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CRITICAL MODULATION FREQUENCY AND CRITICAL BAND BASED ON RANDOM AMPLITUDE AND FREQUENCY CHANGES

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The presented paper deals with determination of the critical modulation frequency (CMF) and critical bandwidth in the case of random amplitude and frequency changes in a sinusoidal signal. The critical modulation frequency is the smallest value of modulation frequency for which thresholds for detecting amplitude and frequency modulation, expressed in appropriate modulation indexes (i.e. *m* and *β*), reach the same values. Random amplitude and frequency changes of the simple tone were produced in the amplitude and frequency modulation process by random modulating signals.

The results of the investigations enable to state that the critical modulation frequency is an increasing function of the carrier frequency. It was also shown that psychoacoustically measurable quantities such as detection thresholds, the critical modulation frequency and quantities connected with it (i.e. critical bandwidth, a range of occurrence of a monaural phase effect), do not depend on a modulating signal character (i.e. whether this signal is periodic or random).

1. Introduction

The sensation of hearing caused by a multi-tone all components of which lie within one critical band considerably depends on mutual phase shifts between components of the multi-tone, Mathes and Miller [9], Fleisher [2, 3], Bunnen et al. [1], Goldstein [6], etc. If one of the components lies outside the specified critical band its initial phase does not significantly affect the sensation caused by the multi-tone. On the other hand, if all components of the multi-tone lie in the range of one critical band, the change of the initial phase of one of them causes a considerable change of the sensation. In the case when the multi-tone is listened to monaurally the mentioned effect is called the monaural phase effect (MPE). So far investigations devoted to the above problem with reference to a three-tone have had an abundant literature and the most of papers deal with the monaural phase effect for sinusoidal signals of the same sound pressure level (see f. ex. Mathes and Miller [9], Fleisher [2, 3], Bunnen et al. [1].)

Researches on the amplitude and frequency modulation (AM and FM) can be an alternative method of investigation of the effect (Zwicker [24], Goldstein [6], Schorer [21]). Spectral structures of AM and FM signals are almost identical when the frequency modulation index (β) does not exceed the value of 0.3 ($\beta<0.3$) which takes place on the FM detection threshold. The only difference between AM and FM spectrum is the phase shift of the lower sideband. This difference causes that AM and FM thresholds expressed in appropriate modulation indexes have decidedly different values for low modulatoin frequencies. They asymptotically approach each other with increasing of the modulation frequency. The exceeding of the certain characteristic value of a modulation frequency, so called the critical modulation frequency (CMF), causes that AM and FM thresholds reach identical values. ZWICKER [24] has shown that the CMF is equal to a critical band half — width connected with the carrier frequency. As long as the frequency band of the signal spectrum is no greater than the critical bandwidth (or as long as modulation frequency is less than the critical value) the sidebands' initial phase plays an important role in evaluation of modulated signals CMF. In other words, the CMF is a threshold for detecting phase changes in the modulation frequency domain, ZWICKER [24].

Literature devoted to the CMF has been very scarce so far and most of investigations have been carried out for periodic amplitude and frequency changes. One of the first papers connected with this problem was that by ZWICKER [24] in which the author showed that the critical modulation frequency is equal to the critical band halfwidth. Zwicker's results have been confirmed by GOLDSTEIN [6] who carried out measurements of AM and QFM (quasifrequency modulation) thresholds. One of the recent papers dealing with this problem is that by SCHORER [21]. In this paper the dependence of the critical modulation frequency on the carrier frequency and on the sound pressure level of the signal was discussed. SCHORER [21] found that CMF slightly depends on the sound pressure level and achieves the local minimum for $L=50$ dB. He also stated that establishing of the width of the critical band on the basis of CMF is a very good method especially for the lowest frequencies of the carrier signal (i.e. no greater than $1-2$ kHz). SCHORER [21] has given several reasons for this:

(i) The smallest bandwidth stimulus. The whole stimulus is situated in a very restricted region (in the frequency domain) connected with one critical band and does not excite any other bands;

(ii) Results of measurements should be affected less by variation in the absolute threshold with frequency because stimulus is as narrow as possible. It is difficult to avoid it using a method based on masking;

(iii) Detection of AM and FM takes place on threshold. Thus, off-frequency listening (PATTERSON and NIMMO-SMITH [19]; O'LOUGHLIN and MOORE [16]), even if it takes place, is the smallest possible;

(iv) There are no combination tones (MOORE [10]). Thus the method is very useful for wide range of sound pressure levels of the stimuli.

Previous experiments devoted to CMF were carried out for periodic amplitude and frequency changes. In real signals periodic amplitude and frequency changes occur very seldom and they have a very short duration. Signals such as music, speech, traffic noise are characterized by approximately random changes both in amplitude and frequency domains. The random character of these changes determines the sensation evoked by an acoustic signal and, as a consequence, influences the detection of the amplitude and frequency changes.

This is the main reason that this paper is devoted to determination of the CMF based on thresholds for detecting random amplitude and frequency changes.

Random changes of these physical parameters were generated in the AM and FM processes using a special class of irregular (random) modulating signals (described wider in Section 2). The establishing of the critical modulation frequency enabled to determine the range in which the monaural phase effect occurs and to determine critical bandwidths for random amplitude and frequency changes.

The spectral and temporal structure of time-varying signals is very important for their perception. Therefore in section 3 of this paper the detailed discussion of a sinusoidal signals modulated by random signals is given.

2. Aim of investigation

The main purpose of the investigations was to determine critical modulation frequency (CMF) and critical bandwidth (CB) based on the thresholds for detecting random amplitude and frequency changes. The author aimed to determine CMF dependence on the carrier frequency and to establish whether CMF depends on a type of the modulation signal. Random changes of amplitude and frequency were obtained in AM and FM processes using the random modulating signals. Furthermore, AM and FM thresholds for a sinusoidal modulating signal (periodic changes of amplitude and frequency) were obtained in order to compare threshold values for both types of the modulating signal.

A simple tone of frequency $f_c = 0.25$, 0.5, 1, 2 and 4 kHz with the sound pressure level of 70 dB SPL was carrier signal. Selection of the modulating signal was an important element in the investigation because according to the assumption it should be a random one. A sinusoidal signal with amplitude randomly changing from period to period in the range $(0 - A_{max})$ was used. Such a signal is characterized by the constant frequency, uniform probability distribution of its amplitude and gaussian distribution of its instantaneous values. Examples of the signals used in the investigation with frequency 4 Hz and corresponding to them distributions of instantaneous values are shown in Fig. 1. For comparison sinusoidal signal and its instantaneous values distribution is also shown in this figure.

A certain factor connected with the dynamics range of amplitude changes, understood as a ratio of its maximum and minimum amplitude is of special importance among parameters describing the signal. In the investigations carried out the value of this coefficient was constant and equal to 34 dB (the quotient of maximum and minimum amplitude value was equal to 50).

For all modulation frequencies (4, 8, 16, 32, 64, 128 Hz) five different time courses of random modulating signal (called R_1, R_2, R_3, R_4, R_5) were used. It was done in

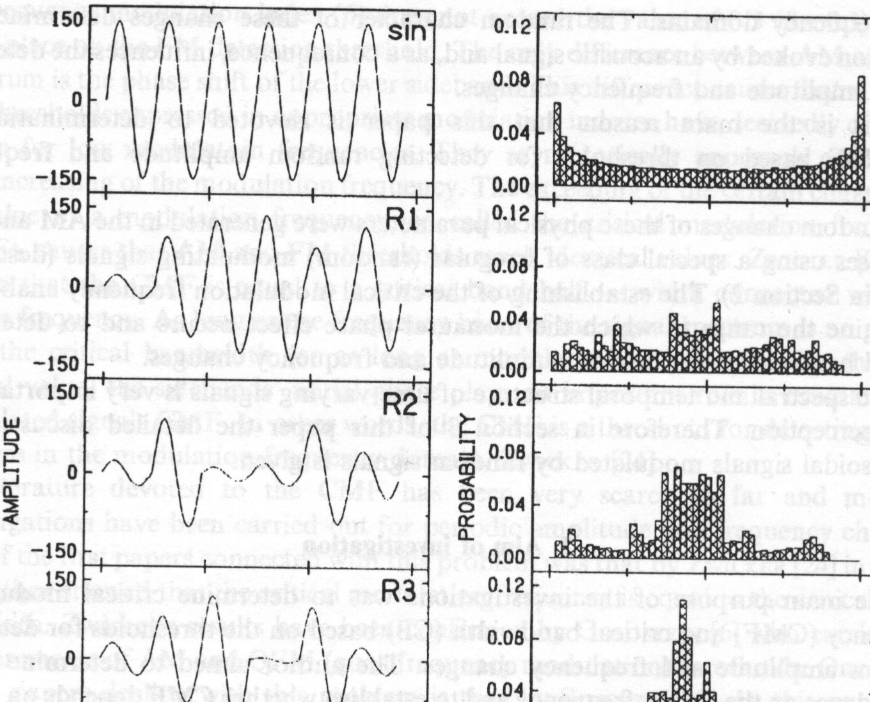

Fig. 1. Temporal structure and distribution of instantaneous values of modulating signals of frequency 4 Hz.

order to establish whether the temporal order of successive maxima and minima of amplitude or frequency changes (in the case of AM and FM, respectively) affects the observed threshold values and consequently whether this order affects the critical modulation frequency. For each value of the modulation frequency modulation signal was calculated separately.

3. Temporal and spectral structure of modulated signals

Analytical considerations aimed to determine the temporal and spectral structure of modulated signals, in the case when simple tones are both the modulating and carrier signal, are reduced to simple trigonometric transformations. Assuming that the carrier signal is of the form:

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

and the modulating signal of the form:

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

then in the case of amplitude modulation:

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

The spectrum of this signal is of the form:

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

where

$$m = \frac{kB}{A_o} \tag{5}$$

is the amplitude modulation index and k is an equipment constant.

In the case of frequency modulation the temporal form of the 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 the frequency modulation index, $\Delta\omega$ is the frequency deviation and k_1 is an equipment constant. Assuming, that $\beta \cong 1$, which is true on FM threshold, the spectrum of FM signal could be expresed as follows:

$$a_{\mathrm{FM}}(\mathrm{kt}) = -\frac{A_o \beta}{2} \cos(\omega_0 - \omega_m)\, t + A_0 \cos(\omega_0 t) + \frac{A_o \beta}{2} \cos(\omega_0 + \omega_m)\, t. \tag{8}$$

Spectra of AM and FM signals are very similar and they are consisted of discrete components, among which the central place is occupied by the component which represents the carrier signal and the remaining components are products of modulation. In the AM case, in addition to the central component, the spectrum consists of two sidebands with equal positive amplitude value, lying at a distance of $\pm\omega_m$ from the carrier frequency. In the FM case (when $\beta \ll 1$), apart from the component which represents the carrier signal, the spectrum consists of two sidebands with equal amplitudes situated symmetrically with respect to central component at separations of $\pm\omega_m$ in the frequency domain. The sideband with frequency less than the carrier is π phase shifted with respect to the other components. This is the basic difference between AM and FM signals spectrum producing the monaural phase effect which is under investigation.

Spectra determination of a simple tone amplitude or frequency modulated by a random signal, is a problem more complex than was in the case with a tone modulated by another one. If a random modulating signal is a realization of a stationary ergodic process with a normal probability distribution, an autocorrelation function can be determined for a modulated signal, (Knoch and Ekiert (1979)). Using the Wiener-Chińczyn theorem we can determine spectral density of the modulated signal power. This method for determining the spectrum of the modulated signal is troublesome since it dos not permit to obtain a direct measure of modulation intensity. Therefore, in order to determine the spectrum of a simple tone amplitude or frequency modulated by a random signal earlier considerations on modulation of the tone-tone type can be used. Assuming that the modulating signal is a sinusoidal signal with randomly varying amplitude, the amplitude and spectral structure of the modulated signal does not undergo significant changes compared with the case of the tone-tone modulation, with the restriction on that that the amplitude of the modulating signal B from expression (2) is a randomly varying quantity. This affects the values of amplitudes of sidebands of the spectrum of the modulated signal, which are subjected to random changes in accordance with the change of the amplitude of the modulating signal. Nevertheless, the spectral structure of the tonal signal modulated by a sinusoidal signal or a random signal is very similar in these cases.

In the simplest case of the tone-tone modulation, the amplitude modulation index m expressed by equation (5) or the frequency modulation index expressed by equation (7) are the measures of modulation intensity. Quantities defined in this way cannot be directly used in the case of modulation by a random signal since the amplitude of a random signal is unspecified. Therefore, in the AM case, quantity m_{RMS}, expressing the ratio of effective values of modulating and carrier signals (Knoch and Ekiert, 1979), was used as the measure of modulation intensity:

$$m_{\mathrm{RMS}} = K\sqrt{\frac{\sigma^2}{A_o^{\,2}}}. \tag{9}$$

In the FM case, on the other hand, quantity β_{RMS} expressing effective index of frequency modulation was used as the measure of modulation intensity:

$$\beta_{\mathrm{RMS}} = k_1 \sigma/\omega_m, \tag{10}$$

where σ is the effective value of a random signal.

4. Method

The two-alternative forced choice method (2AFC) with Levitt's adaptive procedure, Levitt [8] was used. The subject listened monaurally to a pair of signals in a random order. One of them was a reference signal — a simple tone without any changes and the second one a test tone i.e. it a sinusoidal — signal. The subject's task was to indicate the modulated signal. Modulation intensity (i.e. m in AM signals or β in FM signals) was increased 1.5 times each time after an incorrect answer or decreased 1.5 times after two successive correct answers. No feedback was used. This procedure tracks the point on the psychometric function corresponding to 71% correct (Levitt, 1971). A single measurement was finished after obtaining 12 turnpoints. The threshold value from a single measurement was calculated as the arithmetic mean value of the modulation index at the last eight turnpoints. The results presented in this paper are mean values of ten separate measurements. Four subjects with an audiologically normal hearing took part in the investigations.

The signals were generated by a computer through a 12-bit digital-to-analog converter. The duration of each signal was 1500 ms, including rise and decay times equal to 100 ms each. A time interval between signals in a pair was 400 ms. During the listening sessions subjects were in an acoustically isolated chamber and they gave answers using the special keyboard.

5. Results of experimental investigations and their analysis

5.1. Thresholds of random amplitude and frequency changes

In the first part of investigations the detection thresholds of AM and FM for a sinusoidal modulating signal were determined. The solid lines in Fig. 2 show the results of experiments for four subjects AS, JT, WR and RP respectively. The investigations were carried out for a sinusoidal carrier signal with frequency $f_c = 1000$ Hz and a sound pressure level $L_c = 70$ dB.

As is shown in Fig. 2 the increase in a modulation frequency between 4 and 64 Hz causes insignificant increase in the thresholds of the amplitude modulation. For a modulation frequency higher than 64 Hz a decrease in the threshold values can be observed. This is associated with crossing of the critical modulation frequency. It is proper to add that it is a very important moment in which the transfer of spectral sidebands beyond the critical band associated with the carrier frequency takes place. Thresholds for detecting AM obtained in this paper are in the good agreement with those obtained by ZWICKER [24] and GOLDSTEIN [6].

Analogically, the thresholds for detecting FM for a sinusoidal modulating signal were measured. The physical parameters of the carrier signal were analogous to those of AM case. The solid lines in the right column of Fig. 2 show the results of these investigations.

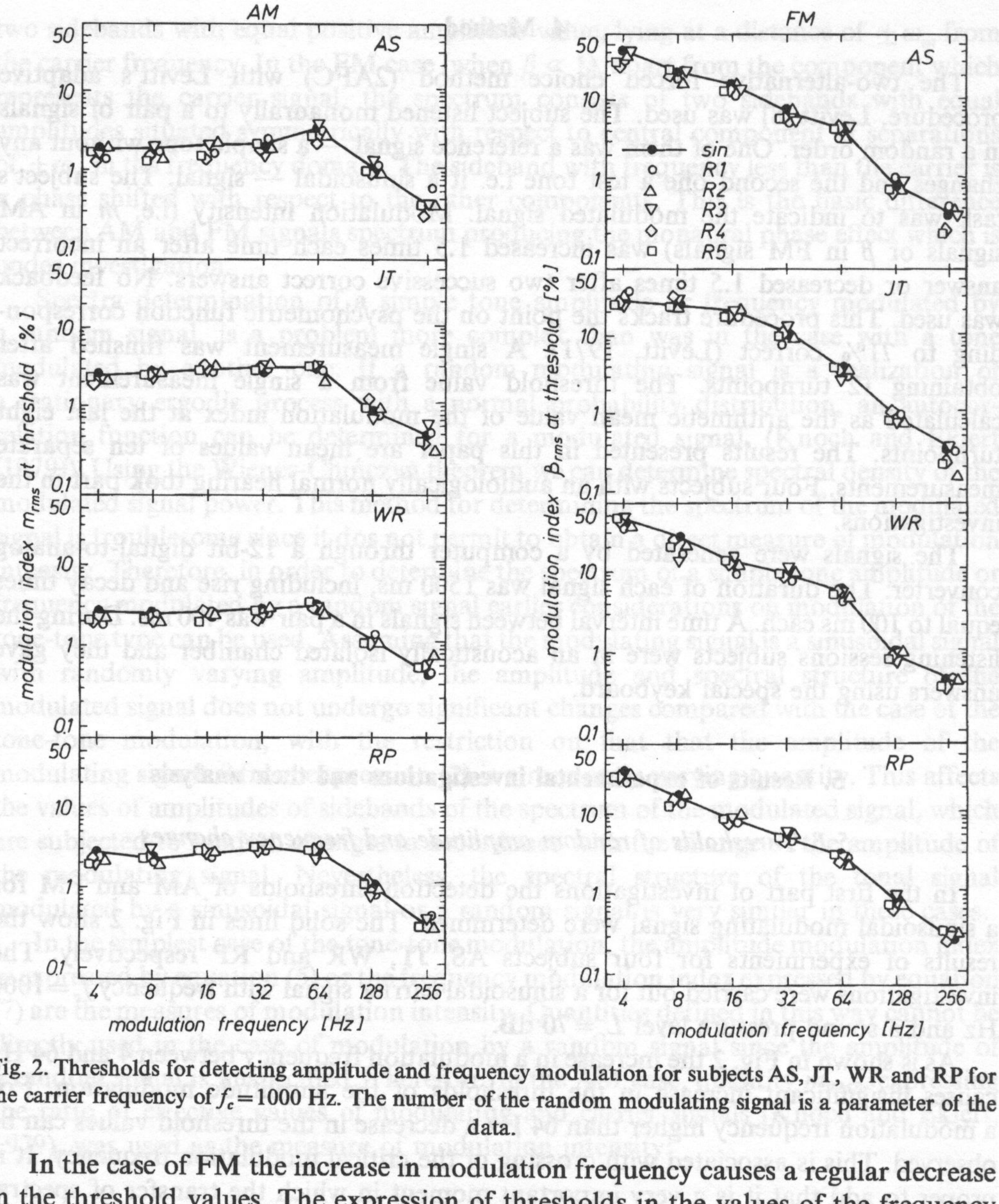

Fig. 2. Thresholds for detecting amplitude and frequency modulation for subjects AS, JT, WR and RP for the carrier frequency of $f_c = 1000$ Hz. The number of the random modulating signal is a parameter of the data.

In the case of FM the increase in modulation frequency causes a regular decrease in the threshold values. The expression of thresholds in the values of the frequency modulation index does not show the existence of any characteristic point connected with the critical modulation frequency. However, this way of data presentation confirms the existence of the nonaural phase effect (it is the range of the modulation frequency where AM and FM thresholds expressed in appropriate indexes differ from each other). When the FM thresholds are expressed as a just noticeably deviation, their dependence on the modulation frequency is completely different (OZIMEK and SĘK [17]), and is similar to those of AM thresholds versus the modulation frequency.

The local maximum which can be seen for the effect described above is connected with the critical modulation frequency (CMF).

The results described in this paper are in agreement for all listeners participating in the experiments. They are also in agreement with results obtained by ZWICKER [24] and GOLDSTEIN [6].

In the main part of the investigation the thresholds for detecting random amplitude and frequency changes of a simple tone were measured. The investigations were carried out for five different realizations of a random modulating signal (see Fig. 1) and their results are shown in Fig. 2. The thresholds for detecting random amplitude changes and random frequency changes versus the modulation frequency are shown in the left and right column of Fig. 2 respectively. The number of the random modulating signal is a parameter of the data. According to the discussion enclosed in Section 3, AM and FM thresholds are expressed in the root mean square values of appropriate modulation indexes i.e. β_{RMS} and m_{RMS}.

The data in Fig. 2 reveal that the thresholds for detecting random amplitude and frequency changes are similar to analogous thresholds for detecting periodic changes of physical parameters of the signal. Furthermore, AM and FM thresholds obtained for all modulating signals used are similar. This means that the number of the random modulating signal does not affect significantly the threshold values. This statement was confirmed by a result of a analysis of variance, that was conducted to this data. There was no significant difference between thresholds for detecting either AM or FM that was obtained for different modulation random signals ($R_1..R_5$). It is worth to point out that this agreement suggests that the thresholds are independent of the temporal structure of the modulated signals. In other words, the temporal order of successively occurring changes of amplitude or frequency does not play an important role in the processes of changes detection. The appropriate modulation index i.e. the amplitude modulation index m in the AM case or the frequency modulation index β in the FM case is the factor which determines detection of any changes.

In the second part of the analysis of variance a comparison between the thresholds obtained for periodic and random changes was made. Taking into account the agreement of the thresholds for detecting either AM or FM for all random modulating signals, the mean values of these thresholds were calculated across the modulators $R_1...R_5$. These mean values were compared with analogous thresholds of the periodic changes. Based on results of this analysis it can be stated that there is no significant difference between thresholds for detecting periodic and random amplitude and frequency changes.

It is worth to point out that the agreement of the threshold values of random and periodic changes was stated for both amplitude and frequency changes. It allows to assume that the thresholds for detecting amplitude and frequency changes produced in the appropriate modulation process (i.e. AM or FM) are independent of the character of the modulating signal. The thresholds expressed in a root mean square values of the appropriate modulation indexes are in agreement for these modulating signals independently of the type of modulating signal.

5.2. The critical modulation frequency

The thresholds for detecting AM and FM were a starting point for calculating CMF. The critical modulation frequency is a characteristic value of the modulation frequency for which the detection thresholds of AM and FM expressed in appropriate modulation indexes (i.e. m and β) reach the same values. In other words, the ratio β/m reach value equal to 1 in a point called CMF.

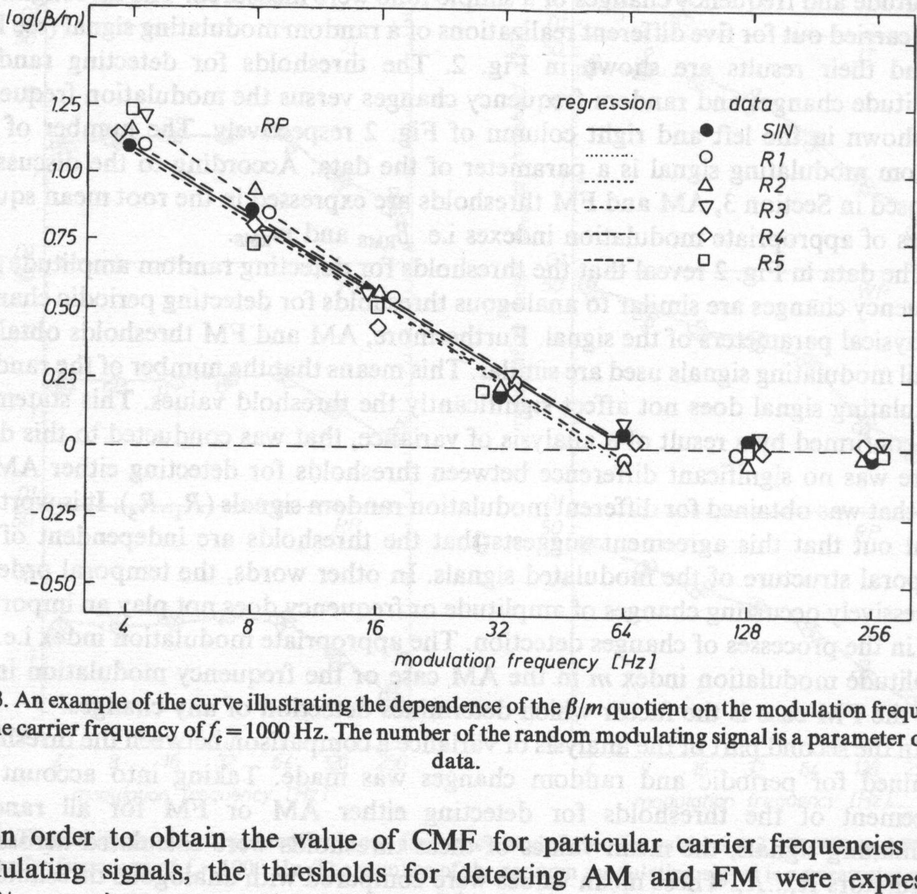

Fig. 3. An example of the curve illustrating the dependence of the β/m quotient on the modulation frequency for the carrier frequency of $f_c = 1000$ Hz. The number of the random modulating signal is a parameter of the data.

In order to obtain the value of CMF for particular carrier frequencies and modulating signals, the thresholds for detecting AM and FM were expressed as β/m quotients versus the modulation frequency. Figure 3 shows an example of the curve obtained for subject RP, for the carrier frequency of $f_c = 1$ kHz. The quotients expressed in logarithmic units are linearly correlated with the modulation frequency, but only in the case when $\beta/m \leqslant 1$. The data satisfying this condition were subjected to a linear regression analysis. As a result of this analysis two coefficients describing the straight line, which was the best approximation of experimental results, were obtained. The values of these coefficients were used for calculation of a value of CMF.

Having the evident form of the function which was the best approximation of the experimental data the values of CMF for both sinusoidal and random modulating signals were calculated. The CMF values obtained for the same carrier frequency differed from each other for different random modulating signals. This was the reason for which these values of CMF were subjected to an analysis of variance. The main aim of this analysis was to check up whether the CMF values obtained for five different modulating signals do not differ significantly. As the result of this analysis it can be stated that the random modulating signal (from the set of $R_1 ... R_5$) did not significantly influence obtained values of CMF. On this basis one can be stated that the temporal structure of the modulating signal amplitude changes, which determines the temporal order of both amplitude and frequency changes (in the case of AM or FM respectively) does not significantly affect the CMF value. This fact allowed to

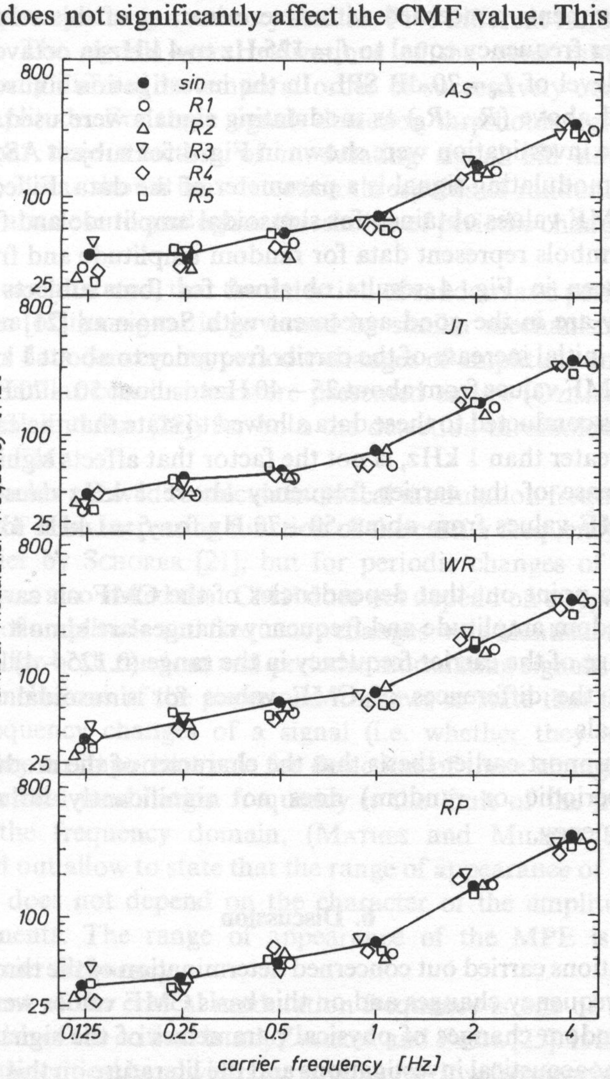

Fig. 4. The dependence of the critical modulation frequency on the carrier frequency for subjects AS, JT, WR, RP respectively. The number of the random modulating signal is a parameter of the data.

average the CMF values obtained for random modulating signals $R_1...R_5$ and to make a comparison between the mean value and the CMF value for the sinusoidal modulating signal. As a result of this analysis it can be stated that CMF obtained for periodic and random modulating signals do not differ significantly.

This conclusion enables to state that the character of amplitude and frequency changes of the sinusoidal signal (i.e. whether the changes are periodic or random) does not significantly affect the CMF.

One of the most important relation that was attempted to determine in the investigation was the dependence of the critical modulation frequency on the carrier frequency. Experiments concerned with determination of this relation were carried out for the carrier frequency equal to $f_c=125$ Hz to 4 kHz in octave steps and for the sound pressure level of $L_c=70$ dB SPL. In the investigation sinusoidal and random signals described above ($R_1...R_5$) as modulating signals were used.

Results of the investigation were shown in Fig. 4 for subject AS, JT, WR and RP. The type of the modulating signal is a parameter of the data. Filled circles and solid line represent CMF values obtained for sinusoidal amplitude and frequency changes whereas open symbols represent data for random amplitude and frequency changes.

As can be seen in Fig. 4 results obtained for four subjects are in the good agreement. They are in the good agreement with SCHORER'S [21] and ZWICKER'S [24] results, too. The initial increase of the carrier frequency to about 1 kHz causes a slight increase of the CMF values from about 25–40 Hz to about 50–70 Hz. The analysis of variance that was conducted to these data allowed to state that the carrier frequency, if its value is no greater than 1 kHz, is not the factor that affects significantly the CMF values. An increase of the carrier frequency above 1 kHz causes a considerable increase, the CMF values from about 50–70 Hz for $f_c=1$ kHz to 250–400 Hz for $f_c=4$ kHz.

It is worth to point out that dependencies of the CMF on carrier frequency for periodic and random amplitude and frequency changes are almost identical. Thus, it seems, that change of the carrier frequency in the range (0.125–4) kHz did not affect considerably on the differences of CMF values for sinusoidal and five random modulation signals.

These facts support earlier thesis that the character of the modulating signal (i.e. whether it is periodic or random) does not significantly influence the critical modulating frequency.

6. Discussion

The investigations carried out concerned determination of the thresholds of random amplitude and frequency changes and on this basis CMF values were calculated. The perception of random changes of physical parameters of the signals is rather a new problem in psychoacoustical investigations and the literature on this problem is scarce. Random amplitude and frequency changes are dominating in the real signals. Periodic changes of these parameters appear very seldom and their duration is very short.

Results of the experimental investigations performed in the paper were obtained for the selected class of the random modulating signals. They were characterized by constant frequency and randomly changing amplitude from period to period. Thus, in the modulated signals the modulation frequency was constant but quantities connected with intensity of modulation were randomly changed (i.e. m in the AM case and β in the FM case).

Detection thresholds of AM and FM as a function of basic parameters of carrier and modulating signals were determined in the first part of the paper. The results of investigation allowed to state that detection thresholds for both random and periodic amplitude and frequency changes are very similar. Five different random modulating signals were used. The signals were realizations of the same random (gaussian) process and they only differed in temporal order of successively occurring maxima and minima of amplitude. For these signals detection thresholds were almost equal. Thus, it seems that time structure of modulating signal did not influence the threshold. Besides, it was shown that detection thresholds of random amplitude and frequency changes are close to analogous thresholds of periodic changes of amplitude and frequency.

On this basis it can be stated, that the detection of random and periodic changes of physical parameters of the signal is governed by similar mechanisms. It allows to generalize literature data concerning periodic changes of amplitude and frequency on random changes. Similar conclusions were presented earlier (OZIMEK and SĘK [18], SĘK and OZIMEK [23], and SĘK [22]) for both the detection thresholds and difference limens of AM and FM.

Obtained thresholds allowed to calculate critical modulation frequency (CMF). It was stated that CMF is an increasing function of the carrier frequency. Such relation was observed earlier by SCHORER [21], but for periodic changes of amplitude and frequency only. It was also stated that CMF does not depend on a type of modulating signal. Thresholds of amplitude and frequency changes were identical to one standard deviation accuracy for both random and periodic modulating signals. It is one of the most important conclusions of the paper and it allows to state that the character of amplitude and frequency changes of a signal (i.e. whether they are periodic or random) do not play an important role for detection of these changes.

However the critical modulation frequency is the limit of the monaural phase effect (MPE) in the frequency domain, (MATHES and MILLER [9]). Results of experiments carried out allow to state that the range of appearance of the MPE in the frequency domain does not depend on the character of the amplitude changes of multi-tone components. The range of appearance of the MPE is an increasing function of the carrier frequency.

The measurement of the critical modulation frequency is one of the methods of determining the width of the critical band, ZWICKER and FASTL [25]. It is a very suitable tool for estimating the critical bandwidth in particular at low frequencies not exceeding 2 kHz SCHORER [21], ZWICKER and FASTL [25]. Thus, on the basis of the CMF values, the widths of the critical band for all carrier frequencies were calculated. Figure 5

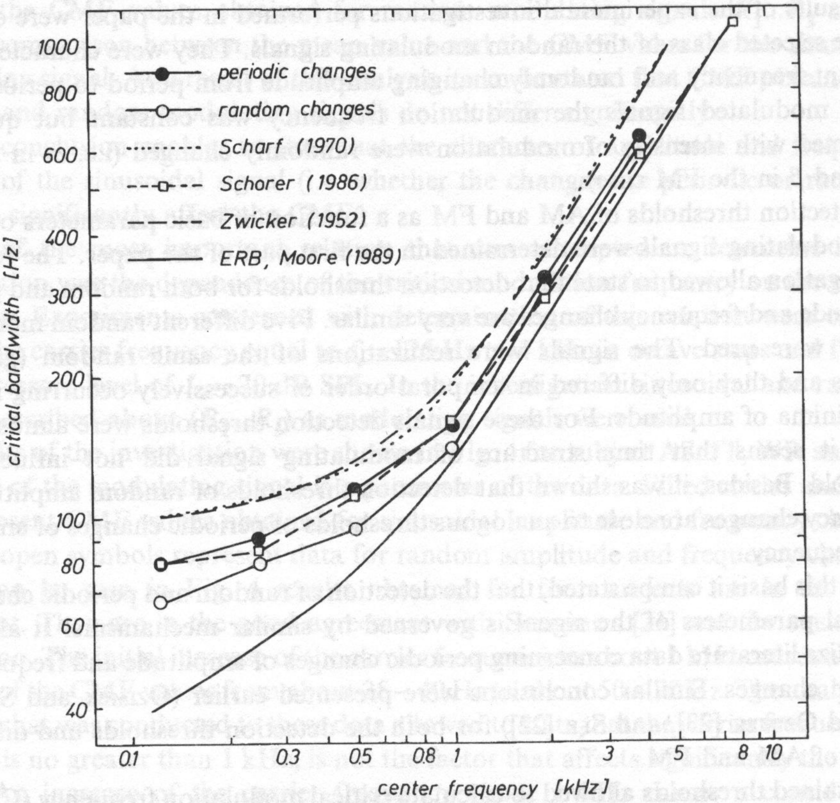

Fig. 5. The comparison between critical bandwidth obtained on the basis of the CMF values calculated for periodic and random amplitude and frequency changes and data presented in literature.

summarizes results for the periodic modulating signal (averaged for four subjects) and for random modulating signals (averaged for signals $R_1 \dots R_5$ and for subjects). Results obtained by ZWICKER [24], SCHARF [20] and SCHORER [21] are also shown in Fig. 5.

This comparison of selected literature data with results included in the paper allows to state that the critical bandwidths obtained in the experiments are fully compatible with SCHORER'S [21] results, because in both paper the same method was used. As can be seen results of critical bandwidths presented are slightly smaller than results of ZWICKER and FASTL [25] and SCHARF [20] especially for carrier frequencies smaller than 1 kHz. Results obtained by ZWICKER and FASTL [25] and SCHARF [20] are mean values calculated on the basis of several methods of determining the critical bandwidth.

The critical bandwidth is a very important element of the several models of the perception of acoustic signals, (MAIWALD [15], GOLDSTEIN [6], FLORENTINE and BUUS [4]). It is usually identified as the width of the auditory filter. An alternative attempt to those models is the MOORE and GLASBERG [11] model. An essential element of this model is auditory filter whose equivalent rectangular bandwidth (ERB) can be calculated based on the formula described by MOORE and GLASBERG [11]. In Fig. 5 the ERB values were also shown as a function of their center frequency. As can be seen for the lowest frequency the ERB is almost by a factor of 2 smaller than the critical bandwidth calculated based on the values of the critical modulation frequency obtained in the paper.

It is worth to point out that using random modulating signal did not influence considerably the critical bandwidth. Similar statement can be found in SĘK and OZIMEK's [23] and SĘK's [22] papers concerned with thresholds for detecting AM and difference limens of modulation. The base measurable quantities such as detection thresholds of amplitude changes (SĘK [22]), detection thresholds of frequency changes (OZIMEK and SĘK [17]), difference limens of AM and FM (SĘK and OZIMEK [23]) do not depend on the character of the modulating signal (i.e. whether it is random or periodic). The above conclusions enable to confirm earlier thesis that the kind of the signal physical parameter changes does not significantly influence the perception of acoustic signals. Thresholds, difference limens, critical modulation frequency and quantities connected with CMF do not depend on the character of amplitude and frequency changes.

7. Conclusions

The results of the investigations enable the formulation of the following conclusions:

1. Threshold for detecting random amplitude and frequency changes are very similar to the analogous thresholds of periodic changes.

2. The critical modulation frequency (CMF) is an increasing function of the carrier frequency.

3. Psychoacoustically measurable quantities such as the detection thresholds, difference limens of modulation, the critical modualtion frequency and quantities connected with it (i.e. the critical bandwidth, the range of occurrence of the monaural phase effect) do not depend on the character of the modulating signal i.e. whether it is periodic or random.

4. The detection of both random and periodic changes of the signal amplitude and frequency is governed by a very similar mechanisms.

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