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DETECTION OF THE AMPLITUDE MODULATION FOR MODULATING SIGNALS CHARACTERISED BY DIFFERENT CREST FACTORS

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This study is concerned with the detection of amplitude modulation (AM) of a tonal signal for modulating signals characterised by a different crest factor and a low frequency. The purpose was to show that the root-mean-square (RMS) value of the modulating signal is not a sufficient measure of the modulation perceived by listeners. In the first experiment, using the 2AFC method with an adaptation procedure, the AM detection thresholds were determined for a 1-kHz tone modulated with 3-component harmonic complexes, the components of which had the same amplitudes. The starting phases of the complexes were chosen arbitrary to obtain the highest (2.44) and the lowest (1.89) values of the crest factor of the same root-mean-square values. The fundamental frequencies of the modulator were 1, 2 Hz and 4 Hz. The AM thresholds gathered for these modulators were characterized by a certain scatter that makes impossible the drawing of any conclusion concerning the influence of the crest factor on those thresholds.

Therefore in the second experiment psychometric functions were determined for the detection of AM using the same carrier and modulators. However, the results of this experiment did not provide unambiguous evidence for a statistically significant effect of the crest factor on the psychometric functions and the AM threshold values. Since the modulators used in the first two experiments were characterised by too small differences in the crest factor, the modulating signal in the third experiment was a harmonic complex consisting of ten pure tones of the same amplitude. The starting phases of all components were chosen so as to obtain signals characterised by the highest (4.47) and the lowest (1.58) crest factor. For these modulating signals, the probability of AM detection was found to depend significantly on the crest factor, i.e. the detection of the AM was considerably easier when a modulating waveform characterised by the highest crest factor was used.

The results of this experiment suggested that, at least for the low-frequency modulator, the description of the AM thresholds by means of the RMS values of the modulator is somehow misleading and does not express properly the abilities of the auditory system to detect low-frequency amplitude changes. It has been also suggested that for a modulating signal of a high crest factor the listeners can follow the amplitude changes over time only when the changes are slow enough, i.e. when sidebands produced by the amplitude modulation are not resolved in the auditory periphery.

1. Introduction

The detection of acoustic signal parameter changes is very often the main topic of papers concerned with psychoacoustics. So far the main dependencies relating the thresholds of amplitude changes to the most important physical parameters of the signal were determined, i.e. just noticeable changes in the amplitude and frequency, describing the absolute sensitivity of the auditory system, were measured. These studies have also proposed a model of the auditory system, the very important part of which is the so-called temporal integration (VIEMEISTER [29]). The most recent studies suggested the existence of a modulation filter bank (MFB) (DAU *et al.* [2, 3]; SĘK [20, 26]; SĘK and MOORE [25]) at higher levels of the auditory system. In these studies different carrier signals were used, i.e. pure tones of different frequency, complex signals, bands of noise (DAU *et al.* [3]) as well as broadband signals (VIEMEISTER [29]). Different types of the modulating waveform were also used, i.e. pure tones, harmonic complexes (MOORE and SĘK [12]) as well as bands of noise (SĘK [19]; SĘK and MOORE [22]; OZIMEK *et al.*, [13]). Random modulating signals were used to enable the analysis of the detection of random changes in the signal amplitude and frequency since such changes are most commonly occurring in natural signals. However, the problems of perception of random changes in the signal amplitude or the absolute sensitivity of the auditory system to those changes have not been satisfactorily resolved yet.

The above mentioned studies have concerned mainly the analysis of periodic changes in the physical parameters of the signal as the first approximation of the real changes in natural signals. However, these changes are much better approximated by random modulating signals, e.g. noise bands or envelopes of music or speech signals. Such experiments were carried out for sinusoidal carrier signals analysing random changes in the amplitude and frequency generated in the process of modulation by noise bands at different centre frequencies and bandwidths (SĘK [19]; SĘK and MOORE [22]; OZIMEK *et al.*, [13]). The thresholds of the sinusoidal amplitude (AM) or frequency (FM) changes, generated by means of a sinusoidal modulating signal, were usually expressed in terms of the amplitude of the modulating signal (MOORE and SĘK [10, 11]; SĘK and MOORE [24]), i.e. by the amplitude modulation index, m, in the AM case or by the frequency modulation index, β, (or the frequency deviation Δf) in the FM case. However, in the case of random changes in these physical parameters of the signal, generated by a random modulating signal, the AM and FM thresholds were expressed in terms of root-mean-square (RMS) values of the modulating waveform (OZIMEK and SĘK [16]; SĘK [19]; OZIMEK *et al.*, [13]).

The results presented in the above mentioned papers are consistent and suggest that the thresholds of amplitude changes do not depend on the modulation rate. They are approximately constant within a wide range of modulation rates, i.e. from the lowest modulation rate to the so-called critical modulation rate (CMR), irrespective of the choice of a measure describing the modulation depth. Moreover, the thresholds for random amplitude changes were approximately the same as those for a sinusoidal modulator (OZIMEK *et al.*, [13]) when the thresholds were expressed in terms of RMS values of the modulator. This applies for the follow-up region (very slow changes in the amplitude) as well as for the roughness area. This implies that the detection of amplitude changes in a wide range of the modulation rate was mainly related to the root-mean-square of the amplitude modulation index. In the follow-up and roughness areas, the main factor determining the detection of amplitude (or frequency) changes is the time pattern of the changes. The frequency resolution of the auditory system is too poor to resolve the components of the modulated signal if the modulation rate is below the CMR (SĘK and MOORE [21]). However, the spectral structure of the modulated signal becomes more important for modulation rates higher than the CMF (so-called sideband separation area).

For rates ranging from the roughness to the sideband separation areas, the AM thresholds were approximately the same for subjects taking part in the experiments (SĘK [18]; OZIMEK *et al.* [13]). However, for the lowest modulation rates used (usually 4 and occasionally 2 Hz) a significant scatter of the thresholds across the subjects was reported (SĘK and MOORE [24]; Ozimek *et al.* [13]; SĘK and SKRODZKA [27]). The scatter was usually interpreted as the influence of the signal duration and making the assumption that for very slow amplitude changes the subjects could use different detection cues. It was assumed that subjects could have based the detection decision on the RMS value of amplitude changes or were able to follow instantaneous changes in the amplitude (loudness or envelope) of the signal. Thus the factor of main importance could be not the RMS of the modulating waveform but its extreme values well described by a crest factor, C_f, defined as the ratio of the peak value and the RMS value of the waveform. Unfortunately, hitherto data on the detection of changes in the amplitude or frequency of the sinusoidal signal do not indicate unambiguously which of the parameters of the modulating signal determines the detection ability for very slow changes. Moreover, they have not indicated the subject's ability to detect instantaneous changes in the amplitude envelope of the signal or instantaneous changes in its frequency (in FM case).

This study is concerned with an analysis of the detection of amplitude changes (AM) of sinusoidal signals imposed by complex periodical waves of low fundamental frequency. The value of this frequency was chosen so as to ensure that the frequency of the highest component of the modulator was still within the roughness range in which the AM detection thresholds do not depend on modulation rate. The use of a harmonic complex of the same amplitude for each component allows to control the crest factor in a certain range by choosing the starting phases of each component of the complex. However, the RMS value of such a harmonic signal does not depend on the starting phase of the particular components but only on their amplitudes and the number of components. Therefore, such modulating signals are especially suitable in the analysis of the perception of slow amplitude changes of acoustic stimuli.

Apart from the RMS value or the crest factor, the ratio or the difference between the maximum amplitude and the minimum one of the signal envelope are often analysed. These statistics have been chosen for problems of discrimination of the modulated sounds (FORREST and GREEN [4]; STRICKLAND and VIEMEISTER [28]), i.e. when time intervals of the modulated signal evoke a clearly audible modulation. However, it seems that the application of those statistics for the detection of amplitude changes is not justified and therefore they have not been discussed in this paper.

The experiments reported in this paper have been carried out for a 1-kHz pure tone carrier, for which the roughness range reaches about 70 Hz (OZIMEK *et al.* [13]). In this range, the AM detection thresholds do not change significantly. Hence, it seems that if the highest component of the modulating multitone has a frequency lower than 70 Hz, the amplitude modulation produced by the modulator is perceived on the basis of time changes in the modulated signal. Moreover, taking into account the independence of the AM thresholds in the range up to 70 Hz, it seems that each component of the harmonic complex will produce the same depth of amplitude modulation perceived by the subjects. Thus none of these components will determine the detection of modulation on its own, but the only factor determining will be the resultant time pattern of the sum of all components of the complex.

2. Experiment I

2.1. The aim

The aim of the first experiment was to determine the AM thresholds for very slow amplitude changes ($f_{\rm mod} < 15$ Hz) and for complex modulating signals, i.e. 3-component complexes, characterized by different crest factors C_f. The C_f of a 3-component complex is determined by the starting phase of each component. If the starting phase is limited to integer multiples of $\pi/2$, the total number of 64 possible 3-component complexes obtained can be divided into six groups of signals of a similar time pattern and equal C_f values. For instance, for the 1-st, 2-nd and 3-rd components (of the same amplitudes) of a complex and for the starting phases of $3\pi/2, \pi$ and $3\pi/2$ respectively, C_f is equal to 1.84, while for the starting phases of $3\pi/2$, π, $\pi/2$, $C_f = 2.44$. However, these two signals are characterised by the same RMS value of 1.22 if the amplitude of each component is equal to 1. The signals of the above starting phases were used in our experiments because of the difference in the C_f values. Four-second intervals of these signals, for the component frequencies of 1, 2 and 3 Hz, are shown in Fig. 1. If the AM detection is based only on the RMS value of the amplitude envelope, then the threshold values should not depend on the starting phases of the 3-component complex. However, if the amplitude change is detected on the basis of the extreme values of the amplitude envelope, the thresholds should depend on the phase structure of the modulating signal, i.e. they should be different for different C_f values.

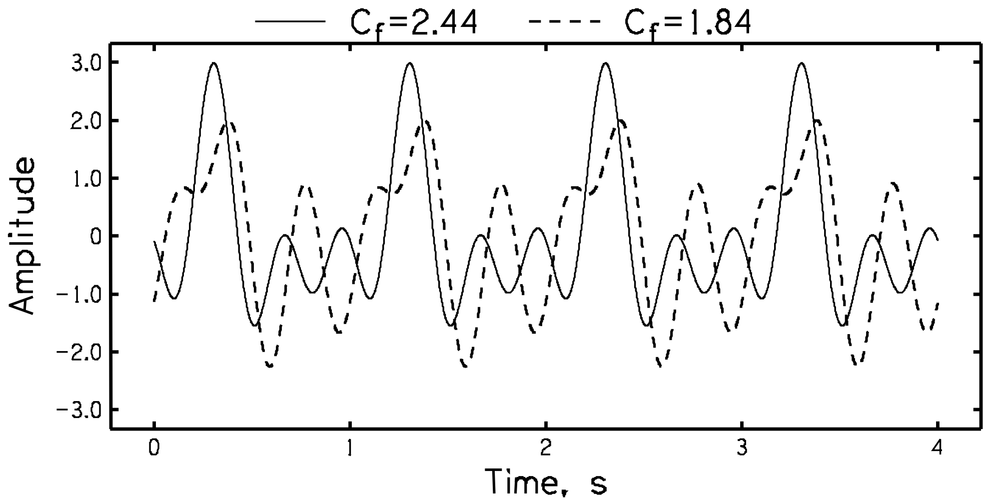

Fig. 1. Four-second courses of the 3-component harmonic complexes characterised by a high (2.44) and a low (1.89) crest factor applied in Experiment I. The components had the same amplitudes and frequencies of 1, 2, 3 Hz. The starting phases of the individual components of the high and low crest factor modulators were equal to $(3\pi/2, \pi, 3\pi/2)$ and $(3\pi/2, \pi, \pi/2)$, respectively.

2.2. The method

The two-alternative forced-choice (2AFC) method was used. The subjects were exposed to pairs of signals of the duration of 2 s each (including 20-ms rise/fall time) separated by 0.4 s silence. One of the signals was amplitude modulated by means of the 3-component complex while the other one was unmodulated. The temporal order of the signals in each pair was random. The subjects were asked to indicate the signal containing modulation. The amplitude of the modulating signal was increased after each incorrect response and decreased after two successive correct responses (LEVITT [7]). The subject was informed whether he/she gave a correct or incorrect answer. Twelve turnpoints were determined and the thresholds for AM detection were calculated as geometrical means based on the last 8 reversals. The data presented hear were calculated based on at least four separate measurements.

The modulating signals were 3-component harmonic complexes at frequencies of (0.5, 1, 1.5), (1, 2, 3), (2, 4, 6), (3, 6, 9), (4, 8, 12) and (5, 10, 15) Hz for the 1-st, 2-nd and 3-rd components, respectively. Within each 3-component complex, the amplitude of each component was the same. Two different 3-component complexes characterized by different crest factors were used. The starting phases of the complex of a high crest factor $C_f = 2.44$ were equal to $(3\pi/2, \pi, \pi/2)$, while those for the complex of a low crest factor $C_f = 1.84$ were equal to $(3\pi/2, \pi, 3\pi/2)$. The overall level of the signal was 70 dB SPL.

2.3. The subjects

The subjects were three persons with normal hearing being from 21 to 35 years old; they were paid for their services. Prior to the experiments the subjects were trained for about 5 hours. One of the subjects was the author WR.

2.4. The equipment

A Tucker-Davis Technology System II was used. The signals were generated by a 16-bit D/A converter (TDT-DD1) at a sampling rate of 50 kHz. The signals were fed to a programmable attenuator (TDT-PA4), used to adjust the same level in both intervals, and then to a headphone buffer (TDT-HB6). The signals were presented monaurally in a double-walled sound-attenuating booth through Sennheiser HD580 headphones. The subjects were asked to give their answers on a response box (TDT-RBOX).

2.5. Results of Experiment I

The AM detection thresholds obtained for the three subjects are shown in Fig. 2; filled squares refer to the modulator characterized by $C_f = 2.44$, while the opened ones to the modulator characterised by $C_f = 1.84$. The mean thresholds for all subjects are depicted in the right bottom panel. The thresholds are plotted as a function of the frequency of the middle component of the modulator (referred here as the modulation rate) and expressed in terms of 20log(m), where m denotes the amplitude modulation index connected with a single component of the 3-component complex. The AM detection thresholds are approximately independent of the modulation rate and their mean values do not change by more than 3 dB for the modulation rate ranging from 1 Hz to 10 Hz with a local minimum at the modulation rate of 6 Hz. Irrespective of a certain scatter of the threshold values across the subjects, the results do not reveal a dependence of the thresholds on the crest factor of the modulator. This fact means that for the slow-changing modulation, the subjects do not make decisions on the basis of the extreme amplitudes (loudness) available in the modulated signal, but their decisions are based on the RMS value of the signal envelope.

This conclusions have been confirmed by the analysis of variance (ANOVA) performed with the following factors: subject, crest factor and modulation rate. The factor of the subject was highly significant, $[F(2, 324) = 32.64$, $p < 0.001]$, as did the modulation rate, $[F(5, 324) = 6.04$, $p < 0.001]$. However the crest factor was not statistically significant, $[F(5, 324) = 1.45$, $p < 0.207]$. The interactions of the crest factor with the other ones analysed were not statistically significant either.

A within-subject analysis of variance, in which the results obtained for individual subjects are treated as repetitions of the same measurement, gave similar results. The modulation rate was marginally statistically significant, $[F(5, 10) = 3.43$, $p = 0.046]$, which is consistent with a small scatter of the threshold values *vs*. the modulation rate.

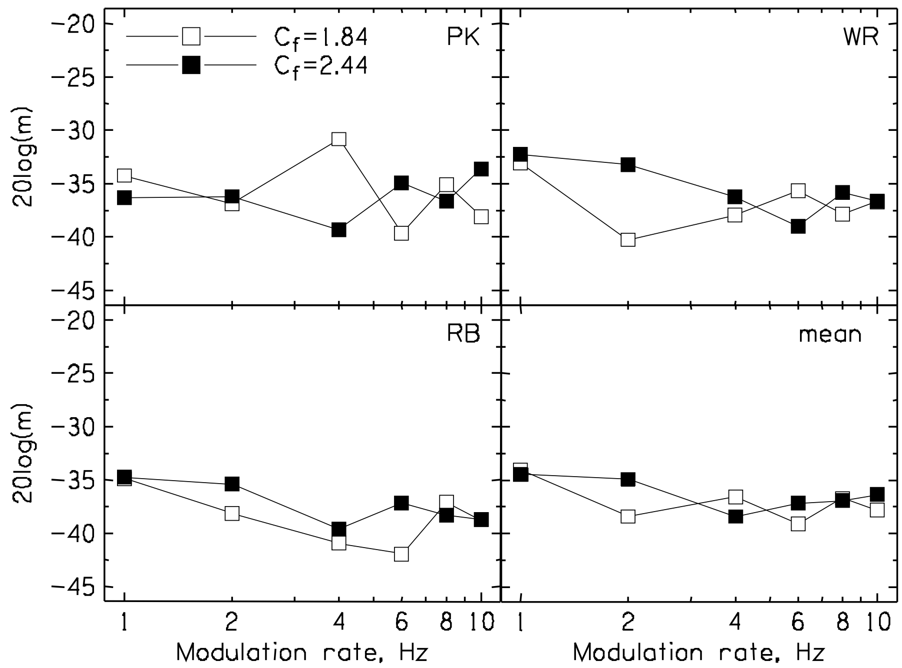

Fig. 2. The AM detection thresholds obtained for signals characterised by different crest factors as functions of the frequency of the modulator centre component. Subsequent panels show the data obtained for three subjects and the mean thresholds.

2.6. Discussion of the Experiment I results

The above-presented results indicate that the detection of the slow amplitude changes is insignificantly related to the modulation rate. From the results it is also difficult to conclude whether the crest factor of the modulator is of any significance. It seems that its role is very limited, which was confirmed also by the analysis of variance. The interpretation of the results should be performed taking into account the following three factors. The first one is the significant scatter of the threshold values for individual subjects reaching about 3 dB or more. After repetition of the measurements, the scatter remained high which means that the subjects could have made their decisions basing on different cues. If, for instance, they based their decisions on the RMS value of the modulator, the thresholds would be high. However, if they made their decision basing on the extreme values of the signal amplitude, the thresholds could be significantly lower. The results do not permit to draw any unambiguous conclusions on the cue(s) used by the subject in a given measurement. The second factor is the use of the 2AFC method, which determines the threshold for 70.9% of correct answers; this is the argument of only one point of the psychometric function. The method does not allow the presentation of the percent of correct answers as a function of the stimulus intensity (i.e. in this case, the amplitude modulation index). When the threshold values are different, the determination of the argument of a single point of the psychometric function can be connected with a substantial error. A comparison of a few values determined in this way has shown that they are equal to the accuracy of standard deviations. The third factor is the use of signals characterised by values of the crest factor ($C_f = 2.44$ and $C_f = 1.84$) that are too small. Although these values are greater than the crest factor of the sinusoidal signal or a narrowband noise used by OZIMEK *et al.* [13–15], they can still be too low to show their effect on the thresholds. This can be the reason why the data for different modulating signals (i.e. different crest factors) do not show significant differences, similarly as the data reported by OZIMEK *et al.*, [13]. The differences too small between the crest factors could also result in ambiguities in the identification of the criterion (criteria) used by the subjects making their decisions.

Since the results did not lead to unambiguous results, the detection of slow changes in the amplitude for the same modulating signals were analysed in two subsequent experiments using a different experimental method (Experiment II) and applying modulating signals of a larger crest factor (Experiment III).

3. Experiment II

3.1. The aim

The results of the first experiment did not show the effect of the crest factor of the modulating signal on the threshold for detecting AM. However, a significant scatter of the results gathered for different subjects suggests that the they could have used different detection cues. The cues include the RMS value of the signal envelope as well as extreme values of the amplitude envelope. Also the 2AFC method could play an important role because it allowed the determination of only a single point on the psychometric function. Although the 2AFC method with the LEVITT [7] procedure is a well established standard in psychophysical studies, in some cases, especially when the effects are small and measurable after many repetitions of the stimulus (MOORE and SĘK [8, 9]; SĘK and MOORE [22, 23]), the psychometric functions are measured since they express the percent of correct answers as a function of an analysed parameter of the stimulus. This method, apart from giving the threshold value, also shows changes in the probability of the signal detection in the vicinity of the threshold and has therefore been used relatively often (MOORE and SĘK [8, 9]; SĘK and MOORE [22, 23]).

At the next stage of the study, the experiment was aimed mainly at the determination of the psychometric functions for the detection of AM for a modulator composed of 3 harmonically spaced sinusoids.

3.2. The method

The psychometric functions for the amplitude modulation imposed by 3-component harmonic complexes were determined by means of the 2AFC method. The subjects were exposed to pairs of signals of 2 s duration each (including 20-ms rise/fall time). One of those signals was modulated and the other one was a sinusoidal signal; the interval between them was 0.4 s. The time order of the signals in the pairs was random, and the subjects were asked to indicate the modulated signal. Five different values of the amplitude modulation depth (m) were applied and the modulated signals with different modulation depth were presented in a random order. In the preliminary measurements, these values were determined individually for each subject, modulation rate and crest factor. The signals with the largest AM were correctly indicated in 85–95% cases, while the signals with the lowest m were indicated correctly in 55–60% cases. The signals were presented in sets of 55 pairs; only one signal in the pair was modulated. The modulated signals in the first five pairs were characterised by the largest value of the AM depth index; these signals were treated as instructive for the subjects. The subjects' responses to these first 5 pairs were discarded. The other 50 pairs of signals were presented in a random sequence. Signals characterised by each of the AM depth index tested appeared in this sequence 10 times. The psychometric functions were determined each time on the basis of at least 10 presentations, which means that each of the modulation depth was judged by each subject at least 100 times.

The modulating signals were similar to those used in Experiment I. They were 3-component harmonic complexes at the frequency of the successive components equal to (2, 4, 6) or (4, 8, 12). The amplitudes of each component within each of the 3-component complexes were the same. The starting phases of the complex characterised by $C_f = 2.44$ were equal to ($3\pi/2$, π, $\pi/2$) for the 1-st, 2-nd and 3-rd component, respectively, and those for the complex of $C_f = 1.84$ were equal to ($3\pi/2$, π, $3\pi/2$). The overall level of the signal was 70 dB SPL and the carrier frequency was 1 kHz.

3.3. The subjects

The subjects were three persons with audiologically normal hearing, aged 21–35, who were paid for their services. Prior to the experiment, the subjects were trained for about 5 hours. One of the subjects was one of the authors WR.

3.4. The equipment

The psychometric functions were measured by means of the experimental set-up described in the Experiment I.

3.5. Results of Experiment II

The probabilities obtained in the experiment were transformed into the detectability domain, d', and presented in Fig. 3 as a function of the AM index square. The left and right columns show the values of d' obtained for the modulating signals, the centre frequency of which were equal to $f_{\mathrm{mod\_c}} = 4$ or 8 Hz, respectively. The successive rows of the figure depict the results obtained for each subject. The data obtained for the modulating signal of $C_f = 1.84$, are marked as empty squares, while those for the

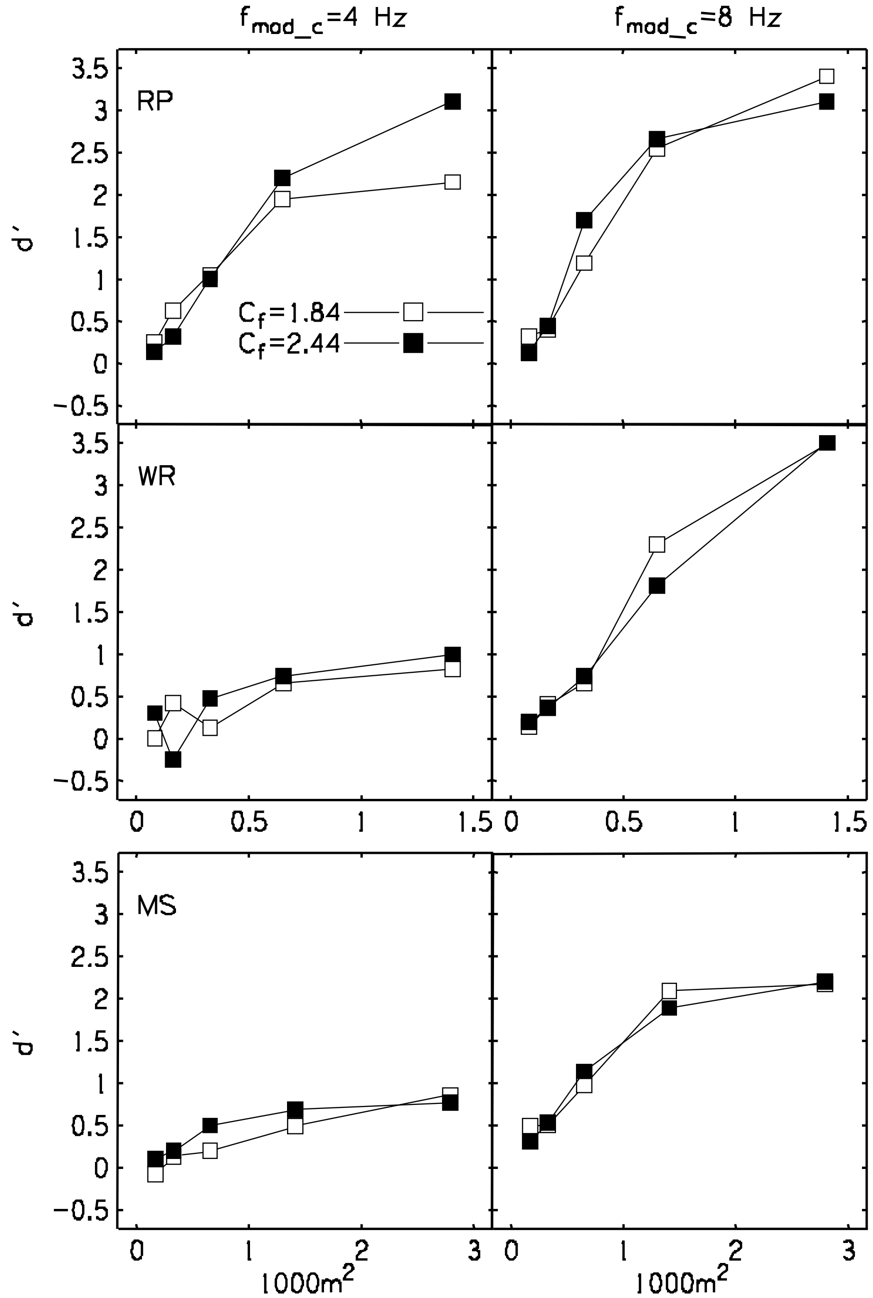

Fig. 3. Detectability d' for the AM detection as functions of the AM index square for modulating signals the centre component frequencies of which were equal to $f_{\mathrm{mod\_c}} = 4$ or 8 Hz (columns) and for three subjects (rows). The data for modulators characterised by different crest factors are presented by different symbols. The starting phases of the individual components of the high and low crest factor modulators were equal to $(3\pi/2, \pi, 3\pi/2)$ and $(3\pi/2, \pi, \pi/2)$, respectively.

signal of $C_f = 2.44$ are given by filled squares. It should be noted that the d' values for the subject MS (bottom row in Fig. 3) were obtained for values of the AM index slightly higher than those for the other two subjects. As follows from the data, the values of d' monotonically increase with the increasing in AM index. For the lowest AM depths, the detectability is proportional to the m square which has been suggested theoretically (HARTMANN and KLEIN [5]) and confirmed in several experiments (MOORE and SĘK [8, 9]; SĘK and MOORE [22, 23]). The values of d' were also found to be independent of the crest factor of the modulating signal. Nevertheless, the values of d' obtained for different modulation rates are in general different (except the subject RP).

The above conclusions were confirmed by the results of a within subject analysis of variance (ANOVA) carried out with the following factors: the crest factor of the modulating signal, the modulation rate (i.e. the frequency of the centre component of the modulating 3-component complex) and the AM index. Since different AM depths were applied for different subjects, in the analysis of the d' values obtained for the subject MS at the highest values of the AM index have not been taken into account. Instead, 4 so-called missing values, i.e. the values of d' for the lowest AM index, have been used in the analysis. These values were approximated on the basis of the four points of measurements taken into this analysis. As expected, the AM index was highly statistically significant $[F(4,7) = 18.85$, $p < 0.001]$. The monotonic increase in the d' with the increasing AM index was fully confirmed. The modulation rate was marginally statistically significant $[F(1,2) = 11.02$, $p = 0.080]$. The type of the modulating signal was not statistically insignificant either, like in Experiment I, $[F(1,2) = 1.88$, $p = 0.304]$. However, in contrast to Experiment I, the interaction between the modulation rate and the crest factor and that between the AM index and the crest factor were marginally statistically significant $[F(1,2) = 18.26$, $p = 0.051]$ and $[F(4,7) = 5.45$, $p = 0.026]$.

3.6. Discussion

As follows from the results shown in Fig. 3, the detection of the slow amplitude changes depended on the modulation rate because the detection probability (or detectability d') obtained for the modulating 3-component complexes of different spectral structure were different. However, the role of the crest factor cannot be concluded from these results. It seems that the main role in the detection of the AM of an acoustic signal plays the RMS value of the signal envelope. If the crest factor played a significant role, the thresholds obtained in Experiment I and the psychometric function slopes determined in Experiment II should differ for signals characterised by different crest factors. Thus, the results of Experiment II showed a similar tendency as those of Experiment I.

It seems that the main reason for the lack of qualitative differences was the application of 3-component complexes of a too small difference in the crest factors ($C_f = 2.44$ and $C_f = 1.84$). Although the C_f values used in the present experiments were higher than the crest factor of the sinusoidal signal or the narrow noiseband used by OZIMEK *et al.* [13], they are probably still too small to allow the observation of any effect of the crest factor on the pattern of the results.

The results of Experiments I and II have brought a partial answer to the problem this study was aimed at. For the modulating signals the crest factors of which do not differ more than by 0.6 ($C_f = 2.44$ and $C_f = 1.84$), the threshold values obtained in Experiment I and the psychometric function obtained in Experiment II do not show significant differences. Therefore we decided to carry out Experiment III to analyse the detection of slow amplitude changes by the modulating signals of significantly different crest factors.

4. Experiment III

4.1. The aim

The results of Experiments I and II did not show the subjects' ability to detect instantaneous changes in the signal envelope. They showed that when detecting the AM at a very low rate, the detection cues are related to the RMS value of the signal envelope rather than to the extreme instantaneous values in the modulator or to its crest factor. One of the possible reasons for such a result could be that modulator crest factors where not sufficiently different, i.e. the highest C_f was not high enough to reveal an effect on both the thresholds and the slopes of the psychometric functions. The differences between the maxima and minima in the amplitude of the AM signal could be too small for the auditory system to be detected as separate events. A much larger dynamic range of the signal, that is also characterised by a higher crest factor, can be obtained for a harmonic signal composed of a larger number of sinusoidal harmonically spaced components the starting phases of which are the same, e.g. zero. Therefore, we decided to carry out the third experiment in order to determine the psychometric functions for AM detection of modulating signals composed of 10 sinusoidal harmonically spaced components at a low fundamental frequency.

4.2. The method

The psychometric functions for AM detection for a sinusoidal carrier at a frequency of 1 kHz, whose amplitude was modulated by a harmonic complex, were determined by a method similar to that used in Experiment II. However, this time the modulating signals were 10-component harmonic complexes at the fundamental frequency of 1, 2 or 4 Hz (referred here as the modulation rate). Each component of the 10-component complex had the same amplitude. The starting phases of the highest crest factor modulator ($C_f = 4.47$) were equal to $3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$, $3\pi/2$ and $\pi/2$ for the 1-st, 2-nd, … and 10-th component, respectively, while for the lowest crest factor modulator ($C_f = 1.58$) the starting phases were equal to 0, $3\pi/2$, 0, $\pi/2$, π, $\pi/2$, π, $\pi/2$, 0 and $\pi/2$. Additionally, we also applied a modulating signal composed of 10 sinusoidal, harmonically spaced components at the same fundamental frequencies but with the so-called positive Schroeder phases (SCHROEDER [17]). For the n-th harmonic of the modulator composed of N components, its starting positive or negative Schroeder phase is given by the following formula:

$$S_{ph} = \pm n\pi(n + 1)/N.$$

The harmonic signals of positive and negative Schroeder phases are characterised by a very smooth time pattern and a low dynamic range. They are often used in the analysis of loudness models or in the analysis of perception of synthetic elements of speech (ALCÁNTARA *et al.*, [1]). Indeed, the use of a 10-component harmonic complex with a positive Schroeder starting phase resulted in a low value of the crest factor of the signal, i.e. $C_f = 1.89$. Examples of the three types of the modulating signals at the fundamental frequency of 4 Hz are shown in Fig. 4.

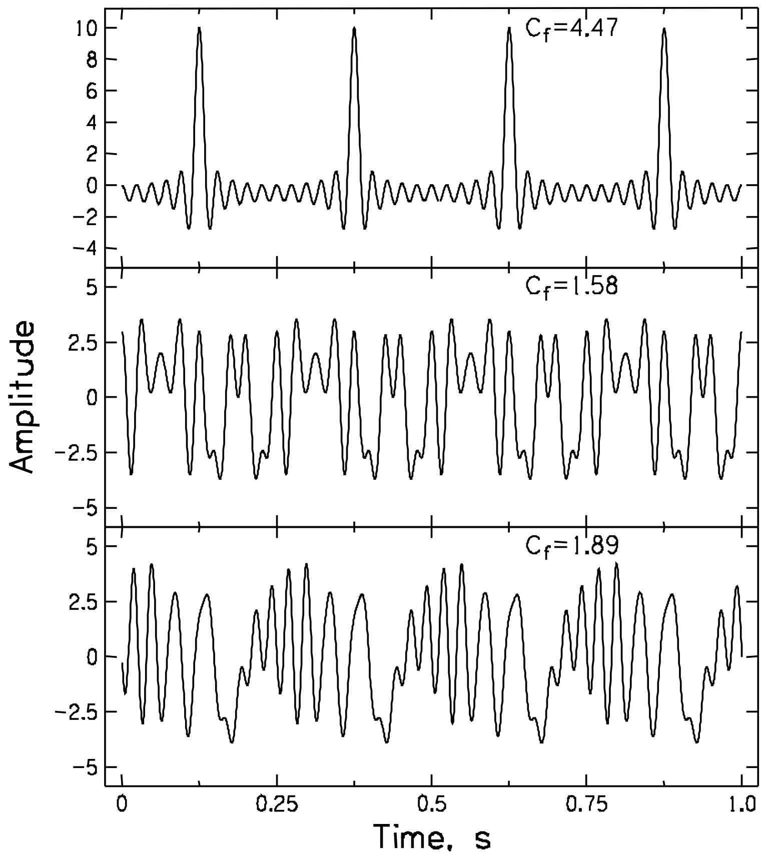

Fig. 4. The 10-component harmonic complex modulators at the fundamental frequency of 4 Hz used in Experiment III. The upper panel shows the modulator of $C_f = 4.47$; the starting phases of the subsequent components were equal to ($3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$, $3\pi/2$, $\pi/2$). The signal with $C_f = 1.58$ (middle panel) had initial phases of the subsequent components equal to (0, $3\pi/2$, 0, $\pi/2$, π, $\pi/2$, π, $\pi/2$, 0, $\pi/2$). The bottom panel shows the modulator at the fundamental frequency of 4 Hz with starting phases of the subsequent components consistent with the Schroeder's formula (SCHROEDER [17]).

Like in the earlier experiments, the carrier signal was a pure tone at a frequency of 1 kHz and its overall level was equal to 70 dB SPL.

4.3. The subjects

The subjects were three persons with audiologically normal hearing, aged 21–35, who were paid for their services. Prior to the experiment the subjects were trained for about 5 hours. One of the subjects was one of the authors WR.

4.4. The equipment

The psychometric functions for the AM detection were measured by means of the experimental set-up described in the Experiment I.

4.5. Results of Experiment III

The results of Experiment III, that is the probability of the modulation detection as a function of the AM index were transformed into the detectability domain, d', and presented in Fig. 5. The figure shows the dependence of d' on the AM index square for three modulators characterized by different crest factor, i.e. $C_f = 4.47$ (filled squares), $C_f = 1.58$ (empty squares) and $C_f = 1.89$ (empty stars – for the starting phases determined by the Schroeder's formula). The results obtained for the individual subjects are given in subsequent rows of the figure, while the columns show the data obtained for three fundamental frequencies of the modulator, i.e. 1, 2 and 4 Hz. The horizontal axis in the bottom row in Fig. 5, which shows the data for the subject AW, comprises a range of m^2 slightly different from the data for WR and MS (two upper rows).

In general, the detectability d' is a monotonically increasing function of the AM index. In a wide range of the AM index square, the dependence $d'(m^2)$ can be approximated by a linear function, which has been shown theoretically (HARTMANN and KLEIN [5]) and experimentally (MOORE and SĘK [8, 9]; SĘK and MOORE [22, 23]) as well as in our Experiment II. However, the rate of increasing of d' depends significantly on the crest factor of the modulating signal. For the positive Schroeder phase and the signal characterised by a low crest factor, the $d'(m^2)$ dependencies are similar. However, the values of d' obtained for the modulating signal characterised by the highest crest factor (4.47) increase much faster than the other ones. If we assume that the threshold value of the AM detection threshold corresponds to the detectability $d' = 1$, then the AM detection thresholds are generally lower for the signals characterized by a higher crest factor, while the thresholds are expressed in terms of the RMS of the modulated signal envelope. In other words, for harmonic complex modulators of the same amplitude of each component (i.e. of the same RMS value), the probability of AM detection is larger for the signals characterized by the highest crest factor.

This conclusion was fully confirmed by the analysis of variance (ANOVA). Because the values of d' in our experiment were obtained for different ranges of the AM indices,

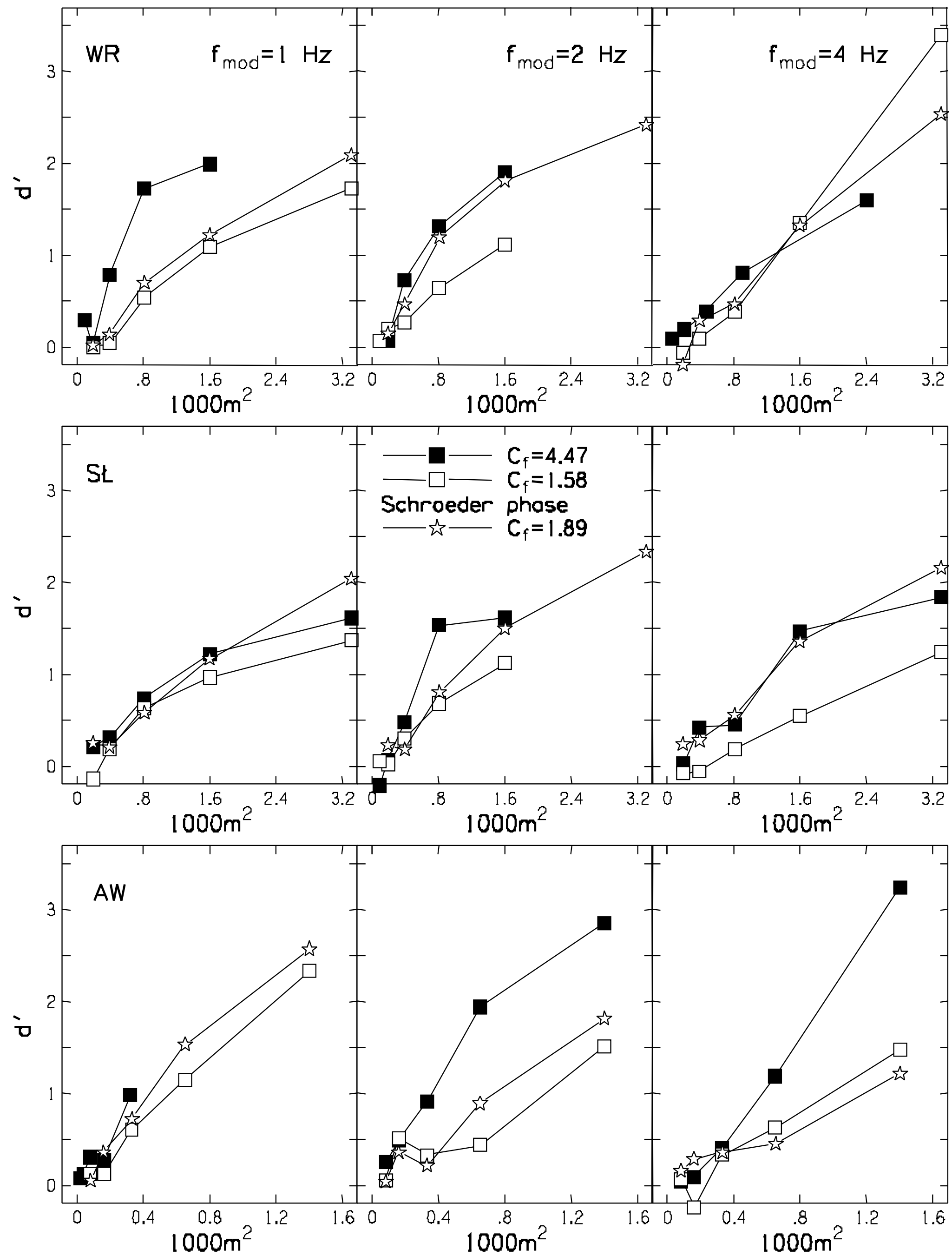

Fig. 5. Detectability d' for the AM detection obtained for 10-component harmonic complexes characterised by different crest factors as a functions of the AM index square.

their use in the ANOVA would require taking into account too many missing values that could lead to an unreliable result. Therefore, the analysis of variance was performed for the slopes of the best fitting straight lines passing through the origin of the coordinate system. They were chosen as describing best the experimental results obtained for each modulating signal, each fundamental frequency and each subject. The slopes were calculated each time on the basis of four values of d' obtained for the lowest AM indices because for these m^2 values of d' seem to be linear a function of m^2. Almost in each case the correlation coefficient was not lower than 0.94. The values of the slopes subjected to the analysis of variance (ANOVA) are given in Table 1. The effects of the modulation rate and that of the crest factor were analysed by means of the within-subject analysis of variance. The most important result of the ANOVA is the high statistical significance of the crest factor $[F(2,4) = 19.96,\ p = 0.008]$ which fully confirms the above formulated conclusion. The modulation rate and its interaction with the crest factor were not statistically significant. $[F(2,4) = 2.93,\ p = 0.165]$ and $[F(4,8) = 0.79,\ p = 0.565]$, respectively.

Table 1. Slopes of the best fitting straight lines.

Subject	Fundamental frequency, Hz	Crest factor, C_f		
		4.47	1.58	1.89
WR	1	2.040	0.645	0.757
	2	1.607	0.783	1.196
	4	1.130	0.732	0.755
MS	1	0.796	0.618	0.724
	2	1.667	0.797	0.929
	4	0.848	0.291	0.818
AW	1	2.226	1.725	2.296
	2	2.946	0.847	1.257
	4	1.646	0.866	0.835

4.6. Discussion of the results of Experiment III

The most important result of this experiment was the prove of statistically significant differences in the slopes of the psychometric functions obtained for modulating signals of different crest factors. The slopes of the best fitting straight lines were considerably different, achieving highest values for the highest crest factor modulator. This evidence allows to conclude that while detecting the AM, the subjects were able to base their decisions on the extreme values of the amplitude envelope of the stimulus. Thus, it seems that they were able to follow up instantaneous changes in the stimulus envelope. However, in such a case the crest factor must be sufficiently high. As indicated by the results of Experiments I and II, if the crest factor is equal to about 2.5, the changes in the signal amplitude are perceived in the same way as for a sinusoidal modulating signal, i.e. the thresholds are related to the RMS value of the modulator.

5. Discussion

The results of the first two experiments reported in this paper showed that the detection of the amplitude modulation of a tonal signal was independent of the type of the modulating signal. No statistically significant differences were found in the AM detection thresholds (Experiment I) and the psychometric functions (Experiment II) for different crest factors of the modulating signal. Two different experimental methods applied to measure the same thresholds brought consistent results. However, it should be emphasised that the difference between the crest factors of the modulating signals used in the Experiments I and II was small. The maximum value of the crest factor (2.44) was closer to the crest factor of the narrowband noise than to that of the broadband noise. Thus, it seems that the low difference between crest factors of the modulators applied was responsible for the insignificance of the differences in the collected data. This observation also means that describing the AM detection thresholds in terms of the RMS value of the AM index (or by means of the AC component of the amplitude envelope of the modulated signal) is fully justified and unambiguous. It is therefore difficult to stress that subjects can follow up instantaneous changes in amplitude of the AM signal.

In this context the results concerned with the perception of the random amplitude and frequency changes of the sinusoidal signal become fully understandable. The results of the studies presented by SĘK [19], SĘK and MOORE [22] and OZIMEK *at al.* [13] have shown that when the AM detection thresholds are expressed in terms of the RMS value of the AM index, they have the same values for sinusoidal and narrowband noise modulators. The narrowband noises applied as modulators in these experiments were characterised by a crest factor too low to influence significantly the threshold of random changes in the amplitude or frequency.

The results obtained in Experiment III have shown that for a modulating signal characterized by a high crest factor the subjects are able to detect instantaneous changes in the amplitude envelope of the modulated signal. It seems that the detection of AM is based on a comparison of the extreme values of the envelope. However, subjects are able to use the information conveyed by the signal envelope effectively only if the crest factor is sufficiently high, i.e. at least $C_f > 4$. As follows from the above-discussed results, for signals with the same RMS values, the subjects detected the amplitude modulation much easier for the modulating signal characterized by the highest crest factors. This conclusion is based on the fact that the slope of the psychometric functions obtained for the high-crest factor modulator was much steeper which implies a lower threshold value. Thus, it is reasonable to suppose that the subjects making their decisions were able to detect the instantaneous changes in the signal envelope and use effectively its extreme values. Moreover, it seems that while perceiving the instantaneous changes in the signal envelope, the subjects were able to compare its values at the maxima and minima and, when the difference between them reached a certain critical value, the subjects were able to detect the changes.

This conclusion is confirmed by a relatively good agreement between the results obtained in this work with the intensity discrimination thresholds. In a classical intensity discrimination experiment, the thresholds are determined by comparing two subsequent bursts of a tone of different intensities; the subject is asked to indicate the louder one. The results of such studies have shown that the just detectable decrease or increase in the intensity is a monotonic function of the intensity and reaches a value of about 2.8 dB (HOUTSMA *et al.* [6]) for a sinusoidal signal of the 70 dB SPL level and frequency of 1 kHz. For the sinusoidal carrier at a level of 70 dB SPL (as used in this study) and for the modulator characterized by $C_f = 4.47$, the maximum level reaches 72.5 dB SPL at the AM threshold, ($d' = 1$). Because the signal with the $C_f = 4.44$ applied in the study was asymmetrical (see Fig. 4), it can be assumed that its maximum corresponds to the signal level increase of 2.5 dB. This value is very close to the threshold of the intensity discrimination (HOUTSMA *et al.* [6]). Therefore, it seems that for slow amplitude changes of a sinusoidal signal and a high crest factor of these changes subjects are able to follow up instantaneous changes in the signal envelope.

6. Conclusions

The above-discussed results of our study lead to the following conclusions:

1. The detection of the amplitude modulation of a sinusoidal signal, for a harmonic complex modulator whose spectral components fell into the so-called follow-up and roughness regions, depends on the crest factor of the modulator. However, the crest factor affects the AM thresholds (or the slopes of the psychometric functions) significantly when its value is higher than 4. This can be easily achieved for a harmonic signal composed of many components.

2. The RMS value of the modulator at the AM threshold is not a sufficient and reliable information describing the threshold, at least for modulators characterized by a high crest factor. For two modulating signals of the same RMS value, the AM is detected easier (lower threshold) for the signal with a higher crest factor.

3. It seems, that when the amplitude of a tonal signal is slowly changed by a modulating signal whose crest factor is high enough (i.e. $C_f > 4$), the subjects are able to follow up the instantaneous changes in the signal envelope and effectively use extreme values of the envelope for making their decisions on the AM detection. The results obtained in this study are consistent with the data on the intensity discrimination thresholds.

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