Modulation thresholds and critical modulation frequency based on random amplitude and frequency changes

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This paper deals with determination of the critical modulation frequency (CMF) for random amplitude and frequency changes in a sinusoidal signal. The CMF is defined as the smallest modulation frequency for which AM and FM detection thresholds, expressed as modulation indices, reach the same values. The random amplitude and frequency changes were produced by modulators which were sinusoidal waves with randomly changing amplitude from period to period. The results indicate that the CMF is an increasing function of the carrier frequency and the sound pressure level. It is also shown that thresholds for detecting modulation, when expressed as root-mean-square modulation index, do not depend on the character of the modulating signal, *i.e.* whether this signal is periodic or random. Further, the CMF is independent of the character of the modulating signal.

Keywords: Modulation, Thresholds, Critical bands

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1. INTRODUCTION

The sensation of hearing caused by a multi-component complex, all components of which lie within one critical band, depends considerably on the relative phase of the components of the tone.¹⁻⁵⁾ If one of the components is separated from the other components by more than one critical band, its initial phase does not markedly affect the sensation caused by the complex tone. However it is possible to detect phase changes between components in a complex sound even when the components are separated by more than one critical band. This is possible because the auditory system is able to compare time patterns at the outputs of different auditory filters.^{6,7)} On the other hand, if all components of a three-tone complex lie within one critical band, a change in the initial phase of a component

of the three can cause a considerable change of the sensation. In the case when the three-tone complex is listened to monaurally, this is called a monaural phase effect (MPE). Most papers dealing with the MPE in a three-tone complex have used sinusoidal components of the same sound pressure level.^{1-8,9)}

Amplitude and frequency modulated signals can also be used to investigate the effect.^{4,8-10)} The amplitude spectra of AM and FM signals are almost identical when the frequency modulation index does not exceed 0.3 ($\beta \ll 0.3$). This condition is usually satisfied at detection threshold. In this case the only difference between the spectra of AM and FM sounds is the phase shift of the lower sideband. This difference causes the AM and FM thresholds, expressed as modulation indexes, to have decidedly different values for low modulation frequencies. The two thresholds approach each other with increasing modulation frequency. Above a certain value of the modulation frequency, called the critical modulation frequency (CMF), the AM and FM thresholds

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become identical. The value of the CMF has been reported to equal half of the critical bandwidth at the carrier frequency.^{4,9-10)} As long as the width of the signals spectrum is no greater than the critical bandwidth (or as long as the modulation frequency is less than the CMF), the components' initial phase plays an important perceptual role. Once the sidebands are resolved in the peripheral auditory system, phase plays a much smaller role.

Most investigations of the CMF have been carried out using periodic amplitude and frequency changes. One of the first papers connected with this problem was that by Zwicker,⁹⁾ in which the author showed that the critical modulation frequency is equal to half of the critical bandwidth. Zwicker's results were confirmed by Goldstein⁴⁾ who carried out measurements of AM and QFM (quasifrequency modulation) thresholds. Schorer⁸⁾ studied the dependence of the CMF on the carrier frequency and the sound pressure level of the signal. He found that the CMF depends slightly on the sound pressure level and has a minimum at 50 dB SPL. Schorer⁸⁾ argued that measuring the CMF was a good method for estimating the critical bandwidth, especially for low frequencies of the carrier signal (*i.e.* no greater than 1–2 kHz). His argument is based on the observation that the stimuli have narrower bandwidth than is the case for other methods of estimating the CB (*e.g.* based on masking), so the results should be affected less by variation in absolute threshold with frequency. However there are problems in interpreting the CMF as a measure of the CB, as will be discussed later.

In environmental signals, periodic amplitude and frequency changes occur seldom and they usually have a very short duration. Signals such as music, speech, and traffic noise are characterized by quasi-random changes both in amplitude and frequency.

This paper describes modulation thresholds for detecting random amplitude and frequency changes of sinusoidal signals and the CMFs derived from the results. Random changes of these physical parameters were generated in the AM and FM processes using a special class of irregular (random) modulating signals (described more fully in section 2).

2. STIMULI

The main aim of this study was to determine how modulation thresholds and CMFs depend on the carrier frequency and the sound pressure level and

to establish whether the CMF depends on the type of the modulating signal. Random changes of amplitude and frequency were obtained using random modulating signals. In addition 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 modulating signal.

A sinusoidal carrier of frequency $f_c = 0.125, 0.25, 0.5, 1, 2$ and 4 kHz was used. The sound pressure level was $L_e = 40, 50, 60, 70$ and 80 dB SPL.

The modulator for random modulation was a sinusoid whose amplitude was randomly changed from period to period in the range $(0 - A_{\max})$. Such a signal is characterized by a constant frequency, uniform distribution of its peak amplitude across cycles and approximately gaussian distribution of its instantaneous values. Figure 1 shows examples of modulators used in the investigation, together with distributions of their instantaneous values. For comparison, a sinusoidal waveform and its distribution of instantaneous values is also shown.

An important parameter describing the random signal is the quotient of its maximum and minimum peak amplitude in individual cycles. This was set to 50 which is equivalent to 34 dB.

Five different time courses of the random modulating signal (called R_1, R_2, R_3, R_4, R_5) were used for all modulation frequencies (4, 8, 16, 32, 64, 128 Hz). This was done in order to establish whether the temporal order of successive maxima and minima of amplitude or frequency changes (in the case of AM or FM, respectively) affects the threshold values and consequently whether this order affects CMF. In the simplest case of sinusoidal modulation, the depth coefficient of amplitude modulation, m , and the index of frequency modulation, β , are the measures of amount of modulation. These quantities cannot be directly used in the case of modulation by a random signal because of the varying amplitude value of the random modulating signal. For all modulating signals, the modulation indices were expressed as their root-mean-square (RMS) values, m_{RMS} for AM, and β_{RMS} for FM. In the rest of this paper AM and FM detection thresholds are expressed in terms of these quantities.

The signals were generated by a computer via a 12-bit digital-analog converter and low-pass filter with cut-off frequency twice the carrier frequency of the signal, and presented monaurally via a TONSIL

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Fig. 1 Temporal structures (left) and distributions of instantaneous values (right) of modulating signals with frequency 4 Hz.

SN-60 electrodynamic earphone. The duration of each signal was 1,500 ms, while the rise and decay times were equal to 100 ms. The time interval between signals in a pair was 400 ms. Subject were tested in an acoustically isolated booth and they responded using a special keyboard.

3. METHOD

A two-alternative forced-choice adaptive method was used.¹¹⁾ The subject listened to a pair of signals in a random order. One of them was a reference signal; it was a sinusoidal carrier without any modulation. The other one was amplitude or

frequency modulated. The subject's task was to identify the signal that was modulated. The modulation index (*i.e.* m_{RMS} for AM or β_{RMS} for FM) was increased by a factor of 1.5 after each incorrect answer and decreased by a factor of 1.5 after two correct answers. No feedback was used. This procedure tracks the point on the psychometric function corresponding to 71% correct.¹¹⁾ 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 audiologically normal hearing were used.

4. RESULTS AND ANALYSIS

4.1 Thresholds for Detecting Random Amplitude and Frequency Changes

The solid lines and filled circles in Fig. 2 show the results using a sinusoidal modulating signal for four subjects: AS, JT, WR and RP. The sinusoidal carrier signal had a frequency $f_c = 1,000$ Hz and a sound pressure level $L_c = 70$ dB. For AM (left column) the threshold is almost constant for modulation frequencies between 4 and 64 Hz. For a modulation frequency higher than 64 Hz the threshold values decrease. AM threshold values agree

with those obtained by Zwicker,⁹⁾ Goldstein,⁴⁾ Schorer⁸⁾ and Moore and Şek.¹²⁾

For FM (right column) increases in modulation frequency cause a progressive decrease in the threshold values. At modulation frequencies below 64 Hz, the AM and FM thresholds differ from each other confirming the existence of a monaural phase effect. The results for FM are also in agreement with results obtained by Zwicker,⁹⁾ Goldstein,⁴⁾ Schorer⁸⁾ and Moore and Şek.¹²⁾

In the main part of the investigation the detection thresholds of random amplitude and frequency changes were measured. The thresholds for detecting random amplitude changes and random frequency changes are shown by open symbols in the

Fig. 2 Thresholds for detecting amplitude and frequency modulation for subjects AS, JT, WR and RP, for a carrier frequency of 1,000 Hz and a sound pressure level of 70 dB. For the open symbols, the number of the random modulating signal is the parameter of the data. Filled circles and solid lines show thresholds for detecting sinusoidal amplitude and frequency changes (sinusoidal modulator).

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left and right columns of Fig. 2, respectively. Each symbol represents one of the random modulating signals.

The detection thresholds for random amplitude and frequency changes are similar to the analogous thresholds obtained for sinusoidal modulation. Furthermore, similar AM and FM thresholds are obtained for all of the modulating signals. Thus the exact form of the modulator has little influence on the results.

A within subject-analysis of variance was conducted with factors modulation rate and type of modulator ($R_1 \dots R_5$). The effect of modulation rate was significant for both AM and FM [AM: $F(6, 18) = 360.3$, $p < 0.001$; FM: $F(6, 18) = 398.0$, $p < 0.001$]. Modulation rate accounted for 93.6% and 98.2% of the variance in the AM and FM data respectively. The effect of type of modulator was not significant [AM: $F(4, 12) = 0.999$, $p = 0.445$; FM: $F(4, 12) = 2.81$, $p = 0.073$]. This suggests that the threshold values are independent of the detailed temporal structure of the modulating 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 modulation detection. The RMS modulation index appears to be an appropriate measure of modulation depth.

It is also worth to point out that averaged thresholds for random modulating signals and thresholds for sinusoidal modulating signals, for both AM and FM, were very close to each other.

4.2 Estimation of the Critical Modulation Frequency

To estimate the value of the CMF for each carrier frequency, sound pressure level and modulating signal, the threshold values obtained above were expressed as the ratio β/m and plotted as a function of the modulation frequency. Figure 3 shows the curve obtained for subject RP, with a carrier frequency of 1 kHz and a sound pressure level of 70 dB. The quotient β/m exhibited a linear relationship with the modulation frequency when plotted on a logarithmic scale but only for $\beta/m \geq 1$, [$20 \log(\beta/m) > 0$]. The data satisfying this condition were subjected to a linear regression analysis. As a result of this analysis, two coefficients describing the best fitting straight line were obtained. The slopes of the straight lines obtained in this way were dependent on sound pressure level. The slope varied from

Fig. 3 Examples of the dependence of the β/m quotient (expressed on a logarithmic scale) on modulation frequency for a carrier frequency of 1,000 Hz and a sound pressure level of 70 dB. For the open symbols, number of the random modulating signal is the parameter of the data. Filled circles and solid lines show thresholds for detecting sinusoidal amplitude and frequency changes.

3~3.5 dB/oct for $L_c = 40$ dB to 8.5~9.2 dB/oct for $L_c = 80$ dB.

The values of the CMF for both sinusoidal and random modulating signals were calculated as the point where the sloping line intersected the horizontal line. The CMF values obtained for the same carrier frequency and the same sound pressure level differed only slightly from each other for different realizations of the random modulating process. A within-subject analysis of variance was conducted with factors type of modulator (sine wave and random modulating signals $R_1 \dots R_5$) and carrier frequency. The effect of carrier frequency was highly significant [$F(5, 15) = 3149$, $p < 0.001$] and will be discussed in section 4.3. Carrier frequency accounted for 98.2% of the variance in the data. The effect of type of modulator was not significant [$F(5, 15) = 1.945$, $p = 0.146$]. The CMF values obtained for the random modulating signals $R_1 \dots R_5$ were averaged to allow a comparison between the mean value and the CMF value for the sinusoidal modulating signal. The CMFs obtained for sinusoidal and random modulating signals were in good agreement (e.g. 65.5 Hz for sinusoidal modulation and 59.1 Hz for the mean of $R_1 \dots R_5$, $f_c = 1$ kHz,

$L_c = 70$ dB SPL).

In conclusion, the character of the amplitude and frequency changes in a sinusoidal carrier (*i.e.* whether the changes are periodic or random) does not significantly affect the critical modulation frequency (CMF).

4.3 Dependence of the CMF on Carrier Frequency

Consider now the dependence of the CMF on the carrier frequency. To determine this dependence, the carrier frequency was varied from $f_c = 125$ Hz to 4 kHz in octave steps, for a sound pressure level $L_c = 70$ dB SPL. The sinusoidal and random signals described earlier were used as modulating signals.

Results are shown in Fig. 4 for subjects AS, JT, WR, RP,

Fig. 4 The critical modulation frequency as a function of the carrier frequency for subjects AS, JT, WR, RP for a sound pressure level of 70 dB. For the open symbols the number of the random modulating signal is the parameter of the data. Filled circles and solid lines show thresholds for detecting sinusoidal amplitude and frequency changes.

WR and RP. The type of modulating signal is the parameter. Filled circles and solid lines represent CMF values obtained for sinusoidal changes of amplitude and frequency. The results are also in good agreement with the results of Schorer⁹⁾ and Zwicker.⁹⁾ An increase of the carrier frequency from 0.125 kHz to 1 kHz causes a slight increase of the CMF values from about 25~40 Hz to about 50~70 Hz. A within-subject analysis of variance was conducted with factors of carrier frequency and type of modulator on the data for carrier frequency no greater than 1 kHz. The analysis showed significant effect of carrier frequencies on CMFs, [$F(3, 9) = 106.8, p < 0.001$]. Thus, the critical bandwidth inferred from the CMF is not constant in this range as Zwicker⁹⁾ stated. An increase of the carrier frequency above 1 kHz causes a considerable increase in the CMF values from about 50~70 Hz for $f_c = 1$ kHz to 250~400 Hz for $f_c = 4$ kHz.

The dependence of the CMF on carrier frequency for periodic and random modulation is almost identical. This supports the earlier conclusion that the character of the modulating signal (*i.e.* whether it is periodic or random) does not significantly influence the CMF.

4.4 Dependence of the CMF on Sound Pressure Level

Consider now the dependence of the CMF on the sound pressure level. This was investigated for a sinusoidal carrier signal with frequency $f_c = 1$ kHz using sound pressure levels from $L_c = 40$ dB SPL to $L_c = 80$ dB SPL, in 10 dB steps. The modulators were the same as described earlier. Results are shown in Fig. 5 for subjects AS, JT, WR and RP. The type of the modulating signal is the parameter. Filled circles connected with solid lines represent CMF values obtained for sinusoidal modulators. The other symbols show data for the random modulators $R_1 \dots R_5$. For each subject, the smallest CMF values were observed for $L_c = 40$ dB. The CMF generally increased with increasing sound pressure level but the increase was not always monotonic. A within-subject analysis of variance was conducted with factors sound pressure level and type of modulator (sine wave and random modulating signals $R_1 \dots R_5$). The effect of sound pressure level was significant [$F(4, 12) = 37.18, p < 0.001$]. Thus the sound pressure level in the range from 40 to 80 dB is an important parameter that influences

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Fig. 5 The critical modulation frequency as a function of the sound pressure level for subjects AS, JT, WR, RP, for a carrier frequency of 1,000 Hz. For the open symbols the number of the random modulating signal is the parameter of the data. Filled circles and solid lines show thresholds for detecting sinusoidal amplitude and frequency changes.

the CB values. Similar results were obtained by Schorer.⁸⁾ He tried to explain them on the basis that the best frequency selectivity of the ear occurs at moderate sound levels.^{13,14)}

The analysis of variance showed also that CMFs obtained for the different type of modulator did not differ significantly ($F(5, 15) = 1.695, p = 0.635$). This supports the conclusion that the character of the modulator does not significantly influence the CMF.

5. DISCUSSION

In the first part of the paper, thresholds for detection AM and FM as a function of basic parameters of the carrier and modulating signals were deter-

mined. The results indicate that detection thresholds for random and for sinusoidal amplitude and frequency changes are very similar when expressed as RMS modulation indices. Five different random modulating signals were used. The signals were realizations of the same random process and they differed only in the temporal order of successively occurring maximum and minimum of amplitude. The detection thresholds for these modulators were almost equal. Thus, it seems that the detailed time structure of the modulating signal did not influence the threshold.

The results suggest that the perception of random and periodic changes in frequency and amplitude is governed by similar mechanisms. Thus conclusions reached in the literature concerning periodic changes of amplitude and frequency can be generalized to random changes. Similar conclusions were reached by Ozimek and Şek,^{15,16)} Şek and Ozimek¹⁷⁾ and Şek,¹⁸⁾ for both the detection thresholds and difference limens of AM and FM.

The results show that the CMF increases with the sound pressure level. Such an effect was observed earlier,⁸⁾ but for sinusoidal changes of amplitude and frequency. It was also found that the CMF does not depend on the character of the modulating signals.

The measurement of the CMF is one of the methods of determining the width of the critical band.¹⁰⁾ On the basis of the CMF values, the widths of the critical bands for all carrier frequencies were calculated as $2 \cdot \text{CMF}$. Figure 6 summarizes the results for the sinusoidal modulating signal (averaged for four subjects) and for the random modulating signals (averaged for signals R1 ... R5 and for four subjects). The figure also shows: mean values presented by Zwicker and Fastl¹⁰⁾ and by Scharf¹⁹⁾ based on several methods of determining the critical bandwidth; Schorer's⁸⁾ critical bandwidths based on CMFs; and the ERB values of Moore²⁰⁾ determined from masking experiments.

The critical bandwidths obtained in the present experiments are fully compatible with Schorer's⁸⁾ results, which is expected because in both papers the same method was used. As can be seen the critical bandwidths obtained are slightly smaller than those of Zwicker and Fastl¹⁰⁾ and Scharf,¹⁹⁾ especially for carrier frequencies below 1 kHz.

The critical bandwidth is a very important element of several models for the perception of acoustic

Fig. 6 Comparison between critical bandwidths obtained from the CMF values and data presented in the literature.

signals.^{4,21,22)} It is usually identified as a measure of the width of the auditory filter,⁶⁾ such as its equivalent rectangular bandwidth (ERB). The value of the ERB can be calculated from the formula given by Moore and Glasberg²³⁾ or Glasberg and Moore.²⁴⁾ Their estimates are based on data from notched-noise masking experiments. In Fig. 6 the ERB values are also shown as a function of their center frequency. For the lowest center frequency the ERB is almost a factor of two smaller than the critical bandwidth calculated from the values of the CMF presented in this paper.

This discrepancy suggests either that the ERB values are incorrect or that the CMF does not provide an appropriate estimate of the critical bandwidth or auditory filter bandwidth. Zwicker⁹⁾ and Schorer⁸⁾ assumed that the CMF corresponds to the point where the overall spectral range of the signal reaches the critical bandwidth. However this may not be a correct analysis of the situation. Hartmann and Hnath,²⁵⁾ and more recently Moore and Sk,¹²⁾ have presented evidence that for high modulating frequencies detection of modulation is based on the most detectable sideband. When the carrier frequency is 1 kHz or higher, the most detectable sideband is the lower spectral component of the modulated (both AM or FM) signal. This may not be the case for carrier frequencies below 0.5 kHz,

because the absolute threshold strongly increases as the frequency decreases. For a modulated signal with carrier frequency less than 0.5 kHz, the lower sideband may be attenuated by the middle ear much more than the upper one. Thus detection of modulation for these carrier frequencies may be based on the upper sideband as well as or instead of the lower one.

Using the Moore-Glasberg model^{23,24)} the excitation pattern produced by the carrier alone and by the carrier plus the lower and upper sidebands was calculated for carrier frequencies $f_c = 125$ and 250 Hz. It was assumed that the CMF values were 40 and 45 Hz respectively (see Fig. 6) and a correction curve connected with absolute threshold was used. The changes of the excitation were bigger for the lower sideband than for the upper sideband when $f_c = 250$ Hz. For $f_c = 125$ Hz, the change of excitation was bigger for upper sideband. Thus, for $f_c = 250$ Hz detection of modulation is probably based on detection of the lower sideband as proposed by Hartmann and Hnath²⁵⁾ and Moore and Sk.¹²⁾ However, for $f_c = 125$ Hz, detection is probably based on the upper sideband of the signal only. The CMF probably corresponds to the modulation frequency at which either the lower or the upper sideband is just detectable. In this case the CMF will depend on the selectivity of the auditory filter centered close to the frequency of the most detectable sideband. Since that sideband appears to change from the lower one to the upper one as the carrier frequency decreases, the CMF is confounded as a measure of the CB. The CB at the frequency corresponding to the upper sideband is greater than CB at the frequency corresponding to the lower sideband. This can explain why the CMF decreases less with decreasing carrier frequency than the ERB.

6. CONCLUSIONS

The results lead to the following conclusions:

1. Thresholds for detecting random amplitude and frequency changes expressed as RMS modulation indices, are very similar to analogous thresholds for detecting sinusoidal changes, both in absolute values and in the way that they vary with carrier frequency and level.
2. The critical modulation frequency (CMF) is an increasing function of the carrier frequency for a fixed sound pressure level of 70 dB.
3. For a fixed carrier frequency of 1 kHz, the

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CMF increases with increases in sound pressure level from 40 to 80 dB SPL.

4. The critical modulation frequency does not depend on the character of the modulating signal (*i.e.* whether it is sinusoidal or random).

5. The CMF does not provide a direct estimate of the critical bandwidth, and may give misleading estimates of the critical bandwidth at low frequencies.

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