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DIFFERENCE LIMENS OF AMPLITUDE MODULATED SIGNALS[1]

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Presented in the literature studies on the perception of amplitude modulated signals concentrate mainly on the determination of modulation thresholds, and of the so-called roughness and amplitude of a signal. Whereas papers concerned with difference limens of amplitude modulation of carriers more complex than a tonal signal are lacking. With this in mind, research aimed in principle at the determination of difference limens of noise octave bands amplitude modulated with sinusoidal signals was undertaken. A comparison of these limens with values of STI which is an objective measure of speech intelligibility in a room was another important aim of performed studies. Such a comparison was a certain psychoacoustic verification of the perception ability of definite changes of the STI by a listener.

Research results proved that difference limens depend significantly on the modulation factor of the reference signal. It was also found that difference in the STI values, determined with the objective method (the so-called RASTI method), which determine room quality from the point of view of speech intelligibility are found in the range of difference limens of amplitude modulated signals or below these limens.

1. Introduction

Research performed up to the present on the perception of amplitude modulated signals concern mainly the determination of modulation thresholds and the evaluation of the so-called roughness and amplitude fluctuation of a signal. Several papers can be found which indirectly are concerned with difference limens of amplitude modulation however with respect only to a simplest case of a modulation of a sinusoidal signal with another sinusoidal signal. Hence, it seems interesting to carry out research on the determination of difference limens of amplitude modulation for a more complex carrier than a tonal signal. Performed studies are directly related to results of papers [3, 4] which prove that changes of the amplitude modulation index of definite white noise bands propagating in a room allow a direct evaluation of speech intelligibility in this room. The so-called speech transmission index – STI is the measure of such intelligibility. With respect to these papers, the problem of difference perception between modulated signals with various values of modulation indices requires further analysis. In principle this problem resolves itself into the deter-

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mination of difference limens for these signals. In terms of experimentally determined values of the STI, these limens can be their interesting psychoacoustic verification. It is obvious that in order to have changes of the modulaton index observed in a room for example percepted by a listener, they have to exceed determined difference limens. The results of our research show that differences of the STI which are important to the diversification of speech intelligibility evaluation in rooms are found at the same level or below difference limens.

2. Review of studies concerned with perception of amplitude modulated signals

Many scientists have dealt with the perception of amplitude modulated sounds [1, 2, 6, 7, 8, 9, 10, 12, 13]. Two fundamental groups of papers can be isolated. The first one is concerned with the determination of amplitude modulation thresholds with the applicaton of a wide class of carrier and modulating signals. The second group of papers is concerned with investigations of the fluctuation intensity of amplitude modulated sounds and of roughness.

2.1. Thresholds of amplitude modulation of signals

ZWICKER'S and FELDTKELLER'S paper [13] widely presents the problem of amplitude modulation thresholds. Apart from classical modulation thresholds, i.e. modulation of a sinusoidal signal by another sinusoidal signal, this paper presents a series of relationships for the preception of amplitude modulated complex signals — especially amplitude modulation of various bands of white noise.

ZWICKER [12] univocally determined relationships between the thresholds amplitude modulation factor, amplitude and frequency of the carrier tone, frequency of modulating signal for a case of investigations of amplitude modulation performed with the utilization of tonal signals only. This led to the identification of certain significant perception ranges of modulated signals, i.e. the so-called "follow-up" range, roughness range and range of separation of side components also characteristic for frequency modulation. Results of this research have contributed to the formulation of a certain perception theory of the monaural phase effect and to the perception of modulated signals [13].

ZWICKER and FELDTKELLER [13] have also stated certain fundamental relationships which govern the perception of various noise bands amplitude modulated with the utilization of various modulating signals. The assignation of relationships between the threshold amplitude modulation factor and band width of carrier signal for a regular (sinusoidal or rectangular) modulating signal with constant frequency equal to 4Hz was the most important problem. It was stated that every increase of the width of the carrier signal band causes a proportional decrease of amplitude modulation thresholds. This dependence is valid for all noise bands with width not exceeding the width of one critical band. In this case, the width of the critical band is of great importance because in accordance with paper [13], when this width is exceeded by a modulated sound then a different in quality perception mechanism is acutated. We have to do with the so-called separation sidebands, or with so-called spectral mechanism of perception in such a case [6].

In the course of detailed analysis of relationships between amplitude modulation thresholds and modulating frequency for various widths of the band of carrier noise it was stated that for a noise with spectrum range not exceeding the width of one critical band, these thresholds in quality are close to thresholds of modulation of a sinusoidal signal with another sinusoidal signal. When the spectrum of carrier signal exceeds the width of the critical band then the effect of separation of side bands is of constant character and does not depend on the value of modulating frequencies. In such a case thresholds of amplitude modulation of such a noise become identical to thresholds of broad-band noise which are approximately proportional in a wide range of modulating frequencies to values of these frequencies.

Presented above conclusions find practical application, because natural sounds of music or speech are broad-band signals and so their perception is governed by principles valid in this range for a broad-band noise.

Also VIEMEISTER'S research [10] was concerned with amplitude modulation perception. He studied the so-called temporal modulation transfer function (TMTF) which is determined on the basis of thresholds of amplitude modulation. Viemeister's research is partly a repetition, but also an extension of results presented in paper [13] for various bands of white noise as the carrier signal.

The temporal modulation transfer function (TMTF) was defined by Viemeister as

$$\mathrm{TMTF} = 20 \lg m \quad [\mathrm{dB}],$$

where m is the threshold amplitude modulation factor.

Viemeister's experimental results are consistent with results given in paper [13] for broad-band noise and they supplement them in many matters. They have proved that thresholds of amplitude modulation of a wide noise band depend on the modulation frequency up to the value of 2 KHz. Whereas a further increase of the value of this frequency does not influence the value of the threshold. This is most apparent in the diagram: TMTF versus modulating frequency.

Like Zwicker, Viemeister noticed that an extension of the carrier signal band distinctly decreases thresholds of amplitude modulation. The value of the determined threshold is strongly influenced by the mid-band frequency in this relationship. According to Viemeister's investigations, decisively higher thresholds are observed for lower mid-band frequencies of carrier signal bands.

Besides presented above conclusions, VIEMEISTER'S paper [10] gives also a development of TERHARDT'S model [8]. According to this model thresholds of amplitude modulation can be interpreted on the basis of a low-pass filter with an adequate limit frequency. TERHARDT [8] grounded his hypothesis on amplitude modulation thresholds derived by Zwicker for tones. This gave a great discrepancy between his theory and experimental data – mainly in frequency range in which the so-called separation of sidebands of the modulated sound is observed. Such an effect took place, because the spectrum of the modulated signal exceeded the width of one critical band. Viemeister applied a wide noise band as the carrier signal and thus completely eliminated the effect of separation of sidebands and obtained absolute (accurate to standard deviation value) compatibility of experimental data with theoretical assumptions.

2.2. Roughness and intensity of amplitude fluctuation of amplitude modulated signals

The problem of perception of the so-called roughness and intensity of amplitude fluctuation intensity of amplitude modulated signals is fairly widely discussed in papers [1, 2, 7, 8, 9]. Roughness as well as amplitude fluctuations are treated in these papers as two independent phenomena. Amplitude fluctuations are such changes of the amplitude which occur not more often than 20 times per second ($f_{\text{mod}} \leqslant 20\,\text{Hz}$). These changes are perceived as succesive minima and maxima of the amplitude of the signal. This means that the organ of hearing "follows-up" with these changes. The sensation of sound roughness is achieved at changes of the signal amplitude greater than 20 times per second ($f_{\text{mod}} \geqslant 20\,\text{Hz}$). In such a case the organ of hearing does not "follow-up" with the observation of succesive amplitude maxima and minima, and receives a global impression of such a type of signal – called roughness in short.

TERHARDT's paper [9] is one of the first which concerns the perception of signal amplitude fluctuations in the conditions of amplitude modulation. The author is interested in the determination of amplitude fluctuation intensity and roughness in terms of physical parameters of signals, i.e. carrier frequency, modulating frequency and amplitude of the signal.

Terhardt stated that amplitude fluctuation intensity and roughness is proportional to the intensity level of a signal in the range from 40 to 80 dB.

The relationship between roughness and carrier frequency f_c can be characterized in two intervals. And so, for $f_c \in (125\text{–}500\,\text{Hz})$ an increase of roughness accompanying an increase of carrier frequency is observed. When f_c reaches the value of 500 Hz roughness assumes a constant value independent from further increase of carrier frequency. Whereas, amplitude fluctuation intensity is independent from carrier frequency.

Yet the relationship between fluctuation intensity and roughness, and modulation factor is the most important relation determined in paper [9]. It was stated that fluctuation intensity as well as roughness is proportional to the square of the amplitude modulation factor.

Another paper written by TERHARDT [8] is concerned with similar problems. Besides information on roughness due to amplitude modulation, also information on roughness in the conditions of frequency modulation and on effects related to the summation of roughness in the conditions of amplitude modulation can be found in this paper.

It should be noted that both mentioned papers by Terhardt are concerned with the classical problem of amplitude modulation, namely modulation of a sinusoidal signal with another sinusoidal signal.

GUIRAO's paper [2] is another paper which deals with roughness in the conditions of amplitude modulation of a sinusoidal signal with another sinusoidal signal and of a narrow noise band with a simple tone. A correlation between the parameters of a modulated signal (especially between modulating frequency and modulation factor) and roughness intensity was sought in this paper. It was stated that roughness is linearly correlated with modulating frequency (in the range 12–55 Hz), and non-linearly correlated with the modulation factor. This refers to tonal as well as noise signals.

Also SCHÖNE's paper [7] is concerned with similar problems. Among others it presents difference limens of amplitude modulation. However, here these limens are investigated with respect to investigations of amplitude fluctuation intensity of an amplitude modulated signal.

However, unlike in paper [2] SCHÖNE did not deal with roughness, but with amplitude fluctuation intensity only. He applied modulating frequencies from the range 1–10 Hz. Among others Schöne stated that amplitude fluctuation intensity is independent from the intensity level of a signal and from modulating frequency. In this range of modulating frequencies the amplitude fluctuation intensity is linearly correlated with the modulation factor, i.e. every increment of the modulation factor (defined here as $d = L_{\max} - L_{\min}$, where $L_{\max}$ and $L_{\min}$ denote the maximum and minimum pressure level of the signal, respectively) causes a proportional increment of fluctuation intensity.

It should be stressed that Schöne performed his studies for several discrete values of the reference amplitude modulation factor which do not exhaust the full range of modulation variability, especially for $m > 0.75$. The greatest value was equal to 75%.

Also FASTL's paper [1] is concerned with the evaluation of fluctuation intensity of signal amplitude. His research was aimed at the evaluation amplitude fluctuation intensity of a wide noise band amplitude modulated by a tone in terms level of the intensity level, amplitude modulation factor and modulating frequency. Fastl stated that an increase of amplitude fluctuation intensity accompanies an increase of the modulating frequency and reaches a maximum for $f_m = 4$ Hz. An increase of the intensity level in the range 40 – 80 dB induces an increase of fluctuation intensity.

Paper [1] states that fluctuation intensity is proportional to the logarithm of the amplitude modulation factor for a noise signal.

It should be particularly noticed that mentioned above papers concerned with roughness and amplitude fluctuations present divergent results, but their general conclusions are rather consistent. Already TERHARDT [8, 9] has noticed this fact and stated that results of such experiments can significantly depend on the choice of reference signal.

The presented above review of literature shows that a majority of papers is concerned with problems of determining perception thresholds of relatively simple modulation, i.e. a modulation of a sinusoidal signal with another sinusoidal signal, and with problems of evaluation of so-called roughness or signal amplitude fluctuations. Therefore it seems useful to carry out research on the determination of difference limens of amplitude modulation for spectrally more complex carrier signals. Thus, achieved results could be referred to evaluation criteria of room quality from the point of view of speech intelligibility given in paper [4].

3. Temporal and spectral structure of a noise band amplitude modulated by a tone

The calculation of the spectrum of a modulated signal is simple in the case of amplitude modulation of a sinusoidal signal, because it is based on simple trigonometric transformations. This simple mathematical procedure can not be applied to determine the spectrum of modulated random signals (irregular), because there is no analytic form of the temporal function of such signals. The spectral structure of this type of signals is derived on the basis of the theory of the autocorrelation function and the Wiener-Chińczyn theorem.

Let us consider a white noise band described with function $S(t)$ with power spectral density $G_s(\omega)$,

$$G_s(\omega) = \begin{cases} G_s \text{for } \omega_{\min} < \omega < \omega_{\max} \\ 0 \text{ for other } \omega \end{cases} \tag{1}$$

Let us assume that signal $S(t)$ is amplitude modulated by a sinusoidal function $b(t)$

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

where

$$\omega_m < \omega_{\min}.$$

Furthermore, let us assume that this signal is a stationary ergodic process with mean value equal to zero and root-mean-square value σ. In order to determine the power spectral density of a signal under consideration, first of all we have to determine its autocorrelation function and then use the Wiener-Chińczyn theorem. In consequence, the power spectral density for a band noise modulated with a tonal signal can be noted as follows:

$$G_a(\omega) = G_s(\omega) + \frac{1}{2}k^2 B^2 [G_s(\omega - \omega_m) + G_s(\omega + \omega_m)], \tag{3}$$

where G_s power spectral density of carrier signal, B and ω_m is the amplitude and pulsation of modulating signal, respectively.

It results from expression (3) that power spectral density of a noise signal amplitude modulated with a tone consists of three bands. The central band is the carrier band, while two sidebands which lie symmetrically with respect to the central band at a distance equal to the value of modulating frequency from it are modulation products. Mentioned three bands overlap at small values of modulating frequencies.

The problem of defining the measure of modulation is an important problem in the discussion of the temporal and spectral structure of modulated noise signals. The modulation factor is such a measure in classical considerations, i.e. in the case of modulation of a sinusoidal signal with another sinusoidal signal. It has the following form

$$m = \frac{kB}{A_0}, \tag{4}$$

where B and A_0 are amplitudes of modulating and carrier signal, respectively, and k is the apparatus constant. In the case under consideration, when value m is determined for an amplitude modulated noise, expression (4) can not be applied directly. The m_{sk} quantity which expresses the ratio of root-mean-square values of the modulating and carrier signal was accepted as the measure of modulations

$$m_{sk} = k\sqrt{\frac{B^2}{\sigma^2}}, \tag{5}$$

where B – amplitude of modulating signal, σ – root-mean-square value of carrier signal, k – apparatus constant.

Achieved threshold values or their differences will be expressed with this quantity, m_{sk}, in the further part of this paper.

It should be added that apart from presented here analytical expressions which enable the determination of spectral density of a modulated noise, also an experimental spectral analysis of modulated noise was performed. This analysis fully confirmed obtained theoretical data.

4. Aim of research, apparatus and measurement methods

Undertaken research was aimed at the determination of difference limens of amplitude modulation of white noise octave bands, performed with sinusoidal signals with chosen frequencies, the reference of these limens to values of the STI which determine the quality of a room from the point of view of speech intelligibility.

The block diagram of the applied apparatus is presented in Fig. 1. White noise generated by noise generator – 1, subjected to filtration in an octave filter – 2 with adequate mid-band frequency f_c and fed to modulator – 6, was the carrier signal. A sinusoidal function generated by generator – 3 was the modulating signal. It was supplied to the switching device – 5 which by turns attached it directly to the modulator and a so-called reference signal was obtained, or indirectly to the modulator through a system of potentiometers – 7,8 and then a test signal was obtained. The listener could set a definite value of the modulation index for a signal

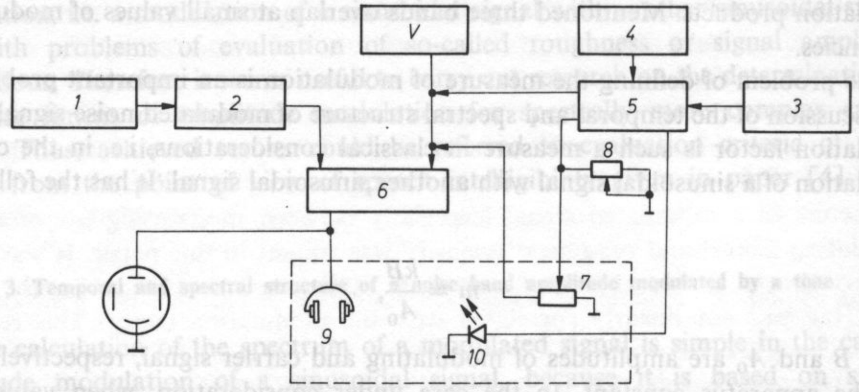

Fig. 1. Block diagram of measuring apparatus. 1 — noise generator, 2 — octave filter, 3 — tone generator, 4 — pulse generator, 5 — switching device, 6 — modulator, 7, 8 — potentiometers, 9 — earphones 10 — diodek

with a potentiometer — 7. This value was signalled with a diode — 10. The switching device — 5 was controlled with a signal from the pulse generator — 4 which generated a symmetric rectangular signal.

The described above set-up could be used to obtain pairs of signals containing a reference signal with a constant value of the modulation index m and test signal with modulation index regulated by the listener.

Duration times of test signals and reference signals were identical and were equal to 2, 3 seconds.

The following four white noise octave bands with mid-band frequencies $f_c = 250$, 500, 1000, 2000 Hz and seven various frequencies of the modulating tone: $f_m = 1, 2, 4, 8, 16, 32, 64$ Hz were applied in performed research. The level of acoustic pressure of the modulated signal was constant and equal to 75dB (SPL). Difference limens were determined for the following amplitude modulation indexes of the reference signals: $m_w = 25\%$, 50%, 75% 100%. For comparative reasons also measurements of classical threshold of amplitude modulation were carried out in the same cycle of experiments with the same methods and in the same apparatus.

Applied research methods are a certain modification of the adjustment method and method of limits [11]. In the course of experiments listeners compared the following pairs of signals consisting of a reference signal with a constant value of modulation factor and test signal with a modulation factor regulated within the range from zero to the value set in the reference signal.

Two separate series of measurements were performed: ascending series (↑) in which the listener was to increase gradually the amplitude modulation factor in the test signal from zero to a moment in which the test signal and reference signal were identical in his assessement; descending series (↓) in which the listener was to decrease gradually the amplitude modulation factor in the test signal from the value set in the reference signal to the moment when the test signal and reference signal differed insignificantly (on threshold level).

Every threshold value was determined on the basis of five ascending series and five descending series. Then threshold values averaged for these series were statistically tested with the F-Snedecor test, the compatibility test and the test of ranks sum at the significance level $\alpha = 0.05$. Tests gave a positive result for a majority of data, whereas in a case of negative test results measurements were supplemented with additional two series.

Thanks to statistic testing results of both series could be considered jointly, and mean values and standard deviations could be determined for them.

Two listeners with audiologically normal hearing participated in experiments.

5. Research results and their analysis

5.1. *Thresholds of amplitude modulation*

In the first place classical amplitude modulation thresholds were determined. They are presented in Figs. 2 and 3 for listeners EO and AS, respectively. The threshold value of the amplitude modulation factor m, in percentage, is expressed in terms of modulating frequency f_m. The midband frequency of a noise octave band (carrier signal) is the parameter of these curves.

It can be seen from these figures that two independent ranges in determined thresholds can be separated in terms of the value of modulating frequency. Modulation thresholds are constant, independent from modulating frequency with an accuracy of confidence interval (marked by a vertical line) for a modulating frequency range up to approximately 16 Hz. This is the so-called "follow-up" range in which the organ of hearing follows-up with temporal changes of signal intensity, i.e. its successive minima and maxima. These changes take place relatively slowly, so the

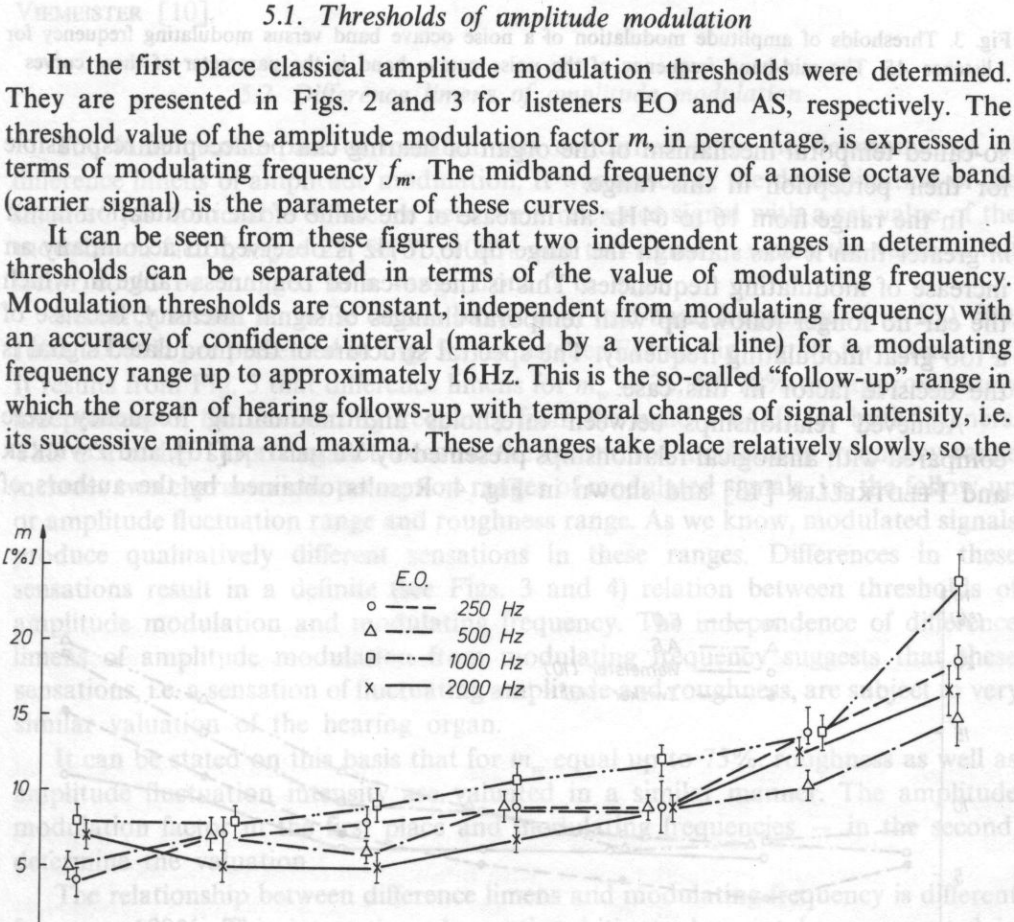

Fig. 2. Thresholds of amplitude modulation of a noise octave band versus modulating frequency for listener EO. The mid-band frequency of the noise octave band is the parameter of these curves

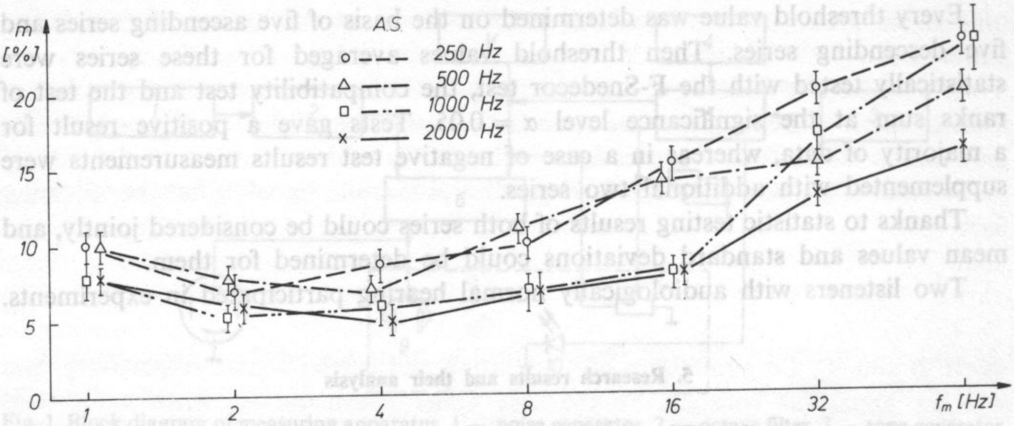

Fig. 3. Thresholds of amplitude modulation of a noise octave band versus modulating frequency for listener *AS*. The mid-band frequency of the noise octave band is the parameter of these curves

so-called temporal mechanism of the organ of hearing can be accepted responsible for their perception in this range.

In the range from 16 to 64 Hz an increase of the value of the modulation factor *m* greater than it was stated in the range up to 16 Hz is observed to accompany an increase of modulating frequencies. This is the so-called roughness range in which the ear no longer follows-up with temporal changes of signal intensity, because of a too great modulating frequency. The spectral structure of the modulated signal is the decisive factor in this case.

Achieved relationships between thresholds and modulating frequency were compared with analogical relationships presented by VIEMEISTER [10], and ZWICKER and FELDTKELLER [13] and shown in Fig. 4. Results obtained by the authors of

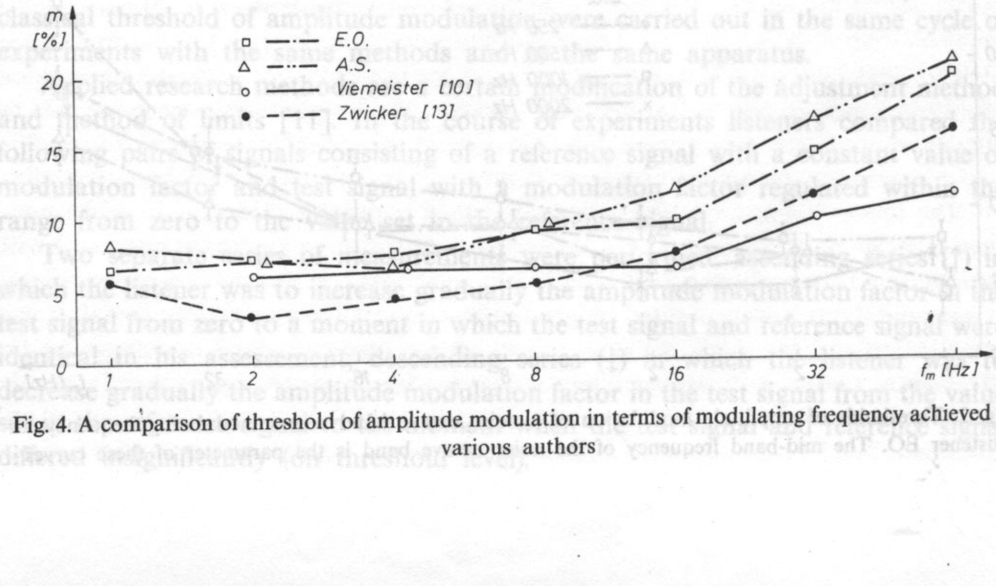

Fig. 4. A comparison of threshold of amplitude modulation in terms of modulating frequency achieved by various authors

this paper, shown in this figure, present average values of the amplitude modulation factor for a noise octave band, whereas VIEMEISTER's results [10] and ZWICKER's-FELDTKELLER's results [13] refer to broad-band noise. A good consistency of results can be observed in the range of low modulating frequencies, which do not exceed 16 Hz.

Whereas, for frequencies $f_m > 16$ Hz, obtained threshold increments are much larger than values given in papers [10, 13]. This discrepancy results from the fact that results in papers [10, 13] refer to a broad-band noise, while results of research carried out by the authors of this paper refer to octave bands.

However, generally it can be stated that obtained values of amplitude modulation thresholds are consistent with data published in literature and they confirm the so-called "narrow-band" hypothesis of amplitude modulation perception given by VIEMEISTER [10].

5.2. *Difference limens of amplitude modulation*

The fundamental part of research was concerned with the determination of difference limens of amplitude modulation. It was aimed at the determination of the smallest, just noticeable difference between a reference signal with a set value of the modulation factor, $m_w = 25, 50, 75, 100\%$ and test signal in which the value of this factor could be changed in a range from 0 to m_w.

Research results for noise octave bands with mid-band frequencies $f_c = 250, 500, 1000, 2000$ Hz are presented in Fig. 5 a for listener EO and in Fig. 5b for listener AS. It results from Fig. 5 that difference limens for $m_w = 25, 50, 75\%$ are approximately independent of the modulating frequency from the band 1–64 Hz for both listeners. This is a rather surprising fact, because the mentioned modulating frequency range includes two characteristic perception ranges of modulated signals, i.e. the follow-up or amplitude fluctuation range and roughness range. As we know, modulated signals produce qualitatively different sensations in these ranges. Differences in these sensations result in a definite (see Figs. 3 and 4) relation between thresholds of amplitude modulation and modulating frequency. The independence of difference limens of amplitude modulation from modulating frequency suggests that these sensations, i.e. a sensation of fluctuating amplitude and roughness, are subject to very similar valuation of the hearing organ.

It can be stated on this basis that for m_w equal up to 75%, roughness as well as amplitude fluctuation intensity are valuated in a similar manner. The amplitude modulation factor in the first place and modulating frequencies – in the second, determine the valuation.

The relationship between difference limens and modulating frequency is different for $m_w = 100\%$. This interesting observation hitherto has not been presented in literature. In this case (see Fig. 5) the initial increase of modulating frequency in the range 1–16 Hz does not influence significantly the value of the difference limen. When f_m exceeds the value of approximately 16 Hz a distinct increase of the threshold is

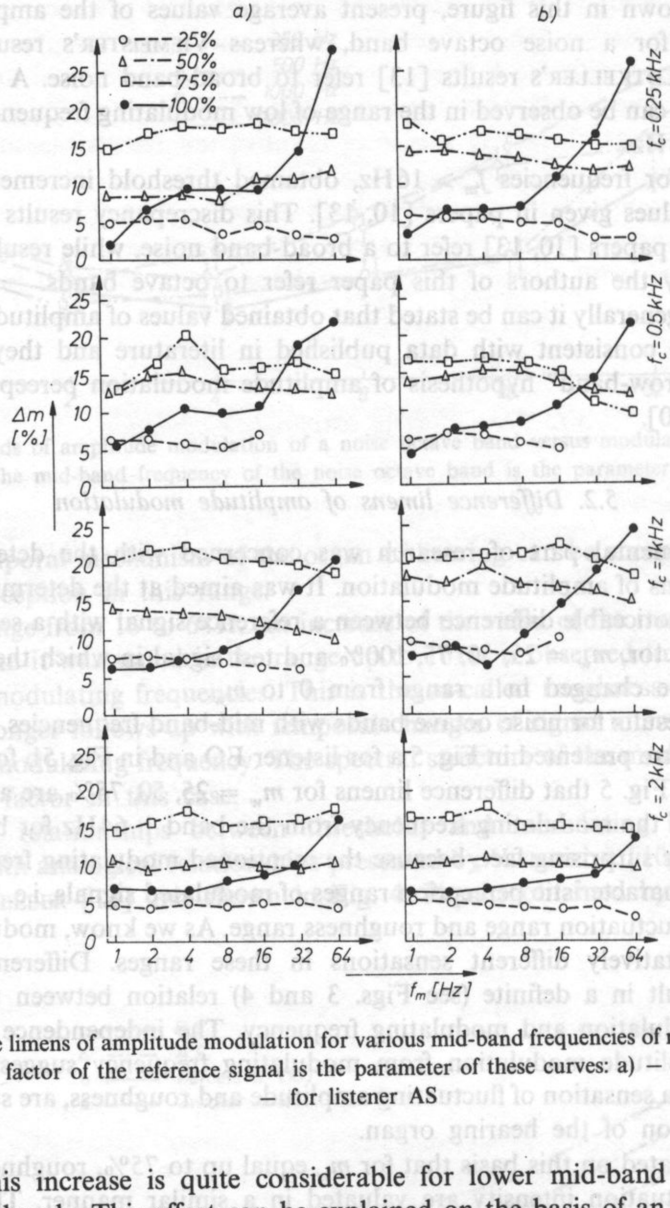

Fig. 5. Difference limens of amplitude modulation for various mid-band frequencies of noise octave bands. The modulation factor of the reference signal is the parameter of these curves: a) – for listener EO, b) – for listener AS

observed. This increase is quite considerable for lower mid-band frequencies of carrier noise bands. This effect can be explained on the basis of an analysis of the temporal structure of the modulated signal. And so the intensity level in terms of time of an amplitude modulated signal with modulation factor below 100% always differs from zero, even at minimum amplitude values. Such a function is percepted as a constant signal with an intensity level changing in time. Investigations of the difference limen for such signals resolve themselves to the determination of just noticeable difference between the reference signal and test signal. This difference can be determined on the basis of the difference of intensity levels in the range of maxima and minima of this signal, or on the basis of the evaluation of the changes of its dynamics, i.e. simultaneously on the basis of the level difference in maxima and minima.

However, for a case of the amplitude modulation factor of a reference signal equal to 100%, the perception of such a signal is completely different. This results from the fact that at a maximum of the amplitude of a signal with 100% modulation its intensity level considerably differs from zero, while at a minimum of the amplitude the intensity level of this signal is close to zero. Therefore, research of modulated signals is qualitatively different in the perception process for signals with $m_w = 100\%$ and signals with $m_w < 100\%$, in spite of the fact that these signals belong to the same class of modulated signals.

It is also worth noticing that in accordance with Fig. 5, a distinct increase of the difference limen level accompanies the increase of value m_w up to $m_w \leqslant 75\%$.

On the basis of data presented in Fig. 5 it can be assumed that difference limens of amplitude modulation are approximately constant and independent from modulating frequency for $f_m < 16$ Hz, i.e. for the so-called "follow-up" range (i.e. amplitude fluctuations).

On this basis these limens were averaged with respect to modulating frequency in the range 1–16 Hz. So obtained functions are presented in Figs. 6 and 7 for listeners EO and AS, respectively. The mid-band frequency of noise octave bands was the parameters of these curves. These figures present also results of certain additional research on difference limens of amplitude modulation carried out in the range of m_w from 75–100% for a noise octave band with mid-band frequency equal to 1000 Hz. These additional studies were to give a more accurate determination of the position of the limen value maximum in terms of function f_m.

It results from Figs. 6 and 7 that an increase of the amplitude modulation factor of a reference signal in the range from zero to 75% causes an approximately linear

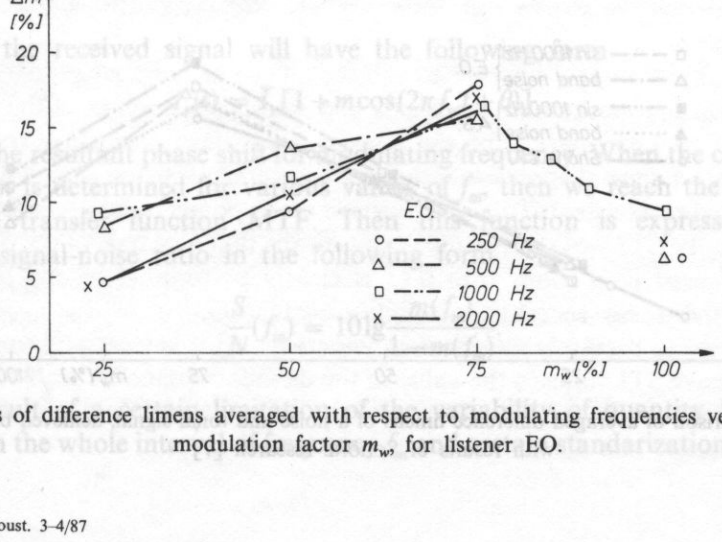

Fig. 6. Values of difference limens averaged with respect to modulating frequencies versus amplitude modulation factor m_w, for listener EO.

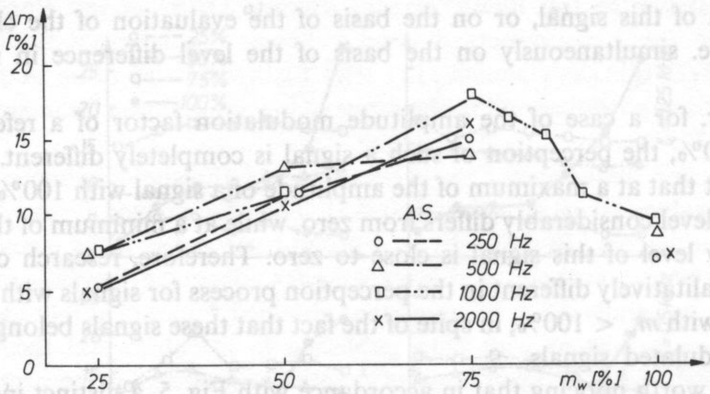

Fig. 7. Values of difference limens averaged with respect to modulating frequencies versus amplitude modulation factor m_w, for listener AS

increase of difference limens up to a maximum in the range $m_w = 75\%$. A further increase of m_w values above the value of 75% induces a considerable decrease of difference limens.

An analysis of data presented in Figs 6 and 7 proves also that in principle difference limens of amplitude modulation are independent from the mid-band frequency of the carrier noise band. On this basis these limens were averaged with respect to mid-frequency of noise bands. Fig. 8 presents the result of averaging for individual listeners. It also shows difference limens of amplitude modulation of a tonal signal with frequency $f_c = 1000$ Hz, and results of SCHÖNE'S research [7].

It results from Fig. 8 that difference limens of amplitude modulation do not depend on the type of carrier signal. This statement corresponds with FASTL'S conclusion [1], according to which the fluctuation intensity of a tone and noise band are governed by similar principles. It also results from the figure that difference

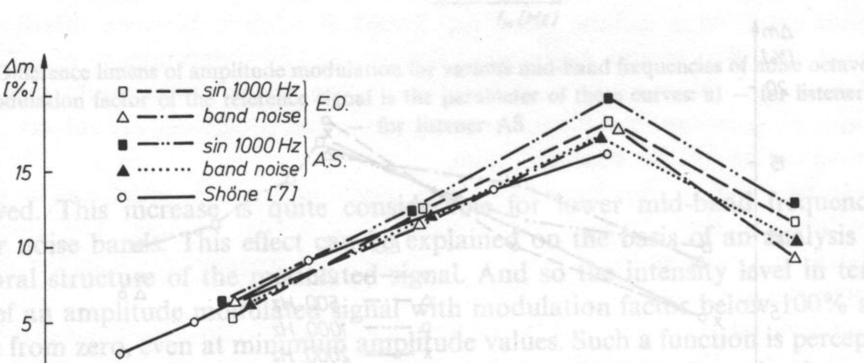

Fig. 8. A comparison of averaged difference limens of a noise and tonal signal, achieved by the authors with results of SCHÖNE research [7]

limens of amplitude modulation are linearly correlated with amplitude modulation factor m_w in the range of m_w up to 75%. A regression analysis performed in this range proves that this dependence can be noted analytically as follows

$$\Delta m = 0.24 \cdot m_w. \qquad (6)$$

SCHÖNE [7] in such case reached a dependence: $d_{\mathrm{DL}} = 0.3 \cdot d$ where $d = L_{\max} - L_{\min}$, $L_{\max}$ and $L_{\min}$ denote respectively the maximum and minimum level of acoustic pressure. A difference in the numerical coefficient results from the fact that expression (6) presents linear quantities, while Schöne's relation presents logarithmic quantities.

5.3. *Difference limens of amplitude modulation related to the index of speech intelligibility in a room (The* RASTI *method)*

In the course of further studies achieved difference limen values were related to the index of speech intelligibility in a room. As we know, such intelligibility is an important criterion of room acoustic quality. During the last several years an interesting method of speech intelligibility measurement in a room was developed. It is called the RASTI method [5]. This method is based on the determination of the so-called modulation transfer function MTF for a given room. It is characteristic for the MTF that the value of the modulation factor of a noise signal is decreased on its path from the sound source to the microphone [4]. A white noise band with a definite mid-band frequency and a 100% modulation factor was the test signal in this method

$$I(t) = \bar{I}(1 + \cos 2\pi f_m t), \qquad (7)$$

where f_m is the modulating frequency.

Due to the room's reverberation and the interfering noise, the modulation factor equal to 100% for a source signal is reduced to the value in a definite measurement point.

Hence, the received signal will have the following form

$$I_r(t) = \bar{I}_r[1 + m\cos(2\pi f_m t + \theta)], \qquad (8)$$

where θ is the resultant phase shift for modulating frequency. When the change of the coefficient m is determined for various values of f_m, then we reach the form of the modulation transfer function MTF. Then this function is expressed with an equivalent signal-noise ratio in the following form

$$\frac{S}{N}(f_m) = 10\lg\frac{m(f_m)}{1 - m(f_m)}. \qquad (9)$$

As a result of a certain limitation of the variability of quantity S/N (f_m), its averaging in the whole interval of frequency f_m and certain standarization, we achieve the so-called sound transmission index STI

$$\mathrm{STI}=\frac{\frac{S}{N}+15}{30}. \tag{10}$$

A special measurement method, called RASTI (Rapid STI), is used to calculate the value of this index.

According to the authors of this method the STI is an objective measure of speech intelligibility in a room. This is illustrated in Fig. 9[4]. Values of speech

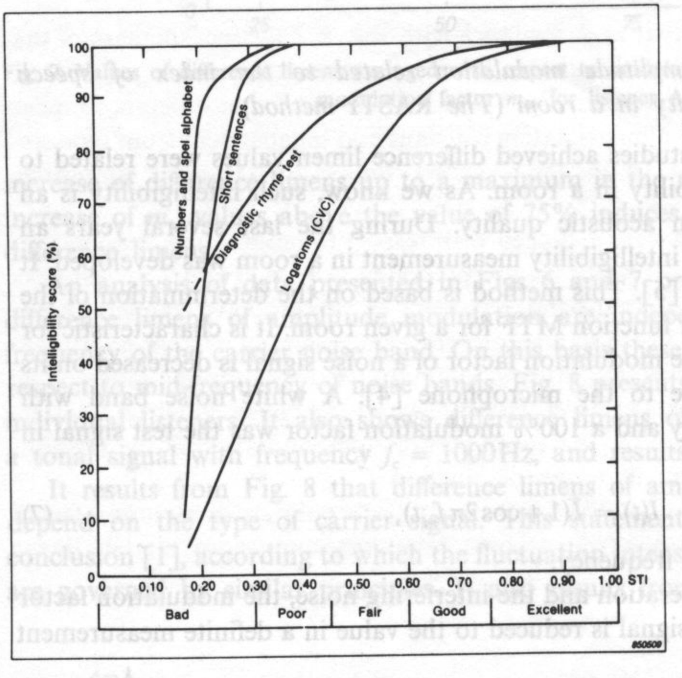

Fig. 9. Relationships between speech intelligibility expressed in percentages and the STI for various test signals [4]

intelligibility in percentage, determined subjectively by listeners which participated in the experiment, are marked on the Y-axis and standarized values of the STI which change from 0 to 1 are marked on the X-axis. A classification scale of room quality from the point of view of speech intelligibility is given below the axis of abscissae. It varies from bad to excellent. This classification corresponds to intervals equal to 0.15 STI in the middle STI variability range. This means that a change of the STI value of a signal measured in a room with 0.15 is clearly perceptible by the listener and significantly influences speech intelligibility evaluation.

With regard to research presented in papers [4, 5] it is interesting to relate the mentioned above STI value to the value of the difference limen for $m_w = 100\%$. This limen expresses the smallest change of the value of m (amplitude modulation factor), just noticeable by the listener.

In order to relate these values, the value of the difference limen for $m_w = 100\%$ had to be expressed in STI units. To this end, values of $\frac{S}{N}(f_m)$ were calculated according to expression (9) for the white noise octave bands with mid-band frequencies equal to 500 and 2000 Hz, and for successive modulating frequencies f_m from the range 1–16 Hz. Then the variability range of the $\frac{S}{N}(f_m)$ value was reduced to an interval $\pm$ 15dB in accordance with expression (10) and the mean value of this quantity was calculated for all f_c and f_m. A difference value equal to 0.16 STI was achieved from formula (10) for $m_w = 100\%$. This means that the listener can univocally state amplitude changes in the modulated test signal at STI values $\geqslant 0.16$. This considerable value of the difference limen does not confirm the conclusion resulting from paper [5], according to which STI changes of about 0.15 radically influence speech intelligibility in a room, i.e. speech sounds have to be univocally percepted by the listener.

It is also worth noticing that in accordance with Fig. 8 the perception of threshold amplitude changes of an amplitude modulated signal depends significantly on the value of the modulation factor of the reference signal (i.e. the m_w value). Therefore, it would be interesting to relate achieved values of difference limens (for $m_w < 100\%$) to changes of the amplitude ("modulation") occurring in real speech signals in further research.

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