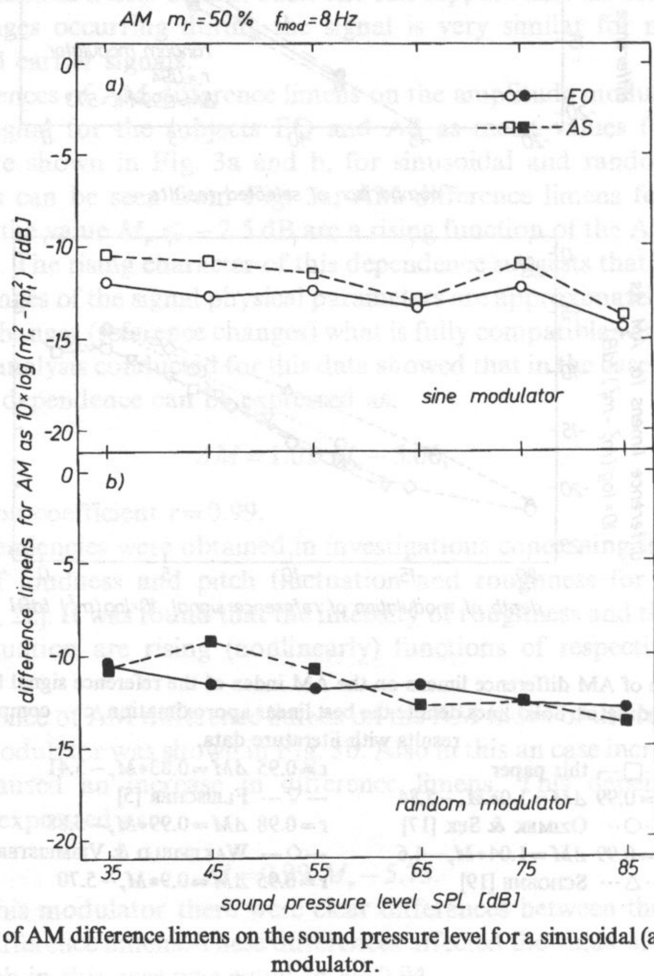

Fig. 4. Dependence of AM difference limens on the sound pressure level for a sinusoidal (a) and a random (b) modulator.

Figure 3c shows a comparison of results obtained in this paper with those obtained by SCHOENE [19], FLEISCHER [5], OZIMEK and SĘK [17] and WAKEFIELD and VIEMEISTER [24]. As can be seen, AM difference limens obtained for different carrier signals and different modulators are approximately characterized by the same dependence on the AM index of the reference signal. This confirms an earlier thesis according to which modulation depth is the basic factor which determines the discrimination of amplitude changes. On the other hand, the type of the modulator or modulation frequency plays a much smaller role.

In this part of the investigations the effect of the sound pressure level on the AM difference limens was also analyzed. The investigations were conducted for a modulation frequency of 8 Hz, AM index of reference signal $M_r = -6$ dB ($m_r = 50\%$) and for a sound pressure level from 35 to 85 dB SPL. The results of these investigations for the subject EO and AS are shown in Fig. 4a and b, for sinusoidal and random modulators respectively. An increase in the sound pressure level causes a certain decrease in the values of difference limens. This indicates that the detection of increasing changes in signal amplitude is easier for greater values of the sound pressure level.

5.2. FM *difference limens*

In the next part of the investigation, FM difference limens were measured as a function of modulation frequency. The experiments consisted in determining a just noticeable difference between the reference signal characterized by a constant deviation value d_r and the test signal in which the deviation changed from 0 to d_r. The carrier signal was a sinusoid with a frequency of 1000 Hz and 70 dB SPL. First, FM difference limens for a sinusoidal modulator were determined. The results of this experiment were shown in Fig. 5, for the subjects EO, AS and BS respectively. The deviation of the reference signal $d_r = 6$, 12, 25 and 50 Hz is the parameter of the data. As can be seen from the above results, FM differences limens do not clearly depend on modulation frequency.

Next, FM difference limens for a random modulator were determined. The results of these investigations for the subjects EO, AS and BS were shown in Fig. 6. The deviation value of the reference signal d_r is the parameter of the data. In this case, difference limens of frequency modulation are approximately independent of modulation frequency. The data obtained for a random and periodic modulation signal were subjected to analysis of variance ANOVA with the following factors: type of modulator, modulation frequency, subject and deviation of the reference signal.

The effect of deviation of the reference signal was very significant [$F(3,86) = 164$, $p < 0.0001$]. The effect of modulation frequency was not significant [$F(3,86) = 1.88$, $p = 0.14$]. This makes possible the confirmation of an earlier idea that FM difference limens do not depend on modulating frequency in a wide range ($2 \div 128$) Hz. The interval covers the three perception ranges of modulated signals i.e., the following-up range, roughness range and the sidebands separation range. FM modulated signals in these ranges generated fairly different sensations. For this reason the thresholds for

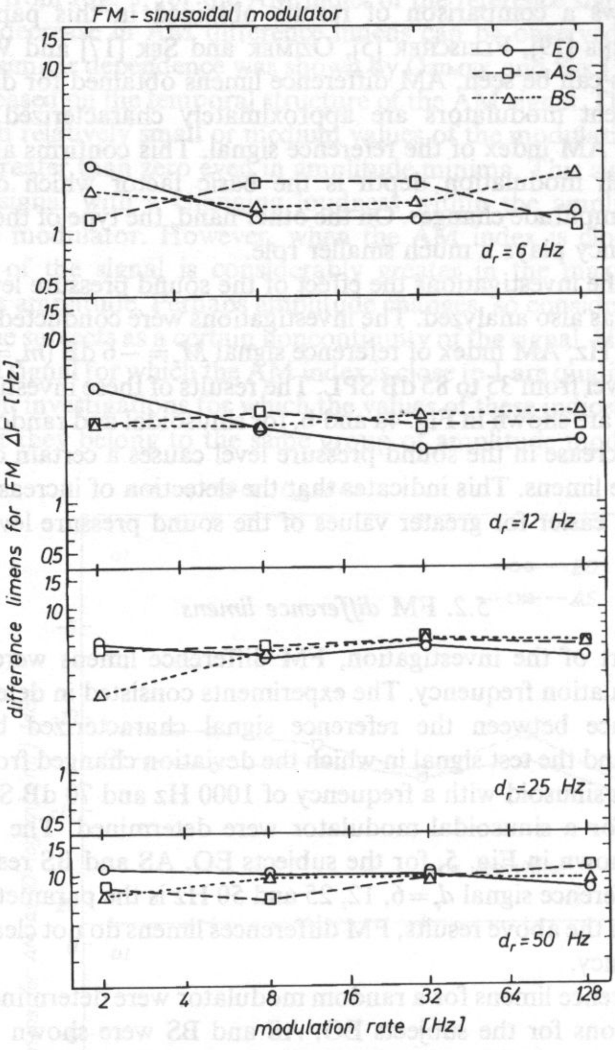

Fig. 5. Dependence of FM difference limens on modulation frequency for a sinusoidal modulator. Deviation of the reference signal is the parameter of the data.

detecting frequency modulation in these ranges are different. On the other hand, as follows from the data, FM difference limens do not depend unequivocally on modulation frequency.

The effect of the type of modulator was not significant [$F(1,86)=0.539$, $p=0.47$]. This suggests that difference limens for both a sinusoidal and random modulator reach approximately equal values. From Figs. 5 and 6 it can be seen that, for the deviation value of the reference signal $d_r = 6$ Hz difference limens have values in the range of $2 \div 2.5$ Hz. A similar situation takes place also for the reference signal deviation values $d_r = 12$ and 25 Hz. DLs of FM have in this case values of about $3 \div 5$

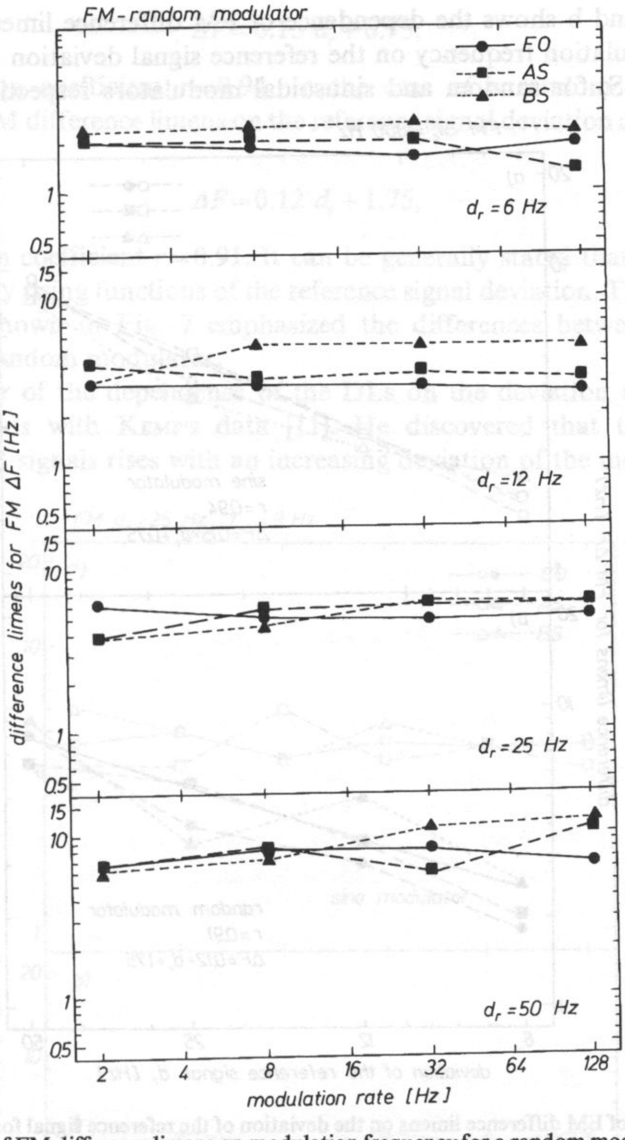

Fig. 6. Dependence of FM difference limens on modulation frequency for a random modulator. Deviation of the reference signal is the parameter of the data.

Hz for both types of modulator. In the case of the greatest value of the reference signal deviation $d_r = 50$ Hz, difference limens reach values in the range of $7 \div 9$ Hz. Thus it can be stated that the character of frequency changes (i.e. whether they are sinusoidal or random) does not significantly affect the discrimination of these changes.

The effect of the subject was not significant [F (2,86) = 1.17, $p = 0.321$]. As can be seen from Figs. 5 and 6, the difference limens of FM are scattered more than DLs of AM, particularly in the random modulator case.

Figure 7a and b shows the dependence of FM difference limens averaged with respect to modulation frequency on the reference signal deviation d_r for the subject EO, AS and BS, for random and sinusoidal modulators respectively. The results

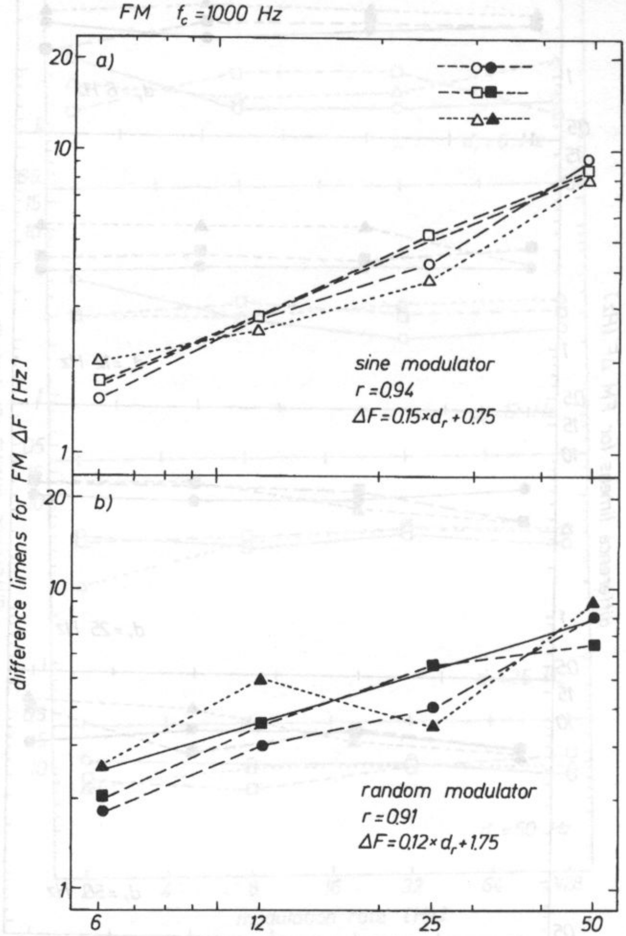

Fig. 7. Dependence of FM difference limens on the deviation of the reference signal for a sinusoidal (a) and a random (b) modulator. A solid line denotes the best linear approximation of the data in accordance with the equations next to the figures.

obtained are compatible for both types of modulator. They show that FM difference limens depend on the deviation of the reference signal. An increase in the reference signal deviation from 6 to 50 Hz causes an increase in difference limens from around 1.5 ÷ 2.5 Hz to around 7 ÷ 9 Hz. This is a linear dependence because the same increases in the reference signal deviation results similar increases in difference limens. The data were subjected to a regression analysis. In the case of the sinusoidal modulator, the dependence can be expressed as:

$$\Delta F = 0.15\, d_r + 0.75, \tag{16}$$

at the correlation coefficient $r = 0.94$. In the case of a random modulator, the dependence of FM difference limens on the reference signal deviation can be expressed as:

$$\Delta F = 0.12\, d_r + 1.75, \tag{17}$$

at the correlation coefficient $r = 0.91$. It can be generally stated that FM difference limens are linearly rising functions of the reference signal deviation. The way in which the data were shown in Fig. 7 emphasized the differences between the subjects observed for a random modulator.

The character of the dependence of the DLs on the deviation of the reference signal corresponds with KEMP'S data [11]. He discovered that the intensity of roughness of FM signals rises with an increasing deviation of the modulated signal.

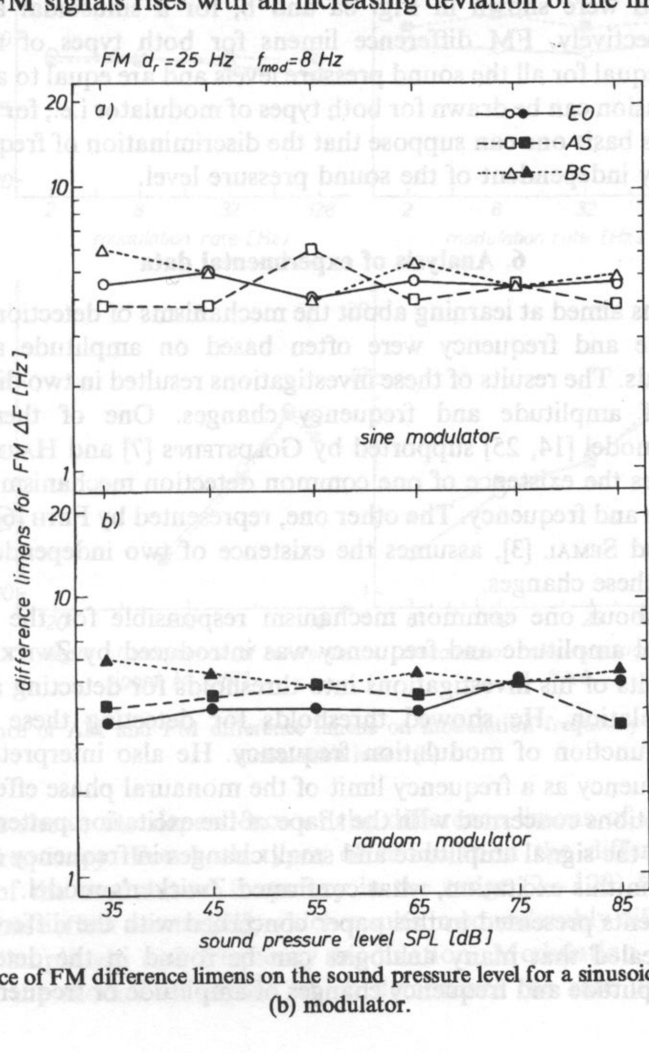

Fig. 8. Dependence of FM difference limens on the sound pressure level for a sinusoidal (a) and a random (b) modulator.

A similar dependence i.e., intensity of roughness as a function of deviation was also observed by TERHARDT [22] with respect to amplitude and frequency modulation. These data are also compatible with the results obtained by OZIMEK and SĘK [18] for a sinusoidal modulator and for a noise with uniform probability distribution.

It should be stressed that the dependence of FM difference limens is analogous to AM difference limens. This can indicates the existence of a very similar discrimination mechanisms of signal amplitude and frequency changes. A similar conclusion was drawn by TERHARDT [22] on the basis of the dependence of the roughness intensity of AM and FM signals on respective modulation indices.

At the last stage of the investigations a dependence of FM difference limens on the sound pressure level was determined. The investigations were conducted for a carrier signal with a frequency of 1000 Hz, reference signal deviation of 25 Hz and modulation frequency of 8 Hz. Then results of these investigations for the subjects EO, AS and BS were shown in Fig. 8a and b, for a sinusoidal and a random modulator respectively. FM difference limens for both types of modulator are approximately equal for all the sound pressure levels and are equal to about 4 – 5 Hz. A similar conclusion can be drawn for both types of modulator i.e., for sinusoidal and random. On this basis one can suppose that the discrimination of frequency changes is approximately independent of the sound pressure level.

6. Analysis of experimental data

Investigations aimed at learning about the mechanisms of detection of changes in signal amplitude and frequency were often based on amplitude and frequency modulated signals. The results of these investigations resulted in two different models of detection of amplitude and frequency changes. One of them, the Zwicker – Maiwald model [14, 25] supported by GOLDSTEIN'S [7] and HARTMANN'S [9, 10] findings, assumes the existence of one common detection mechanism of changes in signal amplitude and frequency. The other one, represented by FETH [6], CONINX [1, 2] and DEMANY and SEMAL [3], assumes the existence of two independent perception mechanisms of these changes.

The claim about one common mechanism responsible for the perception of changes in signal amplitude and frequency was introduced by ZWICKER [25] on the basis of the results of his investigations into thresholds for detecting amplitude and frequency modulation. He showed thresholds for detecting these two types of modulation as function of modulation frequency. He also interpreted the critical modulation frequency as a frequency limit of the monaural phase effect. MAIWALD'S [14, 15] investigations concerned with the shape of the excitation pattern showed that small changes in the signal amplitude and small changes in frequency can cause very similar changes in this excitation, what confirmed Zwicker's model.

The experiments presented in this paper concerned with the difference limens of modulation revealed that many analogies can be found in the detection of supra-threshold amplitude and frequency changes of amplitude or frequency modulated signals. These analogies suggest that the discrimination of pitch and loudness changes, which was evoked by independent physical parameters of the signal, are governed by similar principles.

Figure 9 shows these analogies schematically. On the lefthand side of the figure the difference limens of amplitude modulation are presented. On the righthand side of the figure the difference limens of frequency modulation are shown. The data in these figures are mean values for the subjects who took part in the experiments.

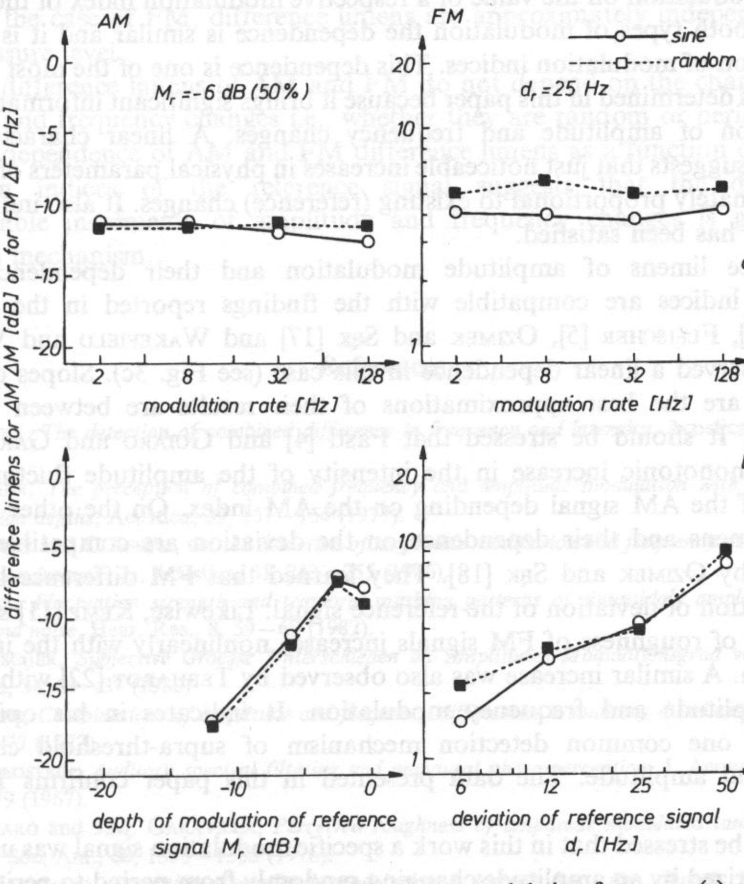

Fig. 9. Dependence of AM and FM difference limens on modulation frequency (a) and a respective modulation index (b).

Figure 9 a shows the dependence of the difference limens of AM and FM on modulation frequency. For both types of modulation the difference limens are independent of the modulation frequency in the range (2÷128) Hz. In this range a monaural phase effect occurs [21], which results in considerably different thresholds for detecting amplitude and frequency modulation. Modulation frequency is the parameter of the modulated signal which determines the rate of changes in the modulated quantity (i.e., how many times within a time unit the maximal and minimal value of the modulated quantity appears. Since the difference limens are independent of the modulation frequency, one can suppose that the rate of amplitude and frequency changes in AM and FM, respectively, does not play a significant role in the discrimination of these changes. Besides, the discrimination mechanism of amplitude changes is very similar to the discrimination mechanism of frequency changes.

Figure 9 b shows the dependence of the difference limens of amplitude and frequency modulation on the value of a respective modulation index of the reference signal. For both types of modulation the dependence is similar and it is a linearly rising function of modulation indices. This dependence is one of the most important relationships determined in this paper because it brings significant information on the discrimination of amplitude and frequency changes. A linear character of this dependence suggests that just noticeable increases in physical parameters of the signal are approximately proportional to existing (reference) changes. It also indicates that Weber's law has been satisfied.

Difference limens of amplitude modulation and their dependence on the modulation indices are compatible with the findings reported in the literature. SCHOENE [19], FLEISCHER [5], OZIMEK and SĘK [17] and WAKEFIELD and VIEMEISTER [24] also observed a linear dependence in this case (see Fig. 3c). Slopes of straight lines which are the best approximations of their results are between the range (0.83 ÷ 1.04). It should be stressed that Fastl [4] and GUIARO and GARAVILLA [8] reported a monotonic increase in the intensity of the amplitude fluctuation and roughness of the AM signal depending on the AM index. On the other hand FM difference limens and their dependence on the deviation are compatible with the data found by OZIMEK and SĘK [18]. They learned that FM difference limens are a rising function of deviation of the reference signal. Likewise, KEMP [11] stated that the intensity of roughness of FM signals increases nonlinearly with the increase of the deviation. A similar increase was also observed by TERHARDT [22] with reference to both amplitude and frequency modulation. It indicates in his opinion, the existence of one common detection mechanism of supra-threshold changes of frequency and amplitude. The data presented in this paper confirms Terhardt's conclusion.

It should be stressed that in this work a specific modulation signal was used which was characterized by an amplitude changing randomly from period to period. Hence in an amplitude modulated signal only random changes in modulation depth were observed, whereas in a frequency modulated signal only random changes of deviation were observed. Modulation frequency was constant. As follows from the investigations, the type of modulator (i.e. whether it was random or sinusoidal) did not affect FM and AM difference limens. Values similar to limens obtained for sinusoidal modulation signals were assumed. A similar conclusion can be found in SĘK's [21] paper where thresholds to detect AM and FM for the same types of modulator were determined.

7. Conclusions

The presented results lead to the following conclusions:

1. AM and FM difference limens are rising functions of respective modulation indices. This is compatible with Weber's law and means that just-noticeable changes of modulation depth or frequency deviation are approximately proportional to the existing changes in the reference.

2. AM and FM differenc limens do not depend on modulation frequency.

3. An increase in the sound pressure level causes a slight decrease in AM difference limens. In the case of FM, difference limens are approximately independent of the sound pressure level.

4. The difference limens of AM and FM do not depend on the character of the amplitude and frequency changes i.e., whether they are random or periodic.

5. The dependence of AM and FM difference limens as a function of respective modulation indices of the reference signal suggests that the detection of just-noticeable increments of amplitude and frequency changes is governed by a common mechanism.

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