AN INFLUENCE OF A MODULATING SIGNAL STARTING PHASE
ON THE MODULATION DETECTION

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This paper is concerned with an influence of a modulator starting phase on psychometric functions of amplitude modulation (AM) and frequency modulation (FM) detection, for low modulation rates, i.e. $f_{mod} = 2$ and 5 Hz. For a sinusoidal carrier at a frequency of 0.25, 1 and 6 kHz it is shown that there is no effect of a sinusoidal modulator starting phase. Data shown in this paper are consistent with predictions of models based on excitation pattern changes and with a concept according to which AM/FM detection at low modulation rates depends mainly on maximum and minimum values of signal amplitude/frequency. Time intervals between beginning of a signal and the moment when the signal reaches maximum/minimum value of amplitude/frequency and a pattern of physical parameter changes as a function of time seem to be less crucial when the changes are continuos in time.

1. Introduction

Measurements of just noticeable amplitude or frequency changes of an acoustic signal are a methods of determination of sensorial limits of the human auditory system. Apart from measurements of difference limens (DL), or just noticeable differences (jnds) of two tones in amplitude or frequency domain, detection thresholds of amplitude modulation (AM) and frequency modulation (FM) are determined as well. Detection of modulation is often considered in a context of excitation pattern changes [10, 27] especially in the situation when amplitude and frequency changes are so slow, that they produce noticeable temporary changes in loudness or pitch [24]. In papers concerning this problem an analysis of the auditory system based on maximum and minimum values of physical parameters of a signal is presented: it is assumed that an acoustic stimulus evokes an excitation pattern in the peripheral auditory system. Extreme levels of the excitation play a crucial role in signal changes detection. The excitation pattern reflects internal activity of the auditory system and it is conceived either as an envelope of the basilar membrane's displacement or as a number of neural spikes per second as a function of their characteristic frequency. It is also assumed that detection of changes in amplitude or frequency occurs when excitation pattern changes at any point (as in Zwicker's model [27]) or when excitation pattern changes of all active auditory filters exceeds certain value (FLORENTINE and BUUS model [2]). The problem of modulation detection is

described in many studies. However, there are not many papers concerning an effect of the starting phase of the modulator on the detection of modulation. Literature related to this problem is very scarce (except papers concerning mixed modulation detection [4, 13]). Such an effect is not expected for a modulation rate, f_{mod}, corresponding to a period shorter than duration of a signal or in a case when the modulation rate is high enough to evoke multitone sensation. Thus, the effect of the starting phase of the modulator should not be observed both in the roughness region [6, 20, 21, 26] where $20 < f_{mod} < $ CMF (CMF – a critical modulation rate [22]) and in the spectral region ($f_{mod} > $ CMF), where modulation detection is based mainly on the spectral structure of the modulated signal. However, for very low modulation rates, or when the period of the modulating signal is comparable to the duration of the signal, or when just a few periods of the modulator are present in the stimulus, an influence of the starting phase of the modulator on modulation detection thresholds cannot be excluded. For stimuli lasting hundreds of milliseconds such a situation takes place when modulation is perceived on the basis of very slow fluctuations in amplitude or frequency only. In such a case extreme values of amplitude/frequency are heard as following changes in pitch or loudness. Thus, the starting phase of the modulating signal and instantaneous values of amplitude/frequency dependent on a starting phase may significantly influence sensation caused by the stimulus. Since the problem of the influence of the starting phase of the modulator is still ambiguous, in many psychoacoustical experiments concerning modulation detection/discrimination a random value of the modulator starting phase is used to avoid its systematic effect on experimental results [11, 20, 22, 25].

Two different mechanisms are usually considered to explain perception of AM and FM signals at a low modulation rate. One of them is based on changes in excitation level (so-called place mechanism) and the second one, additional in some sense, is based on a phase locking phenomenon [16, 19, 24] (temporal mechanism). This additional mechanism, which probably analyses time intervals between succeeding neural spikes in auditory neurones, operates only for low modulation rates ($f_{mod} < 5$ Hz) and for carriers no higher than 5 kHz [24]. This mechanism may evoke a dual result. First, the starting phase of the FM modulator may influence the modulation detection of signals whose frequency is lower or higher than 5 kHz, i.e. it may play an important role both in an area where phase locking is crucial for FM detection and in an area where phase locking does not work. Second, taking into account the fact that this additional mechanism operates in the frequency domain only, it can be expected that the starting phase of the modulator should have a different effect for FM than for AM.

The main aim of the presented work is to answer the following question: Does the starting phase of the AM or FM modulator influence the modulation detection threshold for very low modulation rates? And: Does this effect depend on type of modulation and the carrier frequency?

2. Psychometric functions for modulation detection

Measurements of psychometric functions for AM and FM detection were carried out in the aim to point out an influence of the starting phase of the AM or FM modulator on

detection thresholds. Such measurements describe probability of detection in amplitude or frequency changes as a function of an appropriate modulation index (m or β). This is more sensitive method of measuring of an influence of any parameter on the detection than direct threshold measurements with an up-down procedure [7]. Hence, the main aim of our investigations was to determine psychometric functions for modulation detection as a function of the modulation index m for AM and modulation index β for FM, for different values of the starting phase of the sinusoidal modulating signal.

2.1. Method

Psychometric functions for AM and FM were determined in separate experiments using a 2 AFC method. Subjects were presented with pairs of signals. One of the signals in a pair was AM or FM modulated while the second one was a pure tone carrier. These two signals were presented in random order. Subjects' task was to point out the modulated signal.

The starting phase of the modulator in each trial was randomly chosen from a discrete set of values i.e.: 0, $\pi/2$, π and $3\pi/2$. Signals with the different starting phase were presented in random order and during each experimental run (60 pairs each) number of presentations of each starting phase was the same. Five different values of modulation indices (m or β) were used and they occurred in random order. The highest modulation index corresponded usually to 85–95% correct while its lowest value corresponded usually to 55–60% correct. Values of modulation indices were measured in preliminary measurements. Each value of the modulation index was presented to the subjects at least 200 times.

A 70-dB pure tone at a frequency of 0.25, 1 and 6 kHz was a carrier signal. Modulation rate, f_{mod}, was equal to 2 or 5 Hz. Duration of the signal (including 20-ms raised-cosine rise/fall ramps) was 1 s. 1-s long signal included at least two periods of the modulator. Time interval between signals in a pair was equal to 300 ms. All signals were digitally generated by means of 16-bit AD converter (Tucker and Davis Technology) at a 50 kHz sampling rate and they were presented monaurally by means of Sennheiser HD 414 headphones in an acoustically isolated room. Three subjects with audiologically normal hearing took part in experiments.

2.2. Results and discussion

Probabilities of correct answers obtained during experiments corresponding to appropriate values of modulation indices m and β were converted into detectability domain d' [3, 7]. Generally, data obtained for each subject could be expressed in a following way:

$$d' = K x^{\gamma}, \tag{1}$$

where x denotes FM or AM modulation index, K and γ are constants having different values for different carrier and subject. For functions being the best approximation of experimental data values of exponents γ are included in a range of $(1.83-2.12)$ for AM and in a range of $(1.78-2.21)$ for FM. However to carry out a further analysis, the

experimental data were approximated by a square function, i.e. for $\gamma = 2$. For this exponent the smallest average value of the standard deviation between experimental data and their approximations was found. This exponent is also motivated theoretically [5] and such approximation has been usually used for analysis of similar data [12, 15, 19, 23].

Detectability d' for FM and AM signals as a function of the corresponding modulation index i.e. $d'(\beta^2)$ and $d'(1000 \cdot m^2)$ is shown in Fig. 1. Since the data obtained for all subjects taking part in experiments were qualitatively consistent, averaged results for $f_{mod} = 2\,\text{Hz}$ are shown there. AM data are presented in the left column while FM data are shown in the right one. Following rows of the figure illustrate data for 0.25, 1 and 6-kHz carrier, respectively. The starting phase of the modulator $(0, \pi/2, \pi$ and $3\pi/2)$ is a parameter of the data.

From data presented in Fig. 1 it can be stated that an increase in d', which is related with an increase of an appropriate modulation index, reflects a monotonic increase in psychometric functions. In the case of the AM signal the pattern of results is approximately the same for all carrier frequencies (0.25, 1 and 6 kHz). Moreover the detectability d' seems to be independent of the starting phase of the modulator. There is no such influence for both subthreshold $(d' \leq 1.16)$ and suprathreshold $(d' > 1.16)$ values of the AM modulation index. The situation is somehow different in FM case (see the right column of Fig. 1). For near-threshold values of FM modulation index no influence of the starting phase of the modulator on modulation detection is observed. However, for suprathreshold values of FM index some non-regular influence of the starting phase of the modulator is observed. This effect is visible especially for 6-kHz carrier.

Raw experimental data could not be subjected to an analysis of variance (ANOVA) because values of d' for different carriers were obtained for modulation indices coming from different ranges. Therefore, in the first step of the analysis psychometric functions obtained in the experiment were approximated by monotonically increasing functions, passing through the origin, according to Eq. (1). Then, the slope coefficients, K_{AM} and K_{FM}, were subjected to a within-subject analysis variance with the following factors: starting phase of the modulating signal $(0, \pi/2, \pi$ and $3\pi/2)$ and carrier frequency (0.25, 1 and 6 kHz).

For amplitude modulation AM, the starting phase of the modulator was not statistically significant $[F(3,6) = 0.23, p = 0.875]$. This result confirms that threshold for AM detection does not depend on the starting phase of the modulator. The carrier frequency was not statistically significant, too $[F(2,4) = 2.98, p = 0.161]$. This result is consistent with a finding that AM detection threshold is independent of the carrier frequency at low modulation rates [1, 17, 25, 27]. It is worth to add that an interaction between the carrier frequency and the starting phase of the modulator was not statistically significant, $[F(6,12) = 0.11, p = 0.994]$.

For frequency modulation FM, the starting phase of the modulator was not statistically significant $[F(3,6) = 1.07, p = 0.431]$. Thus, similarly to AM case, it allows to state that the starting phase of the modulator is not a crucial parameter for FM detection too. However, as opposite to AM, it was found that the carrier frequency was highly significant $[F(2,4)] = 52.67, p = 0.001]$. This result reflects a dependence of the
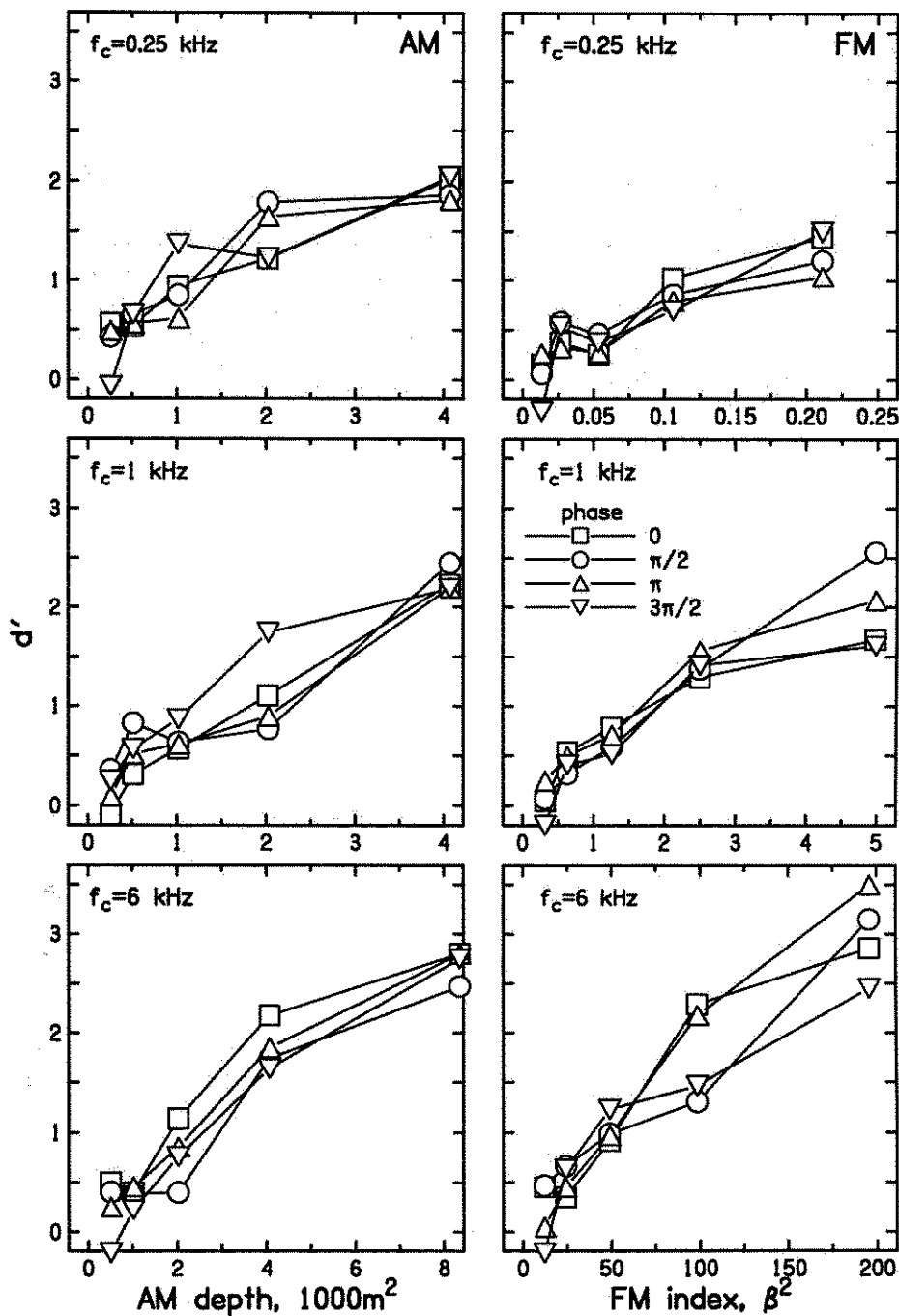
Fig. 1. Psychometric functions for AM (left column) and FM (right column) detection expressed in terms of detectability d' as a function of $1000 \, \text{m}^2$ and β^2 for AM and FM respectively. Following rows show the data for a sinusoidal carrier at a frequency of 0.25, 1 and 6 kHz. Data were averaged across three subjects and the parameter is the value of the starting phase of the modulator: 0, $\pi/2$, π or $3\pi/2$.

FM detection thresholds on the carrier frequency when the thresholds are expressed in terms of FM index, β. This result is in a good agreement with literature [10, 27]. An interaction between the starting phase of the modulator and the carrier frequency was not statistically significant [$F(6, 12) = 1.24$, $p = 0.351$]. It suggests that a scatter of slope values, observed for different values of the starting phase, suprathreshold values of FM modulation index and a carrier frequency, are not crucial.

Data presented above enable us to state that the starting phase of the modulator is not a crucial parameter that determines the shape of psychometric functions and it does not influence the detection thresholds of AM or FM. It seems that when the subject's task is to detect amplitude/frequency changes in a signal, the starting phase of amplitude or frequency changes is not the most important factor. In such cases the basic detection cue is a difference between maximum and minimum value of the discriminated
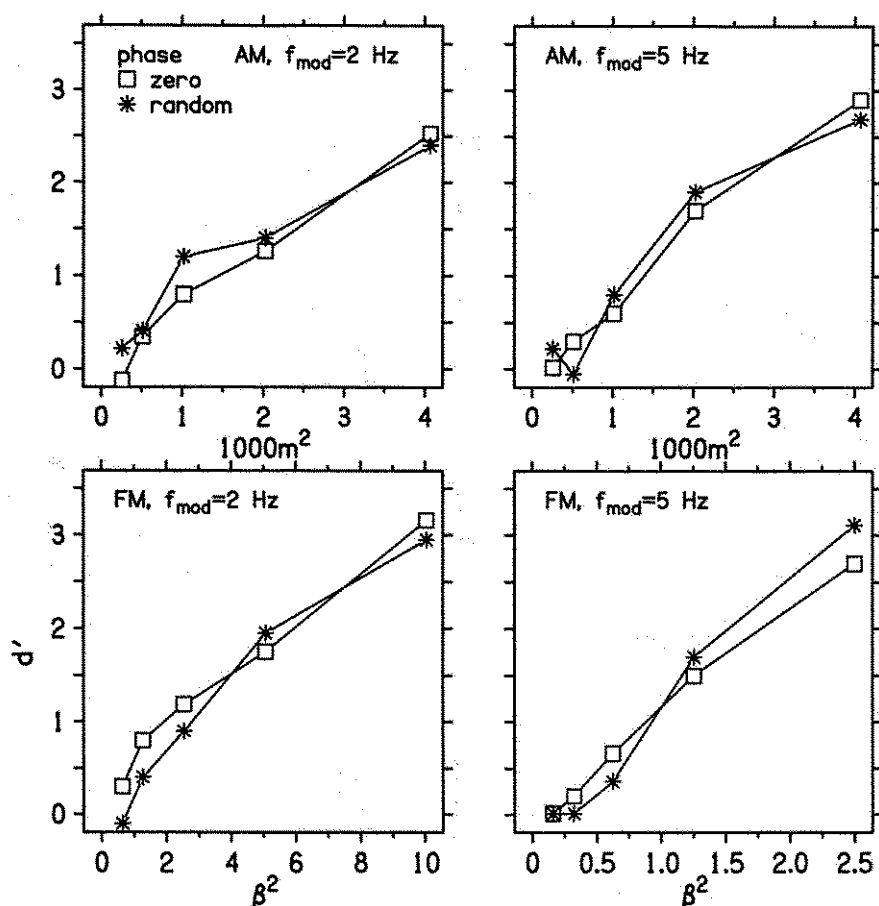

Fig. 2. Psychometric functions expressed in terms of detectability d' as a function of $1000\,\mathrm{m}^2$ for AM and β^2 for FM (lower row) for 1-kHz sinusoidal carrier and for modulation rate of 2 Hz (left column) and 5 Hz (right column). Data were averaged across three subjects and the parameter is the value of the starting phase of the modulator: constant (zero) or randomly chosen from (0–2π) range.

parameter. Lack of the influence of the starting phase of the modulator on psychometric functions is consistent with models based on analysis of extreme values of the excitation pattern (i.e. Zwicker's model [28] or a group of integration models [3]).

Presented above experimental data were obtained for a randomly chosen phase value, taken from four discrete values, i.e. 0, $\pi/2$, π and $3\pi/2$. Although, these starting phases represent the most important starting values and directions of changes in amplitude/frequency which may occur at the beginning of the modulated signal, they are not "random" in a sense of equal probability that phase was taken by chance from the range of $(0-2\pi)$. Therefore an additional experiment (an analogue to described above) was performed. In this experiment psychometric functions for modulation detection, for randomly chosen starting phase from the range of $(0-2\pi)$ and for zero starting phase were compared. The method and signal parameters were similar to those described above. 1-kHz sinusoid was a carrier and modulation rate was equal to 2 and 5 Hz. Results of these additional measurements averaged for three subjects (the same as in previous experiment) are shown in Fig. 2. The upper row shows results obtained for AM and the lower one for FM. In the left column data for 2-Hz modulation rate are shown while in the right column – data for 5-Hz modulation rate are presented. The modulation starting phase is the parameter of the data: it was either random or zero.

From data presented in Fig. 2 it can be seen that psychometric functions expressed in terms of detectability d' are similar for both random and zero starting phase of the modulator. This observation confirms results obtained for the starting phase randomly chosen from four discret values.

3. Summary and conclusions

Experimental data presented in this paper correspond well to detection models based on an analysis of differences in excitation level at extreme values of physical parameters of a signal. It seems that the auditory system analyses short, overlapping time intervals (i.e. by means of the sliding window in time domain [18]) and compares excitation levels evoked by the acoustic signal in these time intervals. However, despite of the duration of the time interval, which is probably related to integration time of the auditory system, information about extreme excitations is stored at higher levels of the auditory system long enough to be further compared with a current excitation coming from the periphery. In the auditory system the time during which the extreme excitation is stored is much longer than integration time, because AM detection thresholds are constant in the wide range of the modulation rate [1]. If this time was short, it would be impossible to detect slow changes in amplitude/frequency of a signal. A sequence of extreme values of physical parameters of the signal and corresponding extreme excitation levels, or the excitation starting value (related to the starting value of the parameter under analysis) does not influence the detection of changes in time. It seems that all models based on the difference in excitation level, corresponding to extreme values of investigated physical parameter and according to which its sequence and the starting phase do not play a crucial role (i.e. FLORENTINE–BUUS model [2] or non-optimal excitation model [19, 24]) describe

the auditory system in a proper way as far as detection of slow amplitude/frequency changes is concerned. If the succession of the temporal order of extreme values of physical parameters in the acoustic signal does not influence the threshold of these changes, then the detection of amplitude/frequency changes should be independent of the time pattern of these changes and should depend on differences in extreme values of the parameter only. Indeed, such relation was observed for linear changes in signal frequency for a wide frequency range [8, 9, 14]: thresholds of such changes were independent of time and direction of changes. The crucial factors were the difference in frequency between the beginning and the end of the signal and its centre frequency.

From the results presented in this paper it can be generally stated that the starting phase of the sinusoidal modulator at a rate of 2 or 5 Hz, superimposed (as AM or FM modulator) on a sinusoidal carrier does not critically influence psychometric functions for AM and FM detection. Both, random and constant starting phases bring about similar results. Even though the auditory system can evaluate changes in physical parameters based on local extrema (in time), the actual course of these changes does not influence the threshold.

However this is true for changes that do not contain any additional detection cues, i.e. the spread of signal spectrum caused by rapid amplitude/frequency changes.

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