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DEVIATIONS FROM EQUAL TEMPERAMENT IN TUNING ISOLATED MUSICAL INTERVALS

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Four music students tuned the frequency of a variable-tone oscillator to set it at given musical intervals up and down from the reference tone of 500 Hz. Pure tones and complex tones were used. Despite the dispersion of the results a general tendency appeared: small intervals were mostly diminished and large intervals mostly enlarged in comparison with their equally-tempered values. No distinct dependence of the size of musical intervals on the sound spectrum could be observed.

1. Introduction

The traditional theory of music attached high significance to mathematical calculations of numerical proportions representing musical intervals. Sets of these proportions, making up theoretical interval systems, had been discussed in numerous papers and treatises in the period preceding the introduction of the equally tempered scale in music. However, still after the introduction of equal temperament, the belief in the superiority of "pure" systems, applying simple proportions of integers, was shared by most musicians. This bielef, which still generally exists, applied not only to harmonic intervals in chords but also to intervals in melodic sequences. Most people speaking of perfect intonation believe that perfection attainable in this respect consists in accurate intonation of intervals corresponding to the frequency ratios resulting from the Pythagorean or just musical scale.

An important stage in the process of studying intonation of musical intervals were investigations by GARBUZOV [1, 2], who found that intonation in solo violin play was performed within certain zones of tolerance. The intonation zones of some intervals exceeded half the semitone. A slightly different approach to this problem was presented by those authors who, by means of electronically generated tones, investigated the intonation of isolated melodic intervals. Some of these investigations were concerned with octaves [11–15]. Within these studies, a tendency was found to tune octaves in a physical interval exceeding the frequency ratio 2 : 1. Investigations of the intonation of the other within-octave intervals [7, 8] indicated that these intervals were characterized by high intonation instability. The ranges within which the intervals tuned by using electronic oscillators were considered correct, appeared repeatedly to be wider than those resulting from the discrepancies between the just, Pythagorean and equally tempered scales.

The discovery of considerable differences in the size of the same interval tuned by the same musician on various occasions led to a revision of the previous views on the problem of melodic intonation and the function of theoretical interval systems in practice. However, in order to generalize these conclusions, some doubts had to be removed. The above-mentioned experiments [7, 8] were carried out by using pure tones as stimuli. It could be suspected that the use of such stimuli, not typical in music practice, had significantly disturbed the results. To clarify the matter, it was decided that experiments on tuning musical intervals would be performed once more, this time with the use of complex tones, in order to apply stimuli more similar to musical sounds.

2. Experiment

The experiment was carried out in individual sessions with four music students (women) who served as subjects. Two of them were pianists and two were violinists. Their task was to tune the frequency of an oscillator to set it at given musical intervals up and down from the preceding reference tone. The time paradigm of the stimuli was the following: 0,5-s reference tone, 0.5-s break, 0.5-s variable tone, 1.5-s break. The tones were presented binaurally through headphones at 50 dB SL. The frequency of the reference tone was 500 Hz, i.e. 79 cents below C_5. The reference tone frequency not belonging to normal musical keys was used to prevent the listeners from performing absolute pitch evaluation. (The basic means of prevention was the fact that none of the subjects had absolute pitch.) Each individual experimental session lasted about one hour with several short breaks. The order of tuning various intervals was quasi-random, indicated by the operator.

At the first stage of the experiment, sine-waves, triangle-waves, and square-waves were employed. After a few training tasks, each subject performed 10 series of experimental tunings for each kind of stimuli (altogether 3×10 series of 12 intervals up and 12 intervals down from the reference tone). Each subject could listen to the repeated sequence of stimuli and correct the frequency

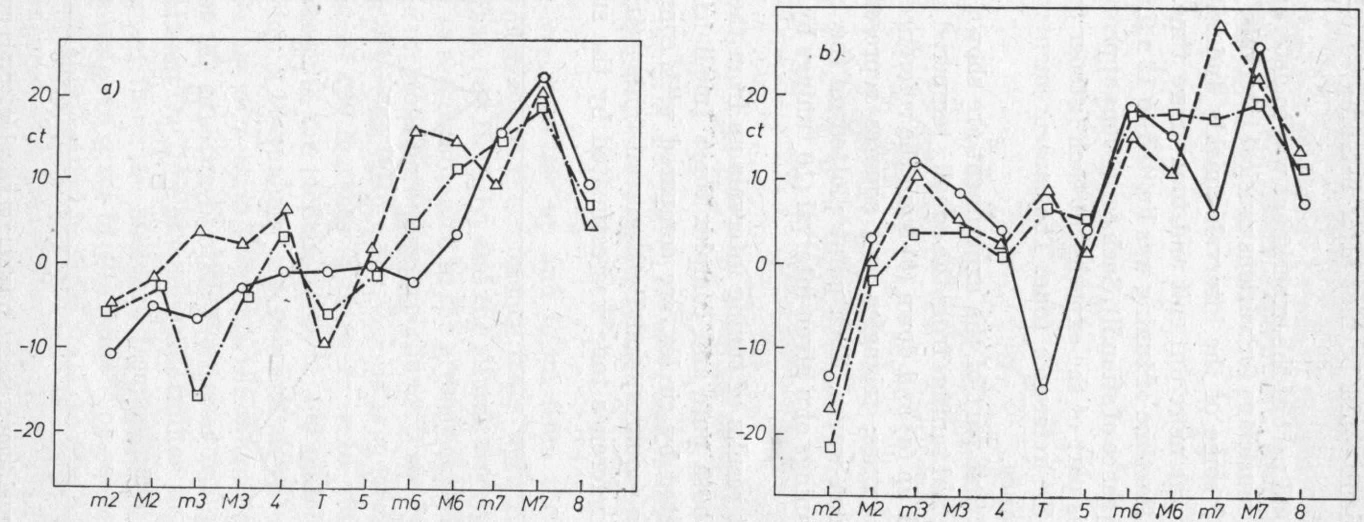

Fig. 1. Deviations from equal temperament in tuning musical intervals up (*a*) and down (*b*) from the reference tone. ○ – sine-wave, △ – trangle-wave, □ – square-wave. Intervals marked on the abscissa: minor and major second, minor and major third, pure fourth, tritone, pure fifth, minor and major sixth, minor and major seventh, octave

of the variable tone, until the given interval appeared to him as satisfactory. In practice, this requirement could be met after listening to 6–20 3-second sequencies.

The aim of the second part of the experiment was to determine the strength of the memory trace in musicians for various musical intervals. It was observed that the listeners tuned some of the intervals quickly and without difficulty. Tuning other intervals was more difficult and took more time. In the second part of the experiment the time of tuning was limited to 12 s (i.e. four presentations of the 3-second sequence of stimuli). Such conditions appeared to be closer to musical practice. In this part of the experiment each listener tuned 10 series of 12 intervals up from the reference tone. The measurements were performed with triangle-wave tones.

The results of the first part of the experiment are shown in Fig. 1 in the form of deviations of actual tunings from the equally tempered scale. The results concern intervals tuned up (*a*) and down (*b*) from the reference tone of 500 Hz. Circles represent pure tones; triangles and squares represent, respectively, triangle-waves and square-waves. Each point plotted on the curve represents a median value of 40 tunings of a given interval (10 tunings by each of the four subjects).

Fig. 2. shows joint results of tuning intervals up from the reference tone, comprising the use of both pure and complex tones (medians of 120 values). These results, represented by circles, are compared with computed values of intervals in just tuning (squares) and Pythagorean tuning (triangles). Tuning intervals up from the reference tone was estimated by the subjects as easier

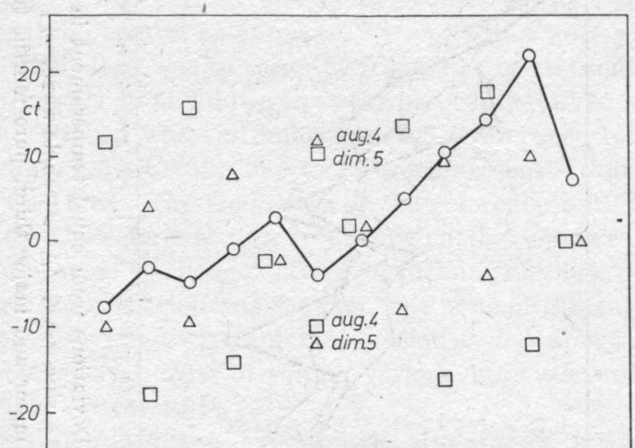

Fig. 2. Deviations from equal temperament in tuning musical intervals up from the reference tone of 500 Hz. Cumulative results ○, comparison with just □ and Pythagorean tuning △; aug. 4 – augmented fourth, dim. 5 – diminished fifth

and more natural than tuning down from the reference tone, therefore only the results of tuning upwards were presented in the figure.

The data in Fig. 2 were next compared with the results obtained in the investigations carried out previously by one of the authors [8]. In these previous investigations, like in the present experiment, four experienced musicians

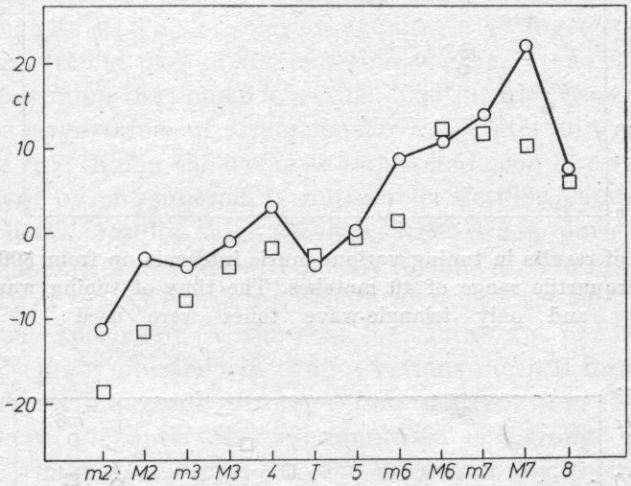

Fig. 3. Cumulative results as in Fig. 2 (○) compared with the results of the previous experiment (□) performed with pure-tone stimuli over a wide frequency range

tuned twelve-octave intervals up and down from the reference tones using headphones. Frequencies of the reference tones were 125, 250, 500, 1000 and 2000 Hz rather than 500 Hz only, and the stimuli were pure tones. The comparison of cumulative results obtained in the present experiment with the cumulative results of the previous pure-tone experiment is shown in Fig. 3. The present results are shown as circles, the previous results as squares. Each circle represents the median value of 120 matches (4 listeners $\times 10$ tunings $\times 3$ waveforms). Each square represents the median value of 400 matches (4 listeners $\times 5$ reference frequencies $\times 10$ tunings $\times 2$ (up and down)).

Fig. 4. shows the dispersion (interquartile ranges) of the results, obtained in second part of the experiment with the use of triangle-wave tones. In this part of the experiment the time of tuning was limited to 12 s and the intervals were tuned only up from the standard frequency 500 Hz. Each circle shows the interquartile range of a set of 40 results representing the deviation of the given interval from the equally tempered scale. In Fig. 5. the results from Fig. 4 (circles) were compared with the results of the previous study (squares). Squares represent interquartile ranges of cumulative data obtained with the use of pure-tones at the reference frequencies of 125, 250, 500, 1000 and 2000 Hz [8].

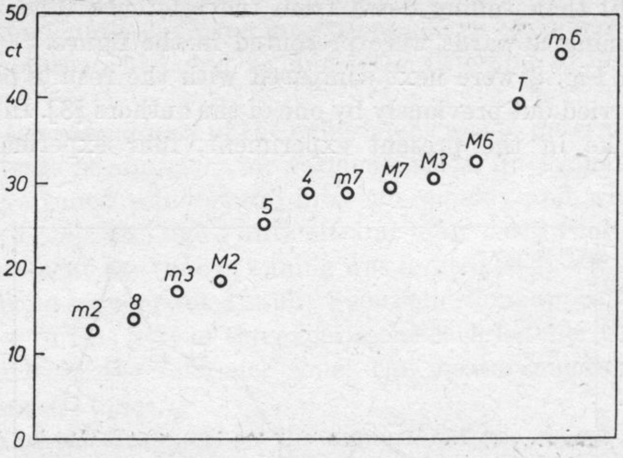

Fig. 4. Dispersion of results in tuning various music intervals up from 500 Hz. Each circle represents the interquartile range of 40 matches. The time of tuning was limited to 12 s and only triangle-wave tones were used

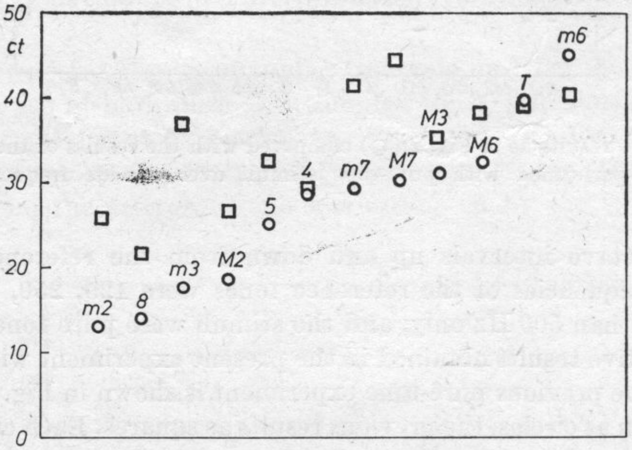

Fig. 5. Interquartile ranges of the results of tuning as in Fig. 4. (○) compared with the results of the previous study (□)

3. Conclusions

The results of the experiment prove that the intonation of melodic intervals is not in any distinct way dependent on the timbre of sounds. In the 1st part of the experiment, it was also confirmed, as had been noted before, that small intervals show a tendency to decrease, while large intervals tend to increase their size in comparison with the equally-tempered values. In this light, the commonly observed phenomenon of "octave enlargement" [11, 12] can be recognized as a symptom of a more general tendency.

An important conclusion follows from the observation of Fig. 2. A comparison of the mean values of freely tuned intervals with the values resulting from the assumption of just and Pythagorean tuning indicates a total lack of correlation with these scales. It can be presumed that neither just nor Pythagorean tuning play such a role in music as a large number of music theoreticians would be likely to assign to it. This conclusion acquires a stronger support following the results of the second part of the experiment. Fig. 4 shows the dispersion of the results in tuning particular intervals. The instability of the intonation, reflected by the large values of dispersion for most intervals, indicates that in the condition of free tuning the accurate implementation of any scale, whether equally tempered, or untempered, is impossible. Besides, comparison with the previously published results (Fig. 5) shows that when pure tones are used and the measurements extended to frequency regions used in music less frequently, the stability of tuning is still less accurate, despite the fact that in the previously described experiment [8] the time for tuning was not limited.

Different accuracy obtained in tuning various musical intervals was assumed to be the factor indicating differentiation in strength of the memory trace for a given interval [7]. Intervals were identified as "strong" when they were characterized by higher stability, i.e. the dispersion by their tuning results was lower. On the basis of the results of the second part of experiment (Fig. 4), the intervals of minor and major seconds, minor third and octave can be classified as "strong", whereas the intervals of minor sixth and tritone are particularly "weak". This classification coincides only partly with the one which could be assumed on the basis of the previous experiment [8] carried out in larger frequency range by using pure tones (Fig. 5), undoubtedly, the question of the criterion of interval strength requires further studies.

While drawing conclusions from the above-described experiments, one can attempt to outline a hypothesis explaining the apparently paradoxical contrast beetween the extremely high frequency sensitivity of the ear [6] and the great tolerance in tuning musical intervals. Musical intervals are discrete quality categories which function in a musical pitch system in a similar way as phonemes in natural language do. They may be considered as elements of the basic communication code in music. Their temporary structures form musical phrases and melodies which convey the largest part of musical "meaning".

Both phonemes of natural language and musical intervals may be objectively described in terms of their physical parameters such as frequency ratios (musical intervals), or time durations and formant frequency (vowels). However, none of those parameters may be considered as representing a single value, a point on the scale of physical magnitude. Rather they represent some more or less broad ranges of values within which the characteristic sensational quality of a given unit of a code is still preserved. Within each category, several narrower variants can be distinguished by ear. The implementation of these variants is related to the practical functioning of a given code. In the natural language they are called phonetic variants. They are divided into two subcategories: combinatorial variants, conditioned by the position of a given phoneme in the sequence of speech, and facultative variants, related to individual pronunciation and being used as indicators carrying information about the spaeker.

The existence of the phonetic variants in language has its analogy in music in form of the so-called intonation variants of musical intervals [9]. Similarly to the phonetic variants of speech, they may be divided into two kinds whose function, however, is slightly different from that in the case of phonetic variants.

The first kind of intonation variants may be called "acoustic variants". They appear as precisely defined versions of the size of a given interval, imposed by objective, physical and psychophysiological facts related to the production and perception of music sounds. Examples of such intonation variants are those which are applied to reach a minimum of dissonance (minimum of beats between partials of simultaneously sounding tones) in the conditions of particularly precise auditory control. The intervals between simultaneous tones set at minimum acoustic beats are characterized by possibly simplest frequency ratios of the fundamental tones. The above principle is best observed in just or "natural" tuning; therefore the thirds, sixths and other intervals are often tuned according to the just scale. This effect can be observed in "barbershop singing" [4] and in tuning such instruments as mouth harmonica.

Another example of acoustic intonation variants are some intervals played on bowed instruments such as the violin. The strings of these instruments are tuned in pure fifths; it forces the performer to raise most intervals in Pythagorean tuning [3]. Other acoustic variants can be observed commonly in piano and organ music and are know as the equally tempered scale. These intonation variants, although initially opposed to by musicians, finally became rooted in the auditory memory of music listeners and even appear to be preferred to others [16].

Whereas acoustic intonation variants are to a large extent objective, the other kind of intonation variants, which can be called "expressive variants", is characterized by direct relation to the subjective sensation of the musical content of a piece. Expressive intonation variants concern changes in intonation subordinated to the expressive function of music. In the Western music, the expression of some specific harmonic structures is emphasized by intonation. The shift of pitch accompaning the harmonic tensions can be mentioned as an example of this phenomenon; e.g. the shift of the leading note towards the keynote, or that of a dissonant tone towards its resolution [5, 10].

In contrast to both acoustic variants in music and phonetic variants in speech, the expressive variants in music can carry important elements of information transferred by the performer to the listener. Intonation deviations of this kind distinctly extend the emotional expressiveness of a piece. The possibility of using them in singing and playing instruments with free intonation gives music a peculiar feature, an additional dimension as it were, impossible to achieve while playing the fixed-pitch instruments.

The intonation variants of a given interval which are implemented according to the current requirements of music in performing a music piece or in listening to it, can occur randomly in the imagination of a musician while producing intervals isolated from the music context. In tuning isolated intervals, as it was done in the experiment described, subjects could not be prevented from relying subconsciously or even consciously upon memorized melodic fragments in which the given intervals were used. This could result in using various intonation variants of the same interval by various subjects or even by the same subject at various repetitions of the same tuning. The above-described processes, entirely beyond control of the experimenter, could have been responsible for the large dispersion of results in tuning isolated melodic intervals.

In the light of the above hypothesis, it should be recognized that those intervals which have more varied intonation variants, appear to be "weak" in free-tuning experiments. Conversely, "strong" intervals are those whose intonation variants in music are less varied. The group of particularly strong intervals includes an octave, a minor second and a fourth. On the other hand, a tritone and a minor sixth belong definitely to the weak group. Classification of other intervals in terms of their "interval strength" needs support in further investigations.

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THRESHOLDS OF PERCEPTION OF JUMP FREQUENCY CHANGES FOR A DECAYING SIGNAL

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The papers devoted in the literature to the subject of the perception of frequency changes most often deal with research on the perception of frequency modulation or its changes of linear character, or the evaluation of the pitch of a signal with frequency varying in time. Within the range of these problems, an interesting question, so far not undertaken, is that of the perception of jump frequency changes occurring in a decaying signal, quite frequent in practice. In view of this, research was undertaken with the essential purpose of determining the thresholds of perception by listeners of single and double frequency changes (jumps) occurring in a decaying signal with an exponential envelope, depending on: the duration of these changes, their mutual time interval and the position of these changes with repect to the onset of the signal. The results obtained indicated a strict relation between the course of the thresholds of the perception of jump frequency changes, depending on the time parameters of these changes.

1. Introduction

The previous investigations of the perception of frequency changes have mainly concentrated on the problems of: the perception of frequency modulation, the perception of changes in the frequency increase rate and the determination of the effect of these changes on the evaluation of sound pitch. The papers devoted in the literature to this range of research [2, 4, 8–10, 18, 19] are concerned mainly with signals with time invariable amplitude. However, in the literature there are no publications on the thresholds of perception of rapid frequency changes occurring in signals of decaying nature, which are encountered e.g. in investigating the phenomena of sound decay in a room [5, 11, 13] and in considering some problems in the range of speech, music acoustics etc. Within this range, one should regard as the most essential the investigation of the fundamentals of psychoacoustic evaluation of frequency changes for signals of this type, which is a quite complex problem. This complexity results from the fact that so far no methodology has been developed for the psychoacoustic research on these signals, nor has any better knowledge been obtained of the mechanism itself of the so-called dynamic perception, which will be understood here to mean the perception of signals with physical parameters varying in time. Within this range of problems, one can distinguish a number of interesting questions. One of them is the determination of the thresholds of the perception of jump frequency changes occurring in a signal with an exponential envelope, which is the essential aim of the research undertaken.

2. Perception of frequency changes occurring over the duration of a signal

In the literature, it is possible to distinguish the following two groups of investigations of the perception of frequency changes occurring over the duration of a signal:

a. Research on the perception of frequency changes caused by modulation or changes with the nature of linear frequency increases.

b. Research on the evaluation of the pitch of a signal with frequency varying in time.

Ad.a. ZWICKER'S paper [19] was the work of fundamental significance for the investigations of the thresholds of the perception of frequency changes. In this paper, it was stated that the thresholds of the perception of frequency changes (deviations) caused by the effect of modulation depend on the frequency and amplitude of the carrier tone, and on the frequency of the modulating tone. An increase in the intensity level of a signal to 30 dB causes a drop in the threshold value, moreover, a further increase in this level does not affect a change in the threshold deviation. An increase in the carrier frequency causes a linear increase in the threshold deviation for carrier frequencies higher than 500 Hz. The most essential relation estabilished in paper [19] cited is the depencence of the threshold deviation on the frequency modulation. In this dependence, the following characteristic intervals can be distinguished with respect to the value of f_{mod}:

$f_{mod} < 15$ Hz, where the hearing organ "follows" the successive frequency changes;

$f_{mod} = 15$–100 Hz, where there is the so-called sound roughness, described in detail in paper [6];

$f_{mod} > 100$ Hz, where the high modulation frequency causes the components to separate, as a result of which the modulated signal is detected as a composite sound.

The thresholds of the perception of frequency changes occurring in signals modulated by various modulating processes were the object of investigations described in paper [4]. The results of these investigations, in addition to a full confirmation of those contained in paper [19], demonstrated the existence of a strict dependence of the threshold of the perception of the frequency deviation on the kind of modulating process. In paper [4] it was found e.g. that the lowest threshold of the perception of frequency modulation occurs for a signal modulated by a rectangular process, whereas the highest one is obtained for a signal modulated by a triangular process.

In addition to the so-called roughness effect mentioned above, frequency modulation also involves the so-called trill effect [7, 15]. This effect occurs at low values of frequency modulation, 2–8 Hz. The threshold of the perception of this effect defined this value of frequency deviation at which a signal is sensed to change from one with fluctuating pitch into two tones with different pitch succeeding each other in time.

The perception of frequency modulated signals, also accompanied by amplitude changes, was the object of investigations presented in paper [3]. In addition to the determination of the modulation perception thresholds, these investigations found that in some conditions the amplitude-modulated tone can cause the same sensation as one frequency-modulated, and conversely.

A separate group of studies was carried out on the perception of frequency changes occurring continuously over the duration of a signal, in the limits between the initial, f_p, and the final, f_k, frequencies. The previous investigations performed in this range [9, 10] indicated that the threshold of the perception of frequency changes of this type depends strictly on the duration of the signal, at the frequency f_p or f_k, and also on the length of the time period in which this change occurs. An increase e.g. in the duration of the signal at the frequency f_p or f_k, and also in the length of the interval of continuous frequency change, is accompanied by a drop in the thresholds of the perception of frequency changes which results from facilitated detection of the frequency increment Δf.

Using similar signals, the thresholds of the perception of changes in the frequency increment rate [8] were also studied. The results obtained indicate that the course of these thresholds depends on the frequency increment Δf; moreover, at determinate Δf these thresholds depend on the frequency change rate, with respect to which they are determined. Furthermore, the course of the thresholds discussed depends strictly on the initial frequency f_p.

Ad.b. The evaluation of the pitch of signals characterised by frequency varying in time, was the object of investigations presented in [1]. These investigations consisted in comparing a simple tone with a signal whose frequency varied continuously in the limits between f_p and f_k. Moreover, the amplitude of the signal also varied by about 12 dB/octave, which, in the frequency variability interval used, corresponded to a value of 6 dB or, alternatively, 12 dB. As a result of the experiments performed, the duration of the signal at the frequency

f_p or f_k was found to have a deciding effect on the evaluation of the pitch of the whole signal. The duration of the signal at the frequency f_p, to which 90% of responses ascribes the pitch of the signal presented, is of particular significance for the phenomenon studies. Investigations of the effect of the frequency increment rate on the evaluation of the pitch of the signal indicated the different perception mechanisms for increasing and decreasing frequencies of the signal. Also here, the durations of the signal at the frequencies f_p and f_k were factors determining the evaluation of the pitch. However, it is difficult to establish to what extent the evaluation of the pitch of such signals depends e.g. on the duration of the signal at the frequency f_p or f_k, or on the frequency change rate, as in the investigations carried out the sum of the duration of frequency change and of the duration of a signal at constant frequency was constant.

Papers [2, 14, 16, 17] are also concerned with similar research problems. Papers [16, 17] considered the problem of the perception of signals whose frequency varied continuously between f_p and f_k and those which were composed of two tonal impulses with the frequencies f_p and f_k, separated by a time interval from each other. On the basis of these investigations, it was found that the two kinds of signals can cause sensations comparable with that caused by a simple tone (with a frequency falling in an interval including the highest and lowest frequencies of a signal varying in time), provided that the frequency change does not exceed some boundary value $|\Delta f|$ over which the two sensations become fuzzy. Just as in paper [1], also here, the effects observed were found to depend on the duration of the signals at the frequencies f_p and f_k, in particular on the duration of the signal at the frequency f_p.

The papers mentioned above within the range of investigations of the perception of frequency changes occurring over the duration of signals, are concerned above all with the determination of the thresholds of the perception of these changes at amplitude constant in time. In the literature, except for paper [12], there are not any other publications devoted to the determination of the thresholds of the perception of frequency changes occurring in signals with a decaying envelope. Bearing this in mind, investigations were undertaken to determine the thresholds of the perception of jump frequency changes occurring in a signal with an exponential envelope. These investigations have essentially a strictly cognitive character. Nevertheless, it should be pointed out that their results can also be of practical significance in establishing e.g. the criterion of the perception of irregular frequency changes occurring for the decay of a signal in a room, whose existence was found in papers [5, 11, 13].

3. Purpose and range of the investigations, equipment and method of the measurement

3.1. *Purpose and range of the investigations*

The essential purpose of the investigations undertaken was to determine the thresholds of the perception by listeners of single and double frequency changes occurring in a signal with an exponential envelope, depending on the duration of these changes, their mutual time interval and the position of these changes with respect to the onset of the signal. The frequency change was assumed to denote jump frequency transition from a value f_0 to some value $f_0 \pm \Delta f$, which remains constant within a time interval ΔT_2 or ΔT_4 (see Fig. 2b), and returns to the value f_0 outside these intervals.

In the investigations carried out, the following signal parameters were assumed to be constant: the intensity level $L_0 = 82$ dB, the fundamental frequency $f_0 = 1000$ Hz, the signal duration $T = 1000$ ms (understood as the total duration of the electric signal) and the duration of the pause between two successive signals $\Delta T = 1500$ ms.

The whole of the investigations was divided into two parts. In the first, attempts were made to determine the thresholds of the listeners' perception of only a single jump frequency change. In this part of the investigations, the variable parameters were the duration of the frequency jump ΔT_2 and the time interval ΔT_1 between this jump and the onset of the signal (see Fig. 2). In the second part of the investigations, attempts were made to determine the threshold of the perception of a single jump frequency change, in the presence of another jump frequency change, in a signal with the predescribed parameters ΔT_1, ΔT_2, Δf_1 (see Fig. 2). In these investigations, the following scheme of changes, frequency jumps, was assumed:

– the first change – predescribed (with a value over or below the threshold);

– the second change, whose threshold of perception was determined.

The time parameters defining the second change were:
ΔT_3 – the time interval between the frequency changes – and ΔT_4 – the duration of the second frequency change.

3.2. *Equipment and method of the measurement*

Fig. 1 shows a schematic diagram of the equipment set-up used to investigate the thresholds of the perception of jump frequency changes occurring in a signal with an exponential envelope. The basic unit of this set-up was the generator of a tone with an exponential envelope *2*, which was voltage controlled, due to which it was possible to obtain any changes in the output frequency of this generator in the direct proportion to the voltage fed to the control input. By means by a pulse, the generator *2* triggered the work of the generator of control processes *4*, which in turn generated the desired voltage process. This process was fed to the control input of the generator *2*, caused a signal with determinate – in terms of value and duration – changes, frequency jumps, to occur at its output (see Fig. 2b). The other elements of the measurement system consisted of a set of digital meters serving for continuous control of the time parameters of the signal and for continuous control of frequency, all of its time fragments. The set-up was complemented by signalling boards for mutual communication between the listeners and the experimentator. Fig. 2 shows schematically the sinusoidal signal with an exponential envelope (with a growth time of 50 ms) and jump variable frequency, obtained at the

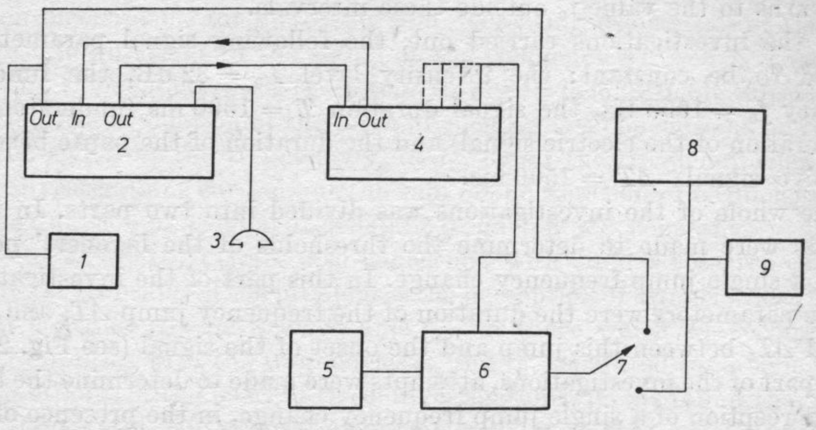

Fig. 1. Schematic diagram of the measurement system, *1* – digital frequency meter, *2* – generator of sinusoidal tone voltage-controlled, *3* – headphones, *4* – generator of control processes, *5* – impulse counter, *6* – time gate, *7* – switch, *8* – generator of the standard tone, *9* – frequency meter

output of the measurement system. In this signal, the following parameters could be modified independently:

– the value and direction of the frequency changes (jumps) Δf with respect to the frequency f_0 filling the signal;

– the duration of the particular frequency changes ΔT_2 and ΔT_4;

– the time interval between these changes ΔT_3;

– the time interval between the frequency change and the signal onset, ΔT_1.

As a result of calibration of the equipment set-up described above, it was found that the error of the frequency measurement at any time fragment of the output signal did not exceed 0.2 Hz, whereas the error involved in the measurement of the time interval distinguished in the signal fell within 0.2 ms.

The following method was applied in the investigations. The listener was asked to evaluate a pair of decaying signals in exponential envelopes. The first in the pair was the standard with a constant frequency of 1000 Hz, whose occurrence was signalled to the listener by a light signal; the other was a test signal containing a jump frequency change. (In turn, in determining the threshold of the perception of a double frequency change, the standard was a signal containing an appropriately chosen frequency change (see section 4.2).)

The listener's task was to state whether he noticed a difference in sound between the standard and the test signal.

The threshold values of the perception of frequency changes were determined from two measurement series:

– descending series (↓) – beginning from large values of frequency changes (jumps), always noticed by the listeners, decreasing it by 1 Hz from signal to signal, until the answer "I can hear the test signal without deformation" was obtained;

– ascending series (↑) – beginning from low values of frequency changes (jumps) and increasing it by 1 Hz from signal to signal, until the answer "I can hear the test signal with some deformation" was obtained.

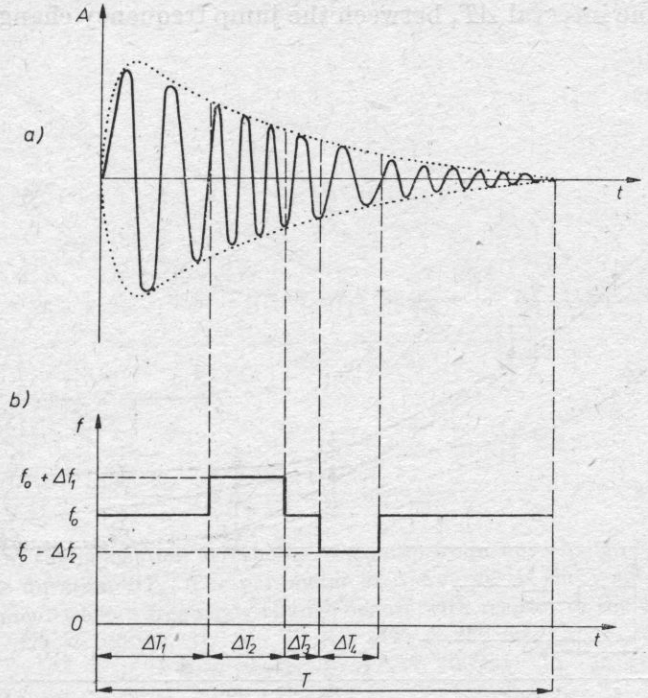

Fig. 2. Time history of the signal obtained at the output of the measurement system (*a*) and the corresponding frequency changes (jumps) (*b*)

The threshold value of frequency changes was determined for one pair of signals ΔT_1 and ΔT_2 on the basis of 10 descending and 10 ascending series. In view of the different mean values for the two series, first a variance analysis (Snedecor F-test) to verify whether the results obtained came from one population) and a test of agreement between the mean values, at the significance level $\alpha = 0.01$, were carried out. These tests gave affirmative results, permitting joint consideration of the results from the two series.

Two listeners, *AF* and *AS*, with audiologically correct hearing, took part in the investigations. A single measurement series did not exceed 15 minutes, and, moreover, over 3 hours no more than 4 series of this type were performed.

4. Measurement results and their analysis

4.1. The threshold of perception of a single jump frequency change

As was already mentioned above, in the first part of the investigations, attempts were made to determined the thresholds of the perception of a single jump frequency change which always occurred towards frequencies lower than the frequency filling the signal. These thresholds were determined, depending on:

— the duration ΔT_2 of the lowered frequency,

— the time interval ΔT_1 between the jump frequency change and the onset of the signal.

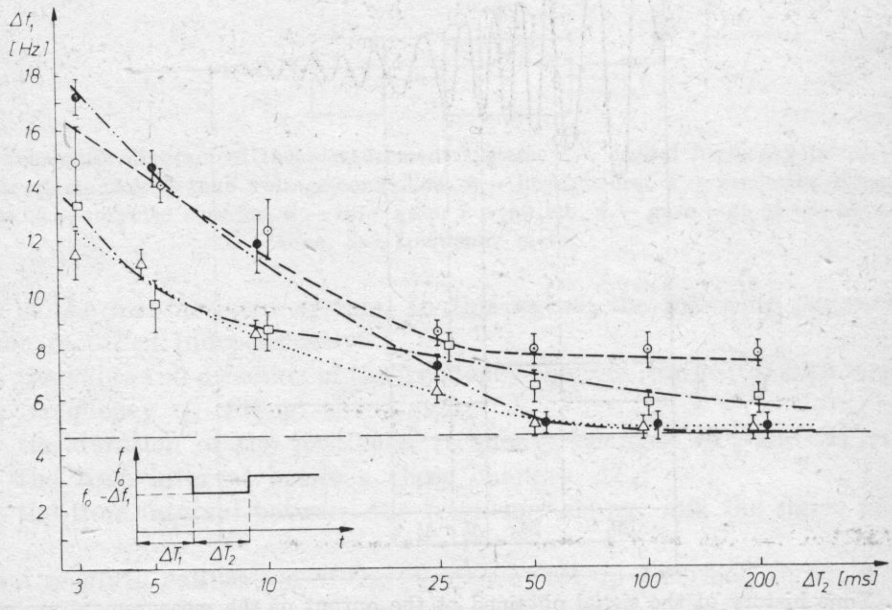

Fig. 3. Courses of the perception thresholds of a jump frequency change for the listener AF, depending on its duration ΔT_2, The parameter of the curves is the value of the time ΔT_1, defining the moment when a frequency change occurs with respect to the onset of the signal. ⊙ — — — — $\Delta T_1 = 100$ ms, □ — · — · — $\Delta T_1 = 250$ ms, △ ..... $\Delta T_1 = 450$ ms, ● — ·· — ·· — $\Delta T_1 = 700$ ms

The results obtained in this part of the investigations are shown in Figs 3, 4, 5 and 6, where, apart from the mean values, the standard deviations are also indicated. Figs 3 and 4 show the dependencies of the threshold of the perception of jump frequency change on its duration ΔT_2, respectively, for the listeners AF and AS. The parameter of these thresholds is the time interval ΔT_1 between the onset of the signal and the moment when the frequency jump occurs. Analysis of the data given in these figures shows that the thresholds of the perception of frequency changes are qualitatively similar for all the values of the parameter ΔT_1 and for the two listeners. Thus, it can be stated, in general, that as the duration of the jump frequency change decreases, the threshold of the perception of this change is increasingly high; moreover, for very short durations ΔT_2 of the order of 3 ms, it falls between 12–17 Hz. This

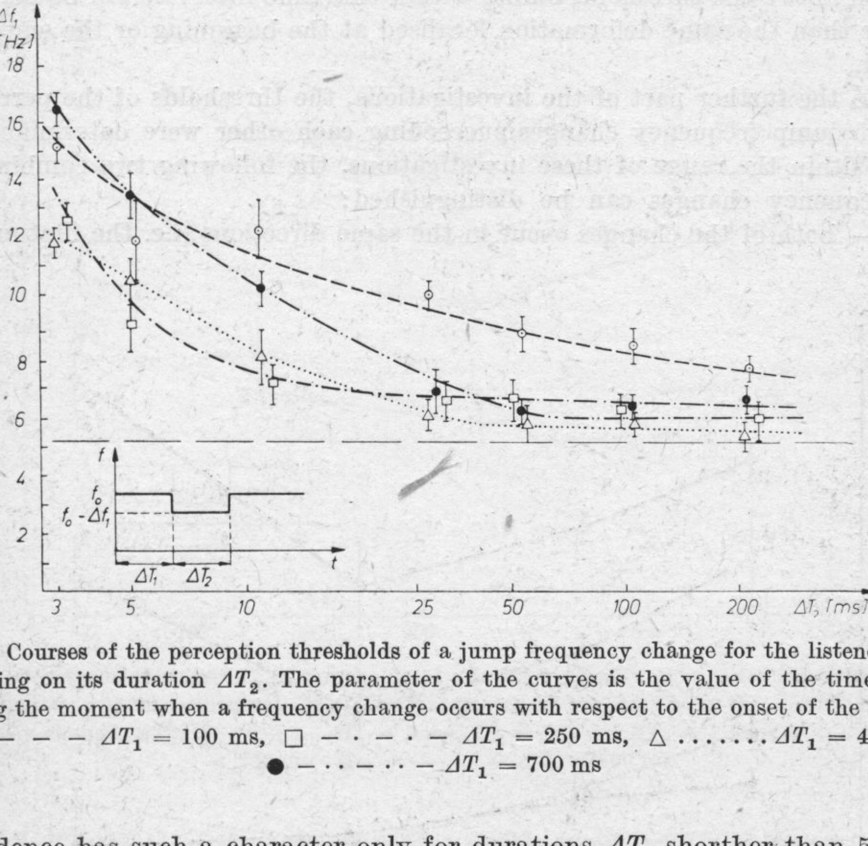

Fig. 4. Courses of the perception thresholds of a jump frequency change for the listener *AS*, depending on its duration ΔT_2. The parameter of the curves is the value of the time ΔT_1, defining the moment when a frequency change occurs with respect to the onset of the signal· ⊙ — — — — $\Delta T_1 = 100$ ms, □ — · — · — $\Delta T_1 = 250$ ms, △ .... $\Delta T_1 = 450$ ms, ● — · · — · · — $\Delta T_1 = 700$ ms

dependence has such a character only for durations ΔT_2 shorther than 50 ms, whereas above this value an increase in the duration ΔT_2 does not any more cause a change in the threshold value. This value remains constant, falling between 5–7 Hz. The existence of this finite and nonzero limit of the dependence discussed admits the presence in the decaying signal, of jump frequency changes with values below 5 Hz, which the listener never notices, irrespective of the duration of these changes. It seems interesting to verify the validity of this statement in relation to the perception of real sounds of speech or music.

Figs 5 and 6 show the thresholds of the perception of jump frequency changes, depending on the time interval ΔT_1. The parameter of these data is the duration of the frequency changes, ΔT_2. Just as in the previous case, the course of the thresholds in the case of the changes ΔT_1 is qualitatively similar for all the values of the parameter ΔT_2 and for the two listeners. It is interesting to note the fact that these thresholds have a characteristic minimum contained in the interval $\Delta T_1 \in (200\text{–}500 \text{ ms})$, and, moreover, this minimum is more distinct for shorter durations of the frequency change, ΔT_2. This fact suggests that for a signal decaying exponentially over this time interval, the hearing organ exhibits the best ability of perceiving frequency changes, i.e. any frequency deformation above the threshold, falling within this time interval, will be perceived better than the same deformation localised at the beginning or the end of the signal.

In the further part of the investigations, the thresholds of the perception of two jump frequency changes succeeding each other were determined.

Within the range of these investigations, the following two combinations of frequency changes can be distinguished:

— both of the changes occur in the same directions (i.e. the first and the

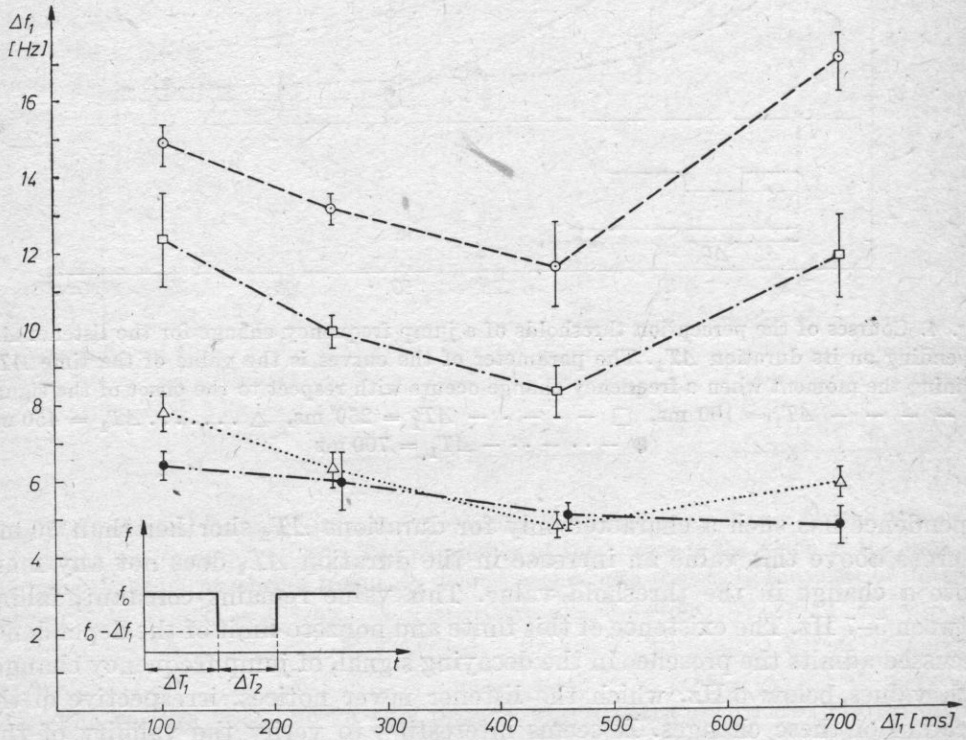

Fig. 5. Courses of the perception thresholds of a jump frequency change for the listener *AF*, depending on the time interval ΔT_1. The parameter of the curves is the duration of the frequency change, ΔT_2. ⊙ — — — $\Delta T_2 = 3$ ms, □ — · — · — $\Delta T_2 = 10$ ms, △ . . . . $\Delta T_2 = 200$ ms, ● — · · — · · — $\Delta T_2 = 500$ ms

second changes are temporary increases or decreases in frequency with respect to the frequency filling the signal);

– the changes occur in the opposite directions (i.e. the first change occurs towards higher frequencies, the second towards lower ones, with respect to the frequency filling the signal).

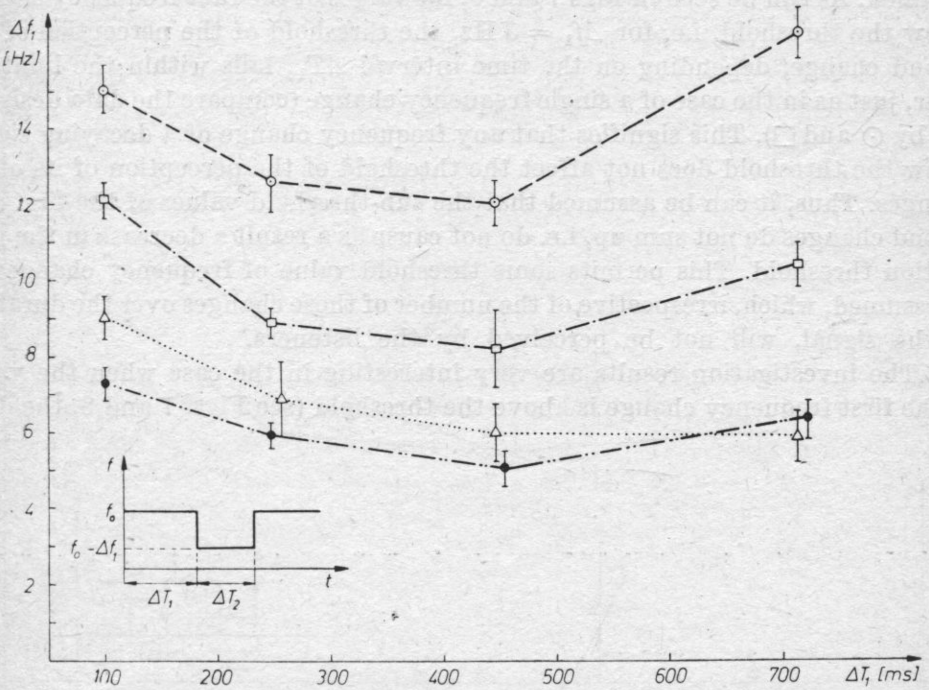

Fig. 6. Courses of the perception thresholds of a jump frequency change for the listener *AS* depending on the time interval ΔT_1. The parameter of the curves is the duration of the frequency change, ΔT_2. ⊙ – – – $\Delta T_2 = 3$ ms, □ – · – · – $\Delta T_2 = 10$ ms, △ . . . . $\Delta T_2 = 200$ ms, ● – · · – · · – $\Delta T_2 = 500$ ms

4.2. Threshold of the perception of a double jump frequency change

4.2.1. Jump frequency changes occurring in the same directions

The purpose of the investigations performed was to discover the mutual interactions of two jump frequency changes succeeding each other. In these investigations, with the predescribed time intervals $\Delta T_1 = 250$ ms, $\Delta T_2 = \Delta T_4 = 25$ ms and the predescribed value Δf_1 of the first change, the threshold of the perception of the second frequency change was determined, depending on the value ΔT_3 defining the time interval between these changes. In the first case, the value of the first frequency change Δf_1 was 5 Hz (below the threshold) and 10 Hz in the second case (above the threshold).

The two changes – frequency jumps – introduced were always made towards frequencies lower than that filling the signal. The results of these investigations are shown in Fig 7 and 8. In those two figures, the symbol ⊙ denotes in addition the values of the threshold of the perception of a single frequency change with the duration $\Delta T_2 = 25$ ms, facilitating comparison of the results obtained. As can be seen in Figs 7 and 8, for values of the first frequency change below the threshold, i.e. for $\Delta f_1 = 5$ Hz, the threshold of the perception of the second change, depending on the time interval ΔT_1, falls within the limits of error, just as in the case of a single frequency change (compare the data designated by ⊙ and □). This signifies that any frequency change of a decaying signal below the threshold does not affect the threshold of the perception of its other changes. Thus, it can be assumed that the sub-threshold values of the first and second changes do not sum up, i.e. do not cause as a result a decrease in the perception threshold. This permits some threshold value of frequency changes to be assumed, which, irrespective of the number of these changes over the duration of the signal, will not be perceived by the listeners.

The investigation results are very interesting in the case when the value of the first frequency change is above the threshold (see Figs. 7 and 8, the data

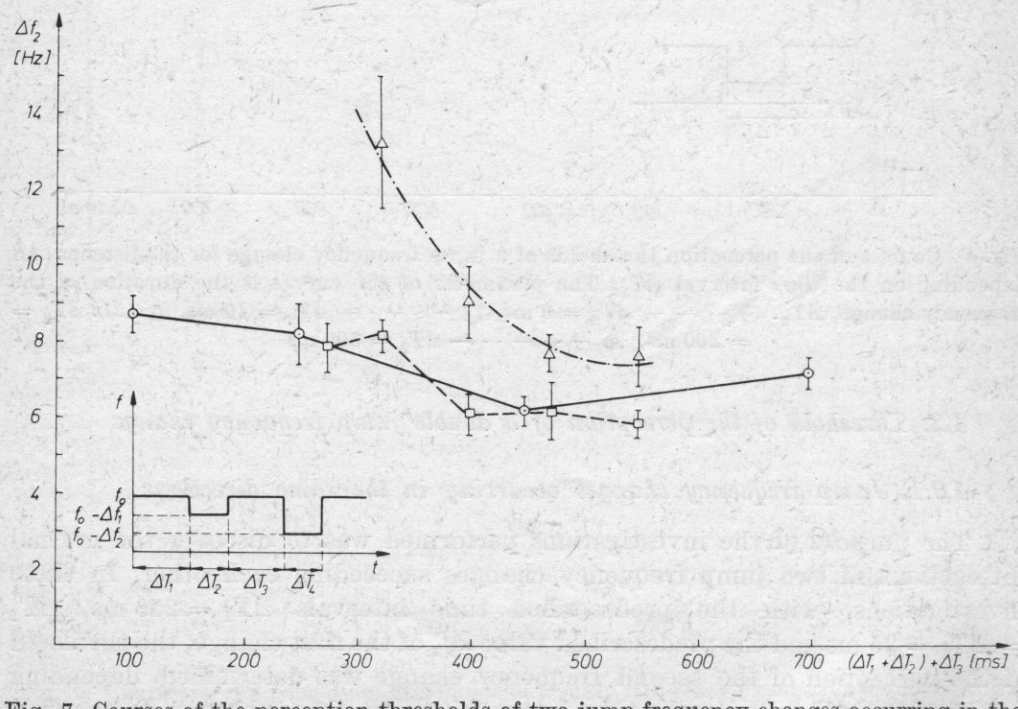

Fig. 7. Courses of the perception thresholds of two jump frequency changes occurring in the same directions, for the listener *AF*, depending onthe value of the time ΔT_3. ⊙ — — — threshold of perception of single change, □ — — — $\Delta f_1 = 5$ Hz, △ — · — · — $\Delta f_1 = 10$ Hz, $\Delta T_2 = \Delta T_4 = 25$ ms, $\Delta T_1 = 250$ ms

marked by Δ). It is then that the existence of the value of the first frequency change above the threshold causes a considerable increase in the threshold of the perception of the succeeding change. The increase in this threshold is the greater, the shorter is the time interval ΔT_3 between these changes. These experimental data can be interpreted in the light of the phenomenon of the second change being "masked" by the first one. It follows from the above

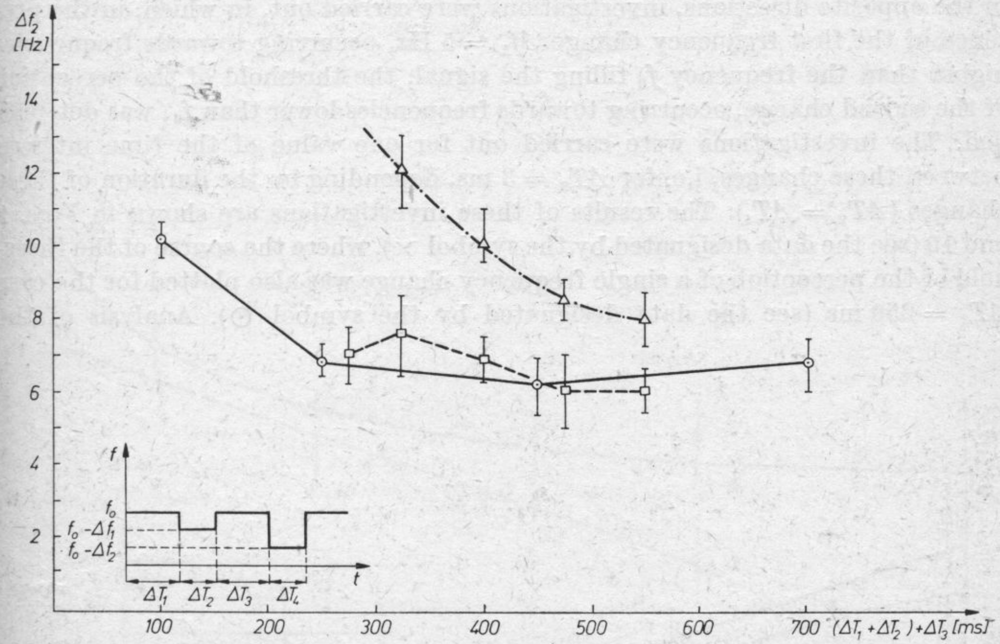

Fig. 8. Courses of the perception thresholds of two jump frequency changes occurring in the same directions, forthe listener *AS*, depending on the value of the time ΔT_3. ⊙ ——— threshold of perception of single change, □ — — — $\Delta f_1 = 5$ Hz, △ — · — · — $\Delta f_1 = 10$ Hz, $\Delta T_2 = \Delta T_4 = 25$ ms, $\Delta T_1 = 250$ ms

considerations that of two just perceptible frequency changes lying close to each other on the time scale, only the first will be perceived by the listener. This phenomenon permits the classiffication of some signal frequency changes above the threshold as imperceptible, on the condition, however, that these changes follow each other with only a slight (about 50 ms) shift in time.

Another aspect of the phenomenon discussed here is the problem of the listeners' perception of two frequency changes succeeding each other, both with values above the threshold. Thus, it follows from the listeners' report that it is very difficult to perceive the second frequency change when these changes lie close to each other on the time scale. Nonetheless, in general, it was possible to find that for durations ΔT_3 longer than 50 ms, the two jump frequency changes with values above the threshold are perceived separately by the listeners.

4.2.2. *Jump frequency changes occuring in the opposite directions*

In order to grasp the cooperation of two jump frequency changes occurring in the opposite directions, investigations were carried out, in which, in the presence of the first frequency change $\Delta f_1 = 5$ Hz, occurring towards frequencies higher than the frequency f_0 filling the signal, the threshold of the perception of the second change, occurring towards frequencies lower than f_0, was determined. The investigations were carried out for one value of the time interval between these changes, i.e. for $\Delta T_3 = 3$ ms, depending on the duration of these changes ($\Delta T_2 = \Delta T_4$). The results of these investigations are shown in Figs. 9 and 10 (see the data designated by the symbol $\times$), where the course of the threshold of the perception of a single frequency change was also plotted for the case $\Delta T_1 = 250$ ms (see the data designated by the symbol $\odot$). Analysis of the

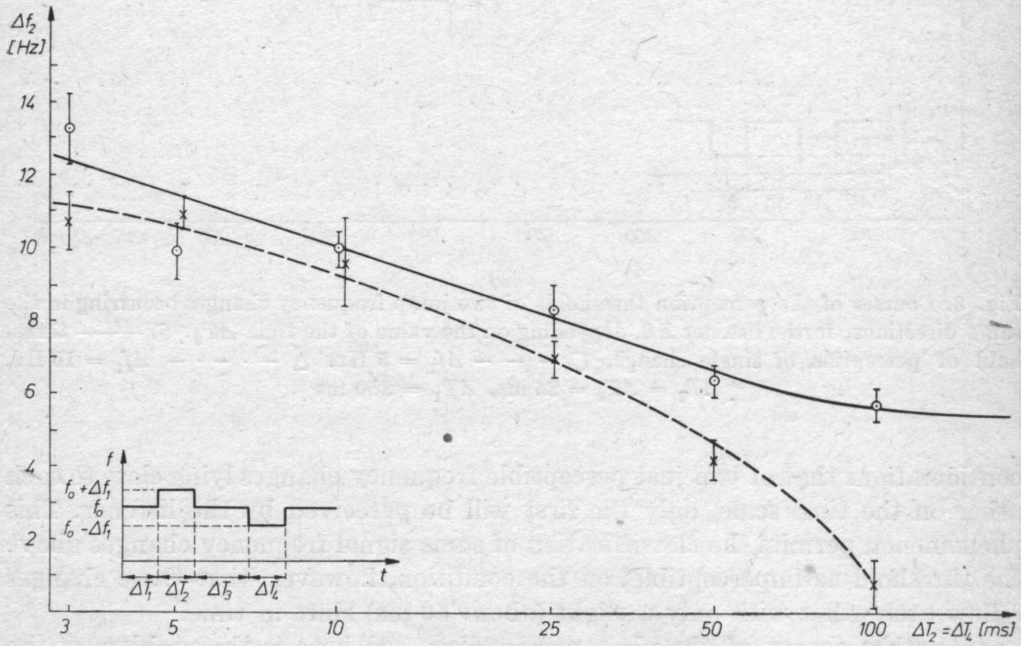

Fig. 9. Courses of the perception thresholds of two jump frequency changes occurring in the opposite directions, for the listener *AF*, depending on the value of $\Delta T_2 = \Delta T_4$. $\odot$ – the threshold of the perception of a single frequency change, x – the threshold of the perception of the second frequency change for the perscribed first change. $\Delta T_1 = 250$ ms, $\Delta T_3 = 3$ ms

course of the thresholds shown in these figures indicates that they are qualitatively similar, for both listeners, and, moreover, in these courses, two characteristic time intervals can be distinguished:

– the interval $\Delta T_2 = \Delta T_4 \in (3\text{–}30 \text{ ms})$, where the threshold of the perception of the second change is independent of the occurrence of the first change;

– the interval $\Delta T_2 = \Delta T_4 > 30$ ms, where the effect of the first frequency change is seen in the continuous decrease in the threshold of the perception of the second change.

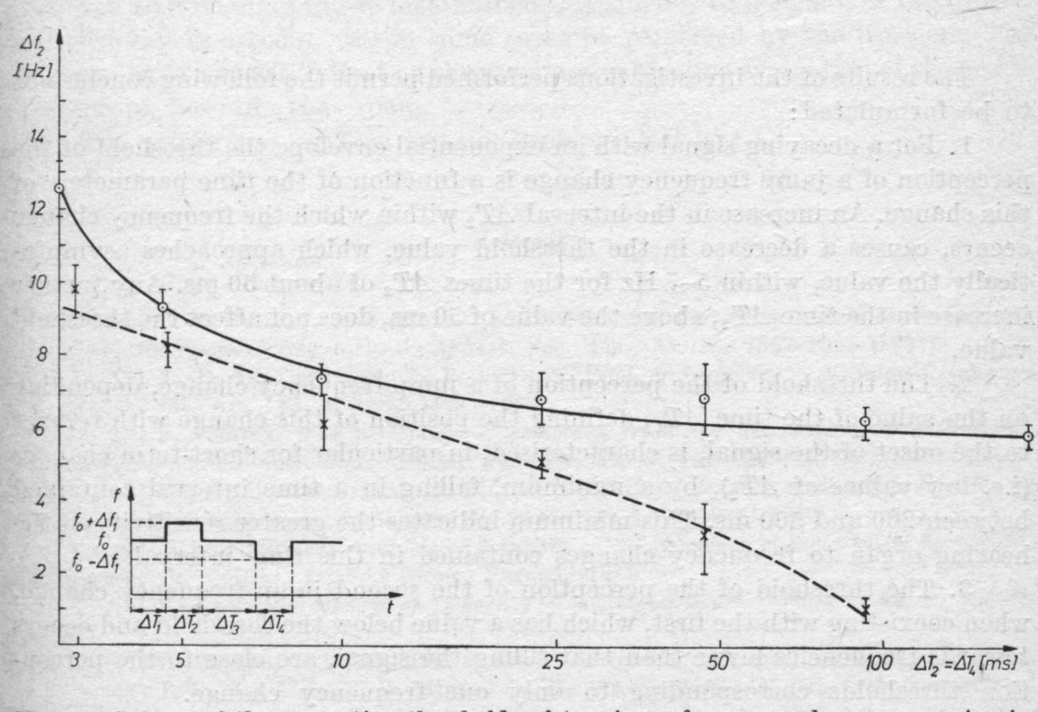

Fig. 10. Courses of the perception thresholds of two jump frequency changes occurring in the opposite directions, for the listener *AS*, depending on the value of $\Delta T_2 = \Delta T_4$. ⊙ – the threshold of the perception of a single frequency change, x – the threshold of the perception of the second frequency change with the prescribed first change. $\Delta T_1 = 250$ ms, $\Delta T_3 = 3$ms

Such a course of the thresholds signifies that for very short durations (up to 30 ms) of frequency changes of the order of $|\Delta f_1| = |\Delta f_2| = 5$ Hz, occurring in the opposite directions, these changes will not be perceived by the listeners.

It is not fully possible to refer the results presented above to those contained in the literature, since there are no publications on the perception of jump frequency changes in signals with amplitude varying in time. As was already mentioned in section 1, the existing papers on the perception of frequency changes are concerned with the thresholds of the perception of frequency modulation [19], the evaluation of the pitch of signals with frequency varying in time [2, 14], the difference pitch thresholds [17], or the evaluation of the pitch of signals with intensity and frequency varying in time [1], and, moreover, the changes in the respective physical parameters are far greater than the threshold values.

5. Final conclusions

The results of the investigations performed permit the following conclusions to be formulated:

1. For a decaying signal with an exponential envelope the threshold of the perception of a jump frequency change is a function of the time parameters of this change. An increase in the interval ΔT_2 within which the frequency change occurs, causes a decrease in the threshold value, which approaches asymptotically the value, within 5–7 Hz for the times ΔT_2 of about 50 ms. Any further increase in the time ΔT_2, above the value of 50 ms, does not affect the threshold value.

2. The threshold of the perception of a jump frequency change, depending on the value of the time ΔT_1, defining the position of this change with respect to the onset of the signal, is characterised, in particular for short-term changes (i.e. low values of ΔT_2), by a minimum, falling in a time interval contained between 200 and 500 ms. This minimum indicates the greater sensitivity of the hearing organ to frequency changes contained in this time interval.

3. The threshold of the perception of the second jump frequency change, when coexisting with the first, which has a value below the threshold and occurs towards frequencies lower than that filling the signal, are close to the perception thresholds corresponding to only one frequency change.

4. The occurrence of two jump frequency changes occurring in the same direction, is accompanied by the phenomenon of "masking", causing an increase in the threshold of the perception of the second change, in the case when the first one has a value above the threshold. It follows from this fact that some signal frequency changes can be recognized as imperceptible, even when they are greater in value than the changes "masking" them, on the condition that the time interval between these changes does not exceed the value $\Delta T_3 = 50$ ms.

5. The threshold of the perception of two jump frequency changes occurring in the opposite directions is, on the assumption that the value of the first of them is below the threshold, determined by the parameters of the two changes. It was found that for short durations of these changes, $\Delta T_2 = \Delta T_4 < 30$ ms, localised close to each other in time ($\Delta T_3 = 3$ ms), the occurrence of the first change does not affect essentially on the threshold of the perception of the

second change. Thus, the role of the sub-threshold frequency change in the definition of the value of the threshold of the second frequency change is slight. In turn, for the times $\Delta T_2 = \Delta T_4 > 30$ ms, the effect of the first frequency change already becomes quite large, causing a considerable decrease in the value of the threshold of the second change.

In conclusion, it is interesting to note that the values of the thresholds of the perception of frequency changes obtained in these investigations, are lower than some changes of the so-called instantaneous frequency, occurring in the process of sound decay in a room [5, 11, 13]. Thus, on this basis, it can be believed that changes in the instantaneous frequency of a signal, in the process of its decay in a room, will in some cases be perceived by the listeners. This fact can have a specific effect on the resultant subjective evaluation of the acoustic properties of the room.

The paper was written within Problem MR.I.24.IX

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THRESHOLDS OF PERCEPTION OF IRREGULAR SIGNAL FREQUENCY CHANGES

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In the literature, the problem of the perception of signal frequency changes has been considered mainly with reference to regular changes, obtained in the process of frequency modulation of a tone by a tone. There are, however, no publications on the thresholds of the perception of irregular frequency changes.

This fact was an encouragement to undertake investigations with the essential purpose of determining the thresholds of the perception of irregular frequency changes for a signal with constant amplitude and a decaying signal with an exponential envelope, depending on: the carrier freguency of the signal, its intensity level and the duration of the decaying signal. The courses of the perception thresholds of irregular frequency changes obtained here are much more general than the data published previously on the subject in the literature.

The investigation results obtained permit better knowledge of the mechanism of the so-called dynamic perception of signals, i.e. the perception of signals with parameters varying in time, whose natural counterpart in practice are the sounds of speech and music.

1. Introduction

The previous investigations carried out in the field of research on the perception of signal frequency changes have been concerned mainly with the determination of the thresholds of the perception of these changes for cases of frequency modulation (FM) [2–6, 8, 21–23] or the evaluation of similarity of modulated signals [5, 14]. The results of these investigations permitted e.g. the determination of the dependence of the threshold frequency deviation Δf (or the quotient $\Delta f/f_m$) on the carrier frequency.

These investigations were developed by HARTMANN [8] and FETH [4], who presented the thresholds of the perception of the frequency modulation of a simple tone by various signals, including rectangular, triangular, trapezoidal and sinusoidal ones.

The results of the previous investigations show that in the process of the perception of modulated signals, the phases of the lateral spectral components of their spectra are of deciding significance only when they are within one critical band. In this range, it is interesting to note ZWICKER's conception [22], according to which the perception of modulated signals can be based on the working principle of the "rectangular filter". This conception was discussed in a large number of papers [2, 3, 5–7, 13]. FETH [3] and CONINX [2] questioned to some extent its validity, while GOLDSTEIN [5], MAIWALD [13] and HARTMANN [6, 7] complemented it, replacing the rectangular filter by a trapezoidal one, which improved distinctly the agreement between these conceptions and then results of experimental research. In this respect, it is particularly interesting to note the investigations carried out by HARTMANN [6, 7], who, after performing a series of experiments, found that the perception of signals modulated by tones depends only on the spectral component with frequency lower than that of the carrier, since the component with the higher frequency is then completely masked.

It is also intersting to mention that some papers in this range of research indicate the existence of some additional effects related to frequency modulation, such as e.g. roughness, studied in detail in paper [11], and the so-called trill effect, considered in papers [15, 20].

A separate group of investigations consists of research on the perception of frequency changes constant in time, occurring between two steady states. The experimental investigations in this rrange [1, 16, 17] indicated that the time parameters of the signal exert a deciding influence on the threshold of the perception of frequency changes of this type. In this case, the durations of the steady states of signals play a particular role. So far, however, it has not been determined sufficiently well to what extent the threshold of the perception of these frequency changes is determined by steady states, and to what extent, by the continuous change in the frequency of the signal.

All the papers mentioned so far were concerned with frequency changes occurring in a signal with constant amplitude.

In the literature, apart from papers [1, 2, 9, 18, 19], there are in fact no more specifically documented data on the perception of frequency changes accompanied by given changes in the intensity level of the signal. In this range, interesting results were introduced in paper by CONINX [2] and HARTMANN [9], dealing with the perception of simultaneous changes in the amplitude and frequency of the signal, and moreover, these changes have the character of frequency and amplitude modulation by the same process. The problem of frequency modulation of a signal with amplitude varying in time was also the object of considerations in paper [18], as a result of which the thresholds of the perception of the frequency changes in a signal decaying exponentially were determined. These investigations found the existence of the dependence of the threshold deviation on the intensity level of the signal and on its carrier and modulating frequencies. In paper [19], in contrast to continuous frequency changes, the perception of jump frequency changes, occurring in a decaying signal, was investigated. Apart from the determination of the thresholds of the perception of a single jump frequency change, depending on its time parameters (i.e. its duration and the time defining its localisation in the signal), investigations were also performed to estabilish the effect of one of the frequency changes on the threshold of the perception of the second change. As a result of these investigations, it was found that in the case of two jump frequency changes, one can speak of the existence of the specific phenomenon of masking, consisting in the increase in the threshold of the perception of the second frequency change, in the case when the value of the first is above the threshold [19]. It should be noted that all the papers mentioned above are concerned with frequency changes of which it can be said that they have a determined character, expressible in analytical form.

A distinct extension and generalization of the problems mentioned above is the question of the determination of the perception thresholds of irregular frequency changes with character close to random, which has no counterpart in the literature. It is significant that this question is related directly to the perception of processes occurring in reality (e.g. natural sounds of speech and music), for which one of the more important characteristics is the stochastic character of amplitude and frequency in time.

The problem of the perception of irregular frequency changes occurring in signals with amplitudes constant and decaying exponentially with time, is the object of the present considerations. The essential purpose of the paper is tc determine the thresholds of the perception of these changes, depending on the carrier frequency of the signal, changes in its intensity level and the duration of the signal.

Within the range of the investigations performed, irregular frequency changes were obtained by way of frequency modulation of a tone by particular bands of white noise. In the process of the perception of the signals thus modulated, the essential role is played by their spectral structure, which will be discussed in greater detail in section 2.

2. Spectral structure of a signal with frequency modulated by band noise

In the case of the frequency modulation of a tone by another, one can, as is known, determine in a relatively simple way, on the basis of Bessel functions, the spectrum of the modulated signal [10, 12]. In addition for a signal of this type, its basic parameters are defined unambiguously, such as the carrier and modulating frequencies and the deviation range. A much more complex matter is the problem of the determination of the spectrum of a tone with frequency modulated by a random signal, which in the case considered was a band of white noise with the power N, defined by the formula

$$G_x(\omega) = \begin{cases} G_x & \text{for } -\omega_g < \omega < \omega_g, \\ 0 & \text{for other } \omega, \end{cases} \tag{1}$$

and the Gaussian probability distribution

$$p(x) = \frac{1}{N\sqrt{2\pi}} \exp\left(-\frac{x^2}{2N}\right). \tag{2}$$

This complexity results from the lack of an analytical expression describing the form of the modulating signal, which is assigned to the class of random signals.

It can be assumed that the random process considered is a stationary ergodic process with the autocorrelation function $R_x(\tau)$ and the variance σ_x^2. The instantaneous frequency $\omega(t)$ of the modulated signal can be expressed, in general, as

$$\omega(t) = \omega_0 + kx(t) = \frac{d\Phi(t)}{dt}, \tag{3}$$

where $x(t)$ is some sample function of the random process, and $\Phi(t)$ is the instantaneous phase of the modulated signal.

In the case considered, the frequency deviation (or the phase deviation) cannot be determined for the modulated signal as the maximum shift in this quantity, as it is done in the case of determined modulating processes. A quantity called the effective frequency deviation $\Delta\omega_{ef}$, which is proportional to the effective (mean square) value σ_x of the modulating signal, is used as the measure of the degree of modulation by random (noise-like) processes, i.e.

$$\Delta\omega_{ef} = k\sigma_x. \tag{4}$$

In order to determine the spectrum of the modulated signal, first its autocorrelation function should be defined. The phase of the very process $\Phi(t)$ can now be considered. Integration of expression (3) gives

$$\Phi = \omega_0 t + k\int_0^t x(t')\,dt' = \omega_0 t + \theta(t). \tag{5}$$

The function $\theta(t)$ also has the Gaussian probability distribution, since it has been formed by integrating the process $x(t)$. The spectral density of the function

$\theta(t)$ can be written in the form

$$G_\theta(\omega) = k^2 \frac{G_x(\omega)}{\omega^2}. \tag{6}$$

Knowledge of phase (5) of the modulated signal and of the probability distribution of the function $\theta(t)$ permits to calculate the autocorrelation function $R(\tau)$ of the modulated signal by statistical averaging. This gives as a result

$$R(\tau) = \frac{1}{2} A^2 \cos\omega_0\tau \exp\{-[R_\theta(0) - R_\theta(\tau)]\}, \tag{7}$$

where $R_\theta(\tau)$ is the autocorrelation function of the function $\theta(t)$. By using now the Wiener-Chinczyn theorem, the spectrum of the modulated signal $G(\omega)$ can be represented in the following way:

$$G(\omega) = \frac{1}{2} A^2 \exp[-R_\theta(0)] \int_{-\infty}^{\infty} \exp[R_\theta(\tau)] \big[\exp[i(\omega+\omega_0)\tau] + \exp[i(\omega-\omega_0)\tau]\big] d\tau. \tag{8}$$

By considering the modulation by a noise band (defined by dependence (1)), which occurs when $R_\theta(0) \ll 1$, the expression $\exp[R_\vartheta(\tau)]$ can be given in the form of a series, taking into account only the first two of its terms. In addition, using dependence (6), it can finally be written that

$$G(\omega) = \frac{A^2}{4} \left[\delta(\omega-\omega_0) + k^2 \frac{G_x(\omega-\omega_0)}{(\omega-\omega_0^2)^2} + \delta(\omega+\omega_0) + k^2 \frac{G_x(\omega+\omega_0)}{(\omega+\omega_0)^2}\right]. \tag{9}$$

The final dependence (9) describes the spectrum of a sinusoidal signal with the pulsation ω_0, frequency-modulated by a band noise, determined by relation (1).

It follows from this formula that the spectrum of the modulated signal contains a sinusoidal carrier signal, represented in this case by the function $\delta(\omega \pm \omega_0)$, while the components with the form $G_x(\omega \pm \omega_0)/(\omega \pm \omega_0)^2$ express the fuzziness of the spectrum, related to the process of frequency modulation

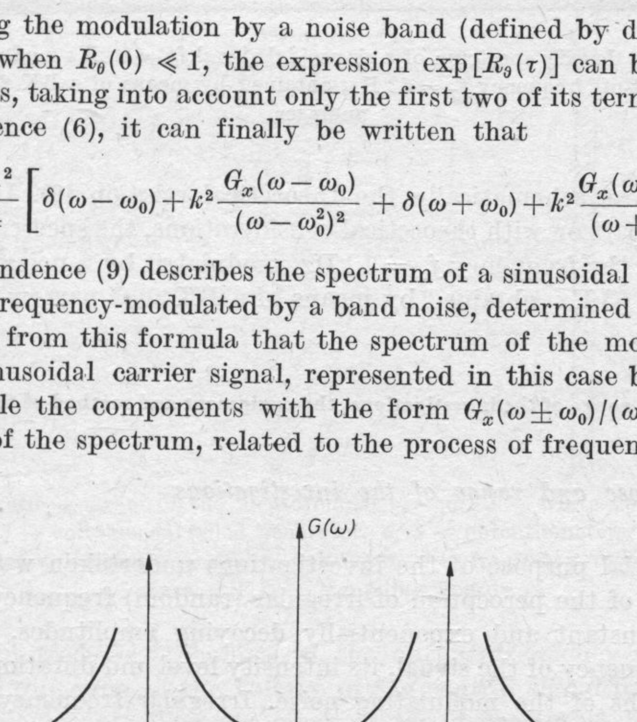

Fig. 1. The power density spectrum of a sinusoidal signal modulated by a noise band with a prescribed cut-off frequency, according to dependence (9)

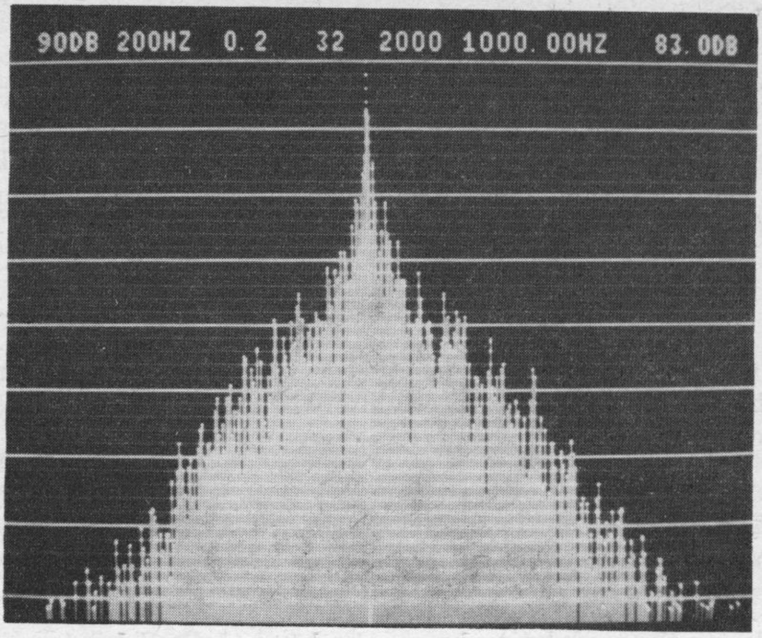

Fig. 2. The power density spectrum of a sinusoidal signal $f_c = 1$ kHz modulated by a noise band with the cut-off frequency $f_g = 63$ Hz, obtained by means of a BK 2033 narrow-band analyser

Fig. 1 shows schematically the theoretical relation (9). In turn, Fig. 2 shows, for comparison with theoretical considerations, the spectrum of a sinusoidal signal with the frequency $f_c = 1$ kHz, modulated by a noise band with the frequency $f_g = 63$ Hz, obtained by means of a BK 2033 narrow-band analyser.

3. Purpose and range of the investigations, the equipment and method of the measurement

3.1. Purpose and range of the investigations

The essential purpose of the investigations undertaken was to determine the thresholds of the perception of irregular (random) frequency changes for a signal with constant and exponentially decaying amplitudes, depending on: the carrier frequency of the signal, its intensity level and duration, for the different bandwidths of the modulating noise. Irregular frequency changes were obtained by frequency modulation of a tone by white noise bands with widths varying in an octave ratio. The deviation range of the signal thus modulated was proportional to the effective value of the noise band, while the bandwidth defined the range of modulating frequencies.

The investigations included:

– change in the carrier frequency f_c in an octave ratio, over the range 125–4000 Hz;

– change in the bandwidth of modulating noise, defined by the cut-off frequency f_g of the band, over the range 31–1000 Hz;

– change in the intensity level of the modulated signal, over the range 55–85 dB (with jumps every 10 dB);

– change in the duration T of the decaying signal, over the range 125 ms–1.5 s.

3.2. *Equipment and method of the measurement*

Fig. 3. shows a schematic diagram of the equipment set-up used to investigate the thresholds of the perception of irregular (random) frequency changes. An essential part of this set-up was the voltage-controlled simple tone generator

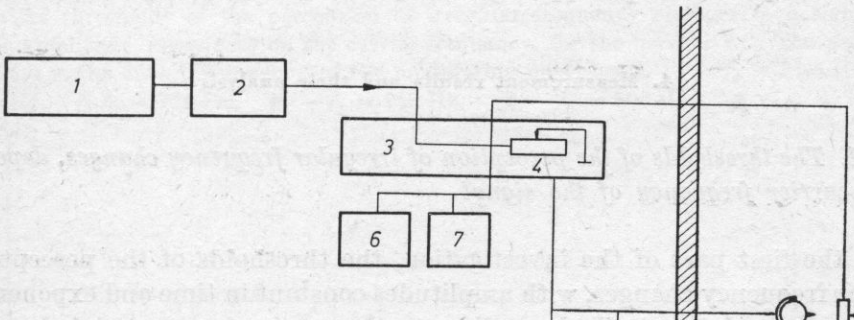

Fig. 3. A schematic diagram of the measurement system: *1* – white noise generator, *2* – low-pass filter, *3* – voltage-controlled generator, *4, 5* – potentiometers, *6* – digital voltmeter, *7* – plotter voltmeter, *8* – digital voltmeter, *9* – frequency meter, *10* – headphones, *11, 12* – signalling boards

3, which permitted any changes in the output frequency to be obtained, in the direct proportion to the voltage of the control signal fed to the control input. The signal controlling the work of the generator *3* was white noise generated by the noise generator *1*, undergoing previous filtration by a low-pass filter *2*, with the cut-off frequency f_g. The effective value of the noise band, responsible for the effective value of deviation, Δf_{ef}, could be adjusted independently by means of the potentiometers *4* and *5*, linked in parallel, at the disposal of the experimentator and observer. Additional elements of this set-up consisted of a system of meters for the control of both the modulating and output signals. The whole of the equipment was complete with SN-60 *10* measurement headphones and the signalling boards of the experimentator *11* and the observer (12).

Measurements of the thresholds of the perception of irregular frequency changes were carried out on the basis of a method which was some modiffication of the limits method. This method consisted in the determination by the listener, by means of the potentiometer *5*, of the just perceptible value of the frequency deviation occurring in a modulated signal, which was regarded as the threshold value of the effective deviation. It should be pointed out that an essential influence on the accuracy of the determination of the threshold deviation value was exerted by the accuracy of the determination of the effective value of the modulating noise band intensity, to which particular attention was paid during the measurements. Two listeners with audiologically normal hearing, over the frequency range applied, took part in the investigations.

4. Measurement results and their analysis

4.1. The thresholds of the perception of irregular frequency changes, depending on the carrier frequency of the signal

In the first part of the investigation, the thresholds of the perception of irregular frequency changes, with amplitudes constant in time and exponentially decaying, were determined, depending on the carrier frequency of the signal. Figs. 4–6 and 7 show successively the behaviour of the threshold values Δf_{ef} obtained over this range for the listeners EO and AS.

The parameter of these thresholds is the cut-off frequency f_g of the modulating noise band. In keeping with the results shown in Figs 4–7, an increase in the carrier frequency of the signal, over the range 125–1000 Hz, causes only a slight change in the value of Δf_{ef}. In turn, any further increase in this frequency, above 1000 Hz, causes a distinct increase in the threshold deviation. The results given by Figs 4–7 also indicate that changes in the threshold deviation Δf_{ef} do not depend unambiguously on the modulating noise bandwidth, or, alternatively, on the cut-off frequency f_g of this band, but that they constitute some scatter of results. This fact is justified by the results of the investigations of the threshold deviation in the case of modulation of a tone by another, according to which the lowest threshold of the perception of the deviation occurs at low modulating frequencies, of the order of a few Hz. This signifies that in the case of modulation by a noise band, the value of the threshold deviation is determined above all by the components lying in the low frequency range,

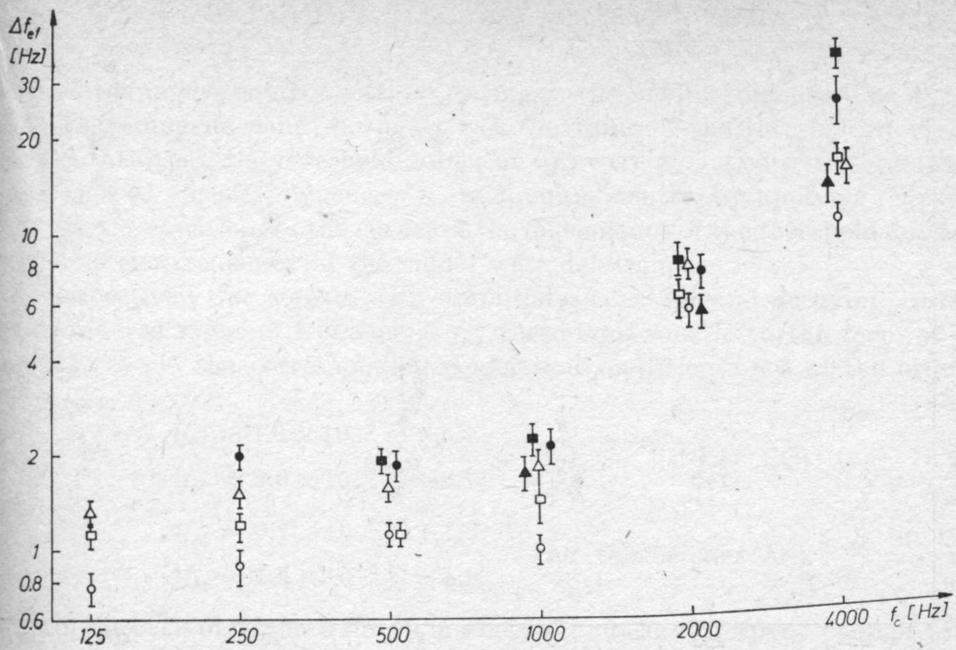

Fig. 4. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on the carrier frequency, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ f_g – 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

Fig. 5. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on the carrier frequency, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g – 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

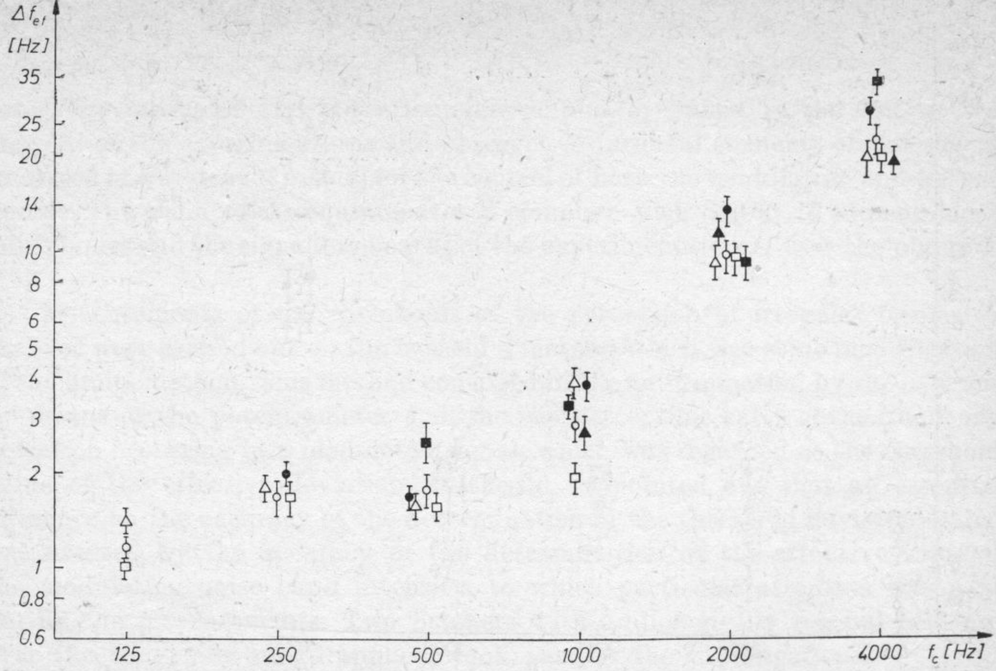

Fig. 6. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on the carrier frequency, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

Fig. 7. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on the carrier frequency, for the listener AS. The parameter of the data is the cut--off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz, ▲ – f_g = 1000 Hz

whereas the higher components, appearing in the modulating signal as a result of a broadening its band, do not affect the value of the threshold deviation.

On this basis, the threshold values of Δf_{ef} were averaged over the range of the measured cut-off frequencies f_g, and, subsequently, by applying regression analysis, the equations of the curves of the dependence of the threshold deviation on the carrier frequency of the signal were determined.

Respectively for signals with amplitudes constant and decaying in time, for considered range of frequencies f_c, these equations have the form of (10) and (11), while the corresponding correlation coefficients are of the order of 95%:

$$\Delta f_{ef} = 1.1\times 10^{-6} f_c^2 + 1.4 \quad \text{(for the listener EO);} \tag{10}$$
$$\Delta f_{ef} = 2.0\times 10^{-6} f_c^2 + 2.1$$

$$\Delta f_{ef} = 0.7\times 10^{-6} f_c^2 + 1.6 \quad \text{(for the listener AS).} \tag{11}$$
$$\Delta f_{ef} = 1.5\times 10^{-6} f_c^2 + 1.9$$

On the basis of the data shown in Figs 4–7 and the corresponding expressions (10) and (11), it can be stated that the threshold value of the deviation perception is proportional to the squared carrier frequency of the signal.

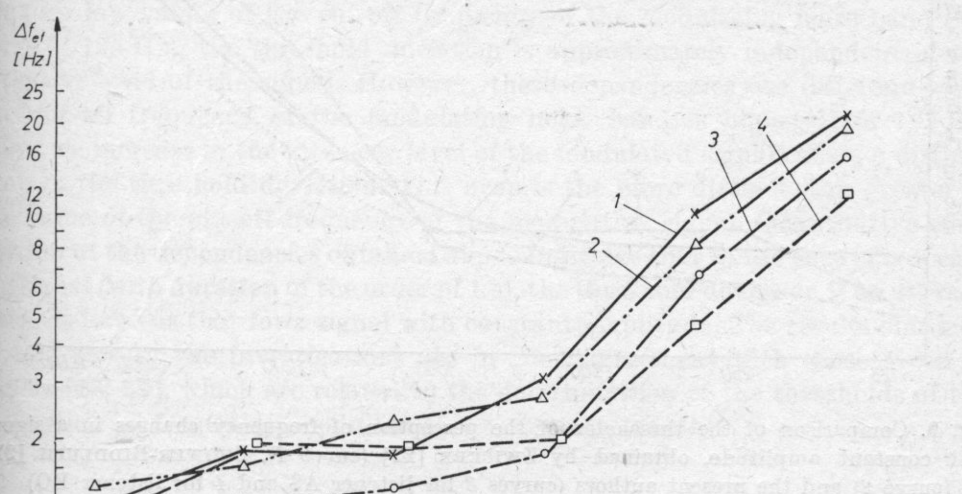

Fig. 8. Comparison of the thresholds of the perception of irregular frequency changes for the cases of a decaying signal (curves *1* and *2*) and one with constant amplitude (curves *3* and *4*). x ——— listener EO (*1*), decaying amplitude; △ — · · — listener AS (*2*), decaying amplitude; □ — · — listener AS (*3*), constant amplitude; ○ — — — — listener EO (*4*), constant amplitude

Fig. 8 shows a comparison of the courses of the thresholds obtained for a signal with constant amplitude (curves 3 and 4) and for a signal with amplitude decaying exponentially in time (curves 1 and 2). As can be seen in this figure, the thresholds of the perception of irregular frequency changes occurring in the decaying signal are distinctly higher than the analogous thresholds obtained in the case of irregular changes occurring in a signal with constant amplitude.

Irrespective of the facts established above, the investigation results obtained for a signal with constant amplitude were compared with the values of the perception thresholds of regular frequency changes occurring in the case of modulation of a tone by another, which were presented in papers [21, 22]. This comparison is shown in Fig. 9.

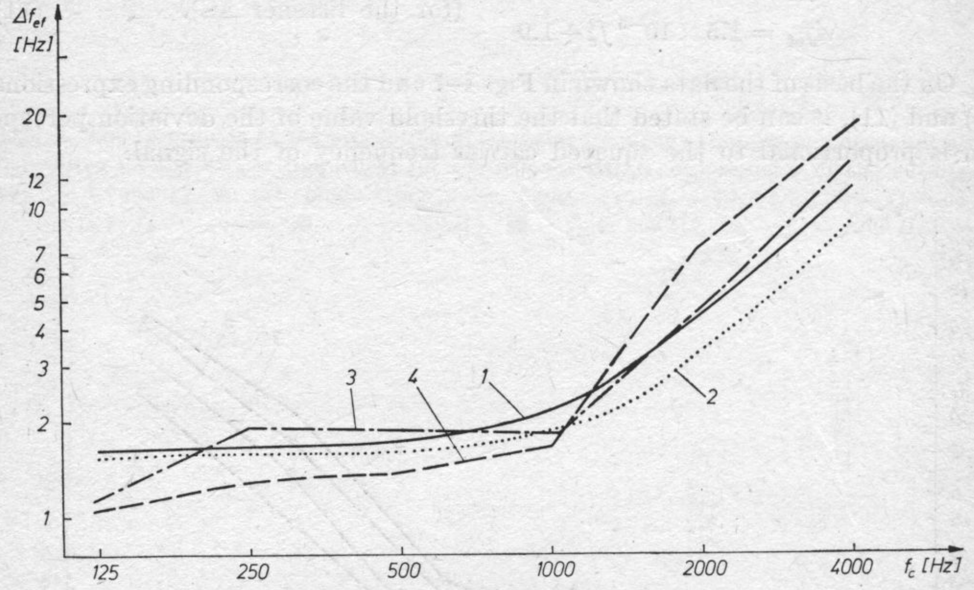

Fig. 9. Comparison of the thresholds of the perception of frequency changes in a signal with constant amplitude, obtained by ZWICKER [22] (curve *1*), SHOWER-BIDDLUPH [21] (curve *2*) and the present authors (curves *3* for listener AS and *4* for listener EO)

The unified threshold values, expressed in units of effective deviation as defined by the following formula, were plotted on the axis of ordinates of the figure:

$$\Delta f_{ef} = \frac{\Delta f_{max}}{\sqrt{2}}, \tag{12}$$

whereas the values of the carrier frequency of the signal were plotted on the axis of abscissae.

It follows from comparison of the curves given in Fig. 9. that both in the case of frequency modulation of a tone by another (curves 1 and 2) and the modulation of a tone by a noise band (curves 3 and 4), there are analogous dependencies of the threshold deviation on the carrier frequency of the signal.

4.2. The thresholds of the perception of irregular frequency changes, depending on the intensity level of the signal

In the second part of the investigations, the thresholds of the perception of irregular signal frequency changes were determined, depending on the intensity level. This signal, with the constant carrier frequency $f_c = 1000$ Hz, was modulated by white noise bands with the cut-off frequencies $f_g = 31.5$ Hz, 63 Hz, 125 Hz, 250 Hz and 500 Hz. The intensity level of the modulated signal varied over the ranges of 55 dB, 65 dB, 75 dB and 85 dB. The investigation results obtained for a signal with constant amplitude and a decaying one are shown successively in Figs 10–13. The parameter of these dependencies is the cut-off frequency of the modulating noise band. It follows from Figs 10–13 that for low values of the cut-off frequency of the modulating noise band (i.e. for $f_g < 125$ Hz), the threshold deviation is approximately independent of the intensity level of the signal. However, these dependencies are different when the cut-off frequency of the modulating noise band is higher than 125 Hz. Then, an increase in the intensity level of the modulated signal causes a distinct drop in the threshold deviation. This drop is the more distinct, the greater is the value of the cut-off frequency of the modulating signal. Quantitative comparison of the dependencies obtained above indicates that in the case of a decaying signal (with duration of the order of 1 s), the threshold deviation is on average twice as large as that for a signal with constant amplitude. The results obtained in this part of the investigations are in good agreement with those given in papers [18, 22], which are related to the determination of the thresholds of the perception of frequency modulation of a tone by another.

4.3. The thresholds of the perception of irregular frequency changes, depending on the duration of the decaying signal

In the third part of the investigations, the dependence of the threshold deviation on the duration of the decaying signal, which was successively 125, 250, 500, 1000 and 1500 ms, was determined. The following parameters were assumed as constant: the intensity level of the signal, $L = 75$ dB, and its carrier frequency $f_c = 1000$ Hz. Just as in the previous cases, also in this part of the investigations, the parameter of the measured threshold values was the

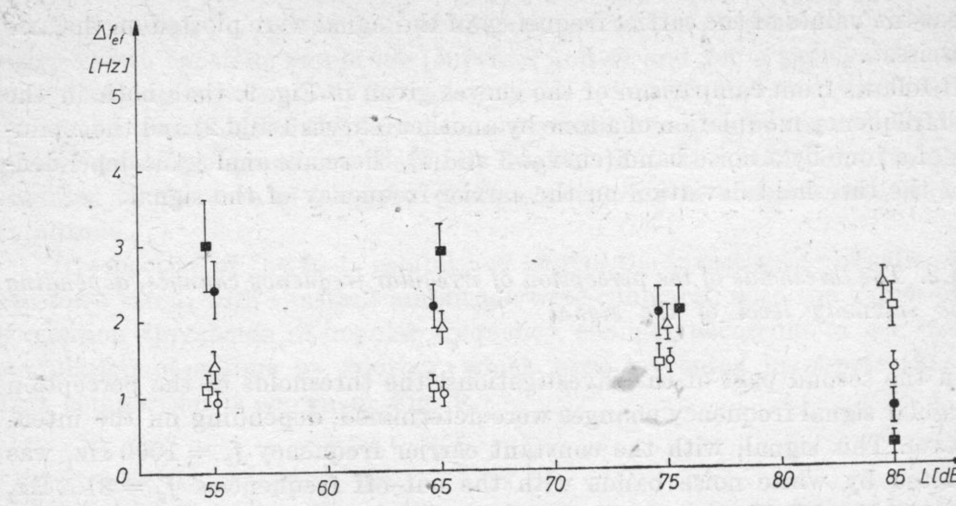

Fig. 10. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on its intensity level, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – $f_g = 31.5$ Hz, □ – $f_g = 63$ Hz, △ – $f_g = 125$ Hz, ● – $f_g = 250$ Hz, ■ – $f_g = 500$ Hz

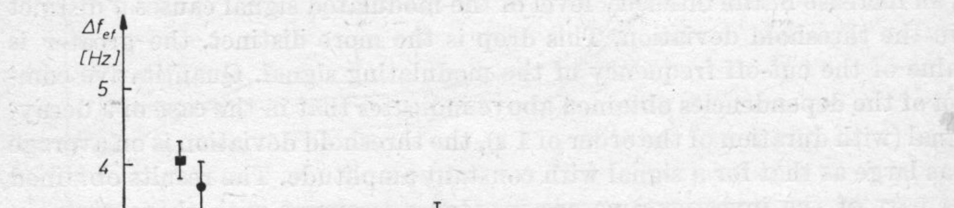

Fig. 11. The thresholds of the perception of irregular frequency changes in a signal with constant amplitude, depending on its intensity level, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – $f_g = 31.5$ Hz, □ – $f_g = 63$ Hz, △ – $f_g = 125$ Hz, ● – $f_g = 250$ Hz, ■ – $f_g = 500$ Hz

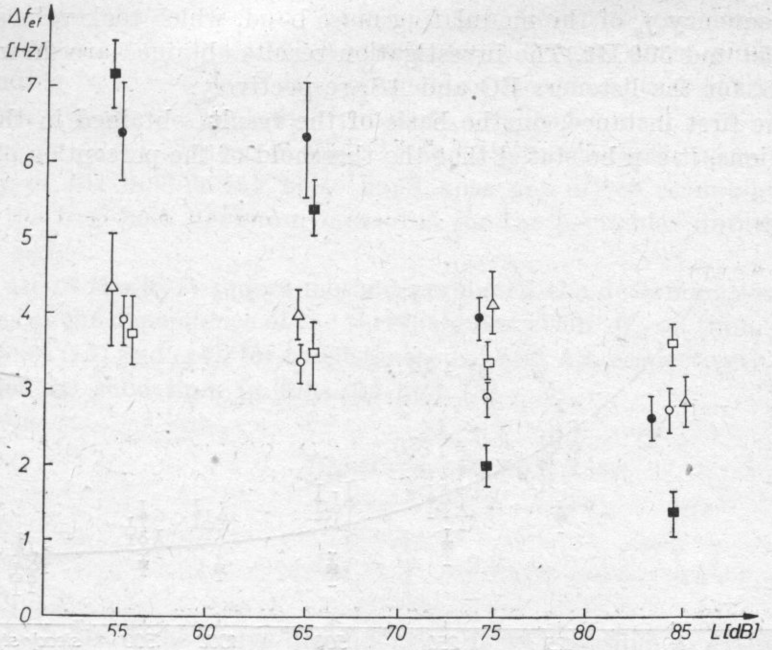

Fig. 12. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its intensity level, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz

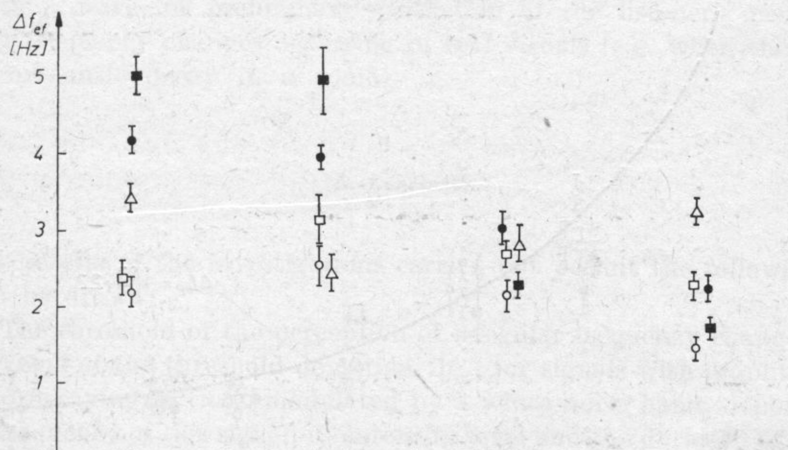

Fig. 13. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its intensity level, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f = 250 Hz, ■ – f_g = 500 Hz

cut-off frequency f_g of the modulating noise band, which took values of 31, 5, 63, 125, 350 and 500 Hz. The investigation results obtained are shown in Figs. 14 and 15, for the listeners EO and AS, respectively.

In the first instance, on the basis of the results obtained in this part of investigations, it can be stated that the threshold of the perception of irregular

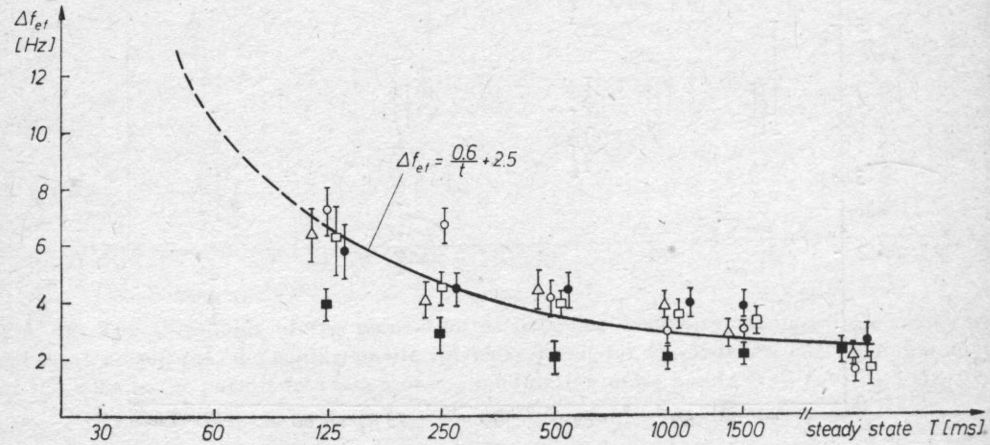

Fig. 14. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its duration, for the listener EO. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz

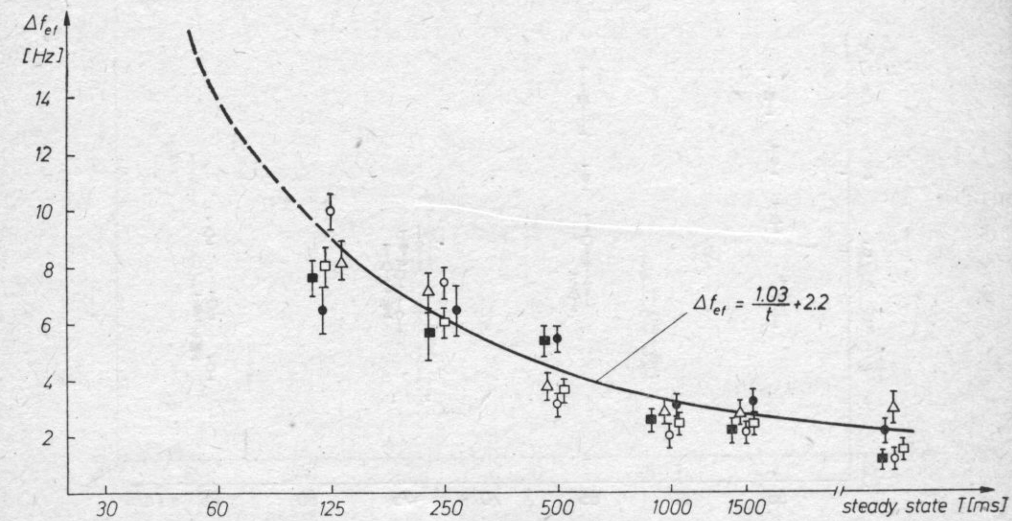

Fig. 15. The thresholds of the perception of irregular frequency changes in a decaying signal, depending on its duration, for the listener AS. The parameter of the data is the cut-off frequency of the modulating noise band. ○ – f_g = 31.5 Hz, □ – f_g = 63 Hz, △ – f_g = 125 Hz, ● – f_g = 250 Hz, ■ – f_g = 500 Hz

frequency changes decreases in the inverse proportion to the duration of the decaying signal. In the limits, it tends to a constant value of the order of 2–3 Hz corresponding to the value of the threshold of the perception of irregular frequency changes for a signal with constant amplitude.

Moreover, it can be seen in Figs. 14 and 15 that an increase in the cut-off frequency of the modulating noise band does not affect unambiguously the value of the threshold deviation measured for the particular durations of the decaying signal.

The use of the least-square method permitted the determination of analytical forms of the dependence of the threshold deviation Δf_{ef} on time, defined by dependencies (13) and (14), for the listeners EO and AS, respectively, which are represented by solid lines in Figs. 14 and 15.

$$\Delta f_{ef} = \frac{0.6}{t} + 2.5, \tag{13}$$

$$\Delta f_{ef} = \frac{1}{t} + 2.2. \tag{14}$$

On the basis of the above dependencies, it was possible to extrapolate the values of the threshold deviation to durations much shorter than 125 ms (see Figs 14 and 15), corresponding approximately to the times of transient transitions occurring in the natural sounds of speech and music. As is known, these transitions are accompanied by large sound frequency changes with a very irregular character. It seems that these thresholds can, after their experimental verification, serve for preliminary evaluation of the listener's perception of irregular frequency changes occurring in real signals (e.g. when the sounds of speech or music decay in a room).

5. Conclusions

The results of the investigations carried out permit the following conclusions to be drawn:

1. The threshold of the perception of irregular frequency changes, defined by the value of the threshold deviation Δf_{ef}, for signals with amplitudes constant and decaying in time, modulated by a white noise band, depends on the carrier frequency of this signal, its intensity level and the duration of the decaying signal.

2. The threshold value of the frequency deviation Δf_{ef} is proportional to the squared carrier frequency f_c of the modulated signal for considered range of frequencies f_c. This dependence can be expressed analytically as $\Delta f_{ef} = Af_c^2 + B$, where the coefficients A and B take specific values for a given listener.

3. For higher cut-off frequencies of the modulating noise band (i.e. for $f_g > 125$ Hz), the value of the threshold deviation decreases as the intensity level of the decaying signal increases, whereas for $f_g < 125$ Hz it is approximately independent of the intensity level of the signal.

4. The thresholds of the perception of irregular frequency changes for a signal with constant amplitude are lower than the analogous thresholds obtained in the case of a decaying signal, for frequencies higher than 500 Hz.

5. The threshold of the perception of irregular frequency changes for the decaying signal is in the inverse proportion to its duration. In the limit, it tends to a value of 2–3 Hz, corresponding to the threshold value of the perception of irregular frequency changes for a signal with constant amplitude.

In conclusion, it should be pointed out that the thresholds of the perception of irregular frequency changes obtained here are much more general than those published so far in the literature, since they are related to signals for which frequency changes in time have approximately a random character, i.e. they belong to a broad class of signals encountered in practice.

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AN ACOUSTIC METHOD FOR DETERMINING THE PARAMETERS OF FAST SURFACE IN SEMICONDUCTORS STATES

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The paper presents an acoustic method for determining the parameters of fast surface states in semiconductors. This method uses the interactions of the photon-electron type for determining both the effective carrier life-time τ influenced by the fast surface states and the velocity g of the carrier trapping by surface traps. Some experimental results of the parameters τ and g on a real (111) Si surface, obtained by this method of investigation are presented.

1. Introduction

An ever-growing interest in the physical properties of semiconductor surfaces results both from the influence of the processes, occuring at the surface, on the bulk properties of semiconductors, and from the influence of the physical and chemical surface structure on the operation of semiconductor devices [1, 6, 9, 10, 15].

Among the methods of investigation of semiconductor surfaces, the methods which investigate the energy surface states play an important role [5, 14, 15]. Up to now the existing electrical methods allow only the investigation of surface states with carrier life-times τ of above 10^{-9} s. For extrinsic semiconductors the surface states may, however, be considerably faster (the carrier life-time in surface traps is usually less than 10^{-9} s). In such cases the existing methods for determining the parameters of fast surface states allow us only to estimate these parameters; since the obtained results have the considerable errors. It is the purpose of great interest to search new and more precise investigation methods.

Recently more and more attention has been paid to the possibilities of applying Rayleigh's acoustic surface waves to semiconductor surface investigations [3, 4, 7, 8, 11, 12, 16].

In our previous paper [13], the theoretical basis of a new acoustic method for the investigation of fast surface states in semiconductors has been represented. The method uses the effect of surface wave propagating in a piezoelectric-semiconductor structure for determining both the effective carrier life-time τ influenced by fast surface states and the velocity of carrier trapping, g.

2. The conception of the acoustic method for determining the parameters of fast surface states in semiconductors

A surface wave which propagates on a piezoelectric waveguide surrface, is acompanied by an alternating electric field. If there is a semiconductor over the propagation surface, then the electric wave field penetrates the semiconductor to a depth equal to Debye's screening length [2, 13]. Thus, the values characterizing the wave and carrier interaction will be influenced by the properties of the layer nearest to the semiconductor surface.

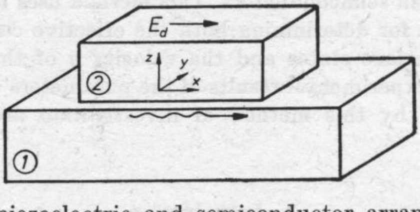

Fig. 1. A diagram of the piezoelectric and semiconductor arrangement (1 – piezoelectric, 2 – semiconductor) used in the experiments

Let us consider the surface wave which propagates in a piezoelectric. In the same direction the external electric drift field is applied to the semiconductor. The electronic coefficient of the damping of the surface wave in such a system

$$a_e = \eta H \frac{\dfrac{\varepsilon_1}{\varepsilon_2}\dfrac{\omega}{\omega_c}(\gamma+a)\left[1+\dfrac{\gamma+a}{\omega/\omega_c[(\gamma+a)^2+b^2]}\right]}{\left[1+\dfrac{\omega}{\omega_c}\left(1+\dfrac{\varepsilon_1}{\varepsilon_2}\right)b^2\right]+\left[(\gamma+a)\left(1+\dfrac{\varepsilon_1}{\varepsilon_2}\dfrac{\omega}{\omega_c}b\right)\right]^2}, \tag{1}$$

where

$$a = \frac{g}{v_f}\frac{\omega\tau}{1+\omega^2\tau^2}, \quad b = \omega\tau a;$$

v_f – the surface wave velocity, g – the velocity of the carrier trapping charge by surface states in a semiconductor, τ – the carrier life – times in surface states, ω — the surface wave frequency, η — the square of the electromechanical feedback coefficient, $\gamma = 1-\mu_0 E_d/v_f$ — drift parameter, the charge carrier mobility in a semiconductor, μ_0 — the electric field of a drift, ω_c — the so called "frequency of Maxwell's conductivity relaxation", ε_1, ε_2 — the dielectric constants of a piezoelectric and a semiconductor, H — a constant, whose value depends on the elastic and piezoelectric properties of the waveguide and semiconductor.

The electric field which accompanies the surface wave, affects the change in the carrier concentration in the conductivity band, valency band and surface traps. The process of trapping carriers in surface states in a semiconductor, under the influence of a surface wave which propagates in a piezoelectric, was considered in detail in paper [13]. The critical electric drift field is a field at which the attenuation of the wave is equal to zero:

$$a_e(E_{d_{cr}}) = 0. \tag{3}$$

In our previous paper [13], it was shown that the equation for a critical drift field has the following form:

$$E_{d_{cr}} = \frac{v_f}{\mu_0}\left[1 + \frac{g}{v_f}\frac{\omega\tau}{1+\omega^2\tau^2}\right]. \tag{4}$$

Accordingly,

$$E^0_{d_{cr}} = \frac{v_f}{\mu_0}, \tag{5}$$

where $E^0_{d_{cr}}$ is the critical drift field for the theoretical case, where no surface states exists in the semiconductor; from equations (5, 4) it follows that the relative change of the critical drift field, caused by surface states, is given by

$$\frac{E_{d_{cr}} - E^0_{d_{cr}}}{E^0_{d_{cr}}} = \frac{\Delta E_{d_{cr}}}{E^0_{d_{cr}}} = \frac{g}{v_f}\frac{\omega\tau}{1+\omega^2\tau^2}. \tag{6}$$

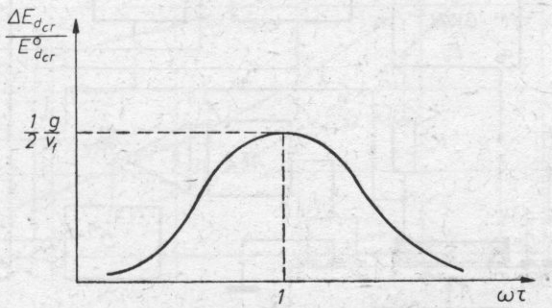

Fig. 2. The characteristics $\frac{\Delta E_{d_{cr}}}{E^0_{d_{cr}}} = f(\omega\tau)$

The idea of determining the parameters τ and g of surface states consists in determining the electric attenuation coefficient as the drift field function for different frequencies of the surface wave. From the characteristics $\alpha_e = f(E_d)$, we can find $E_{d_{cr}}$ for each frequency ω. From the position of the maximum of the characteristics $\Delta E_{d_{cr}}/E^{0}_{d_{cr}} = f(\omega)$ at the frequency axis ω, we can determine the carrier life-time τ in surface states as

$$\tau = \frac{1}{\omega_m}. \tag{7}$$

The velocity of trapping is defined by the relation

$$g = 2v_f \left[\frac{\Delta E_{d_{cr}}}{E^0_{d_{cr}}}\right]_{\max}. \tag{8}$$

Therefore, if the surface wave propagates in the system of a piezoelectric and a semiconductor, two essential parameters of surface states in a semiconductor can be determined from the measurements of velocity and attenuation of the wave.

3. Experimental procedure

As a piezoelectric waveguide base, the following monocrystals were used:

— lithium niobate $LiNbO_3$ (propagation plane [Y] with the wave propagation direction [Z];

— bismuth – germanium oxide $BiGeO_{20}$ (propagation plane [111], with the propagation direction [110]).

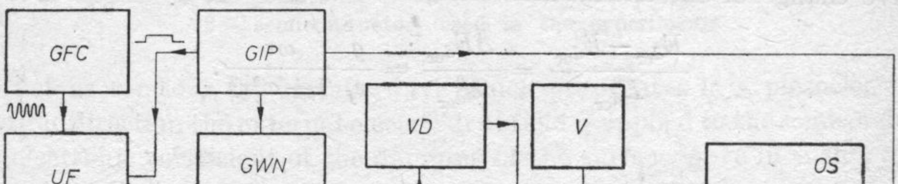

Fig. 3. The system for measuring the electronic attenuation coefficient α_e as a function of the drift field E_d

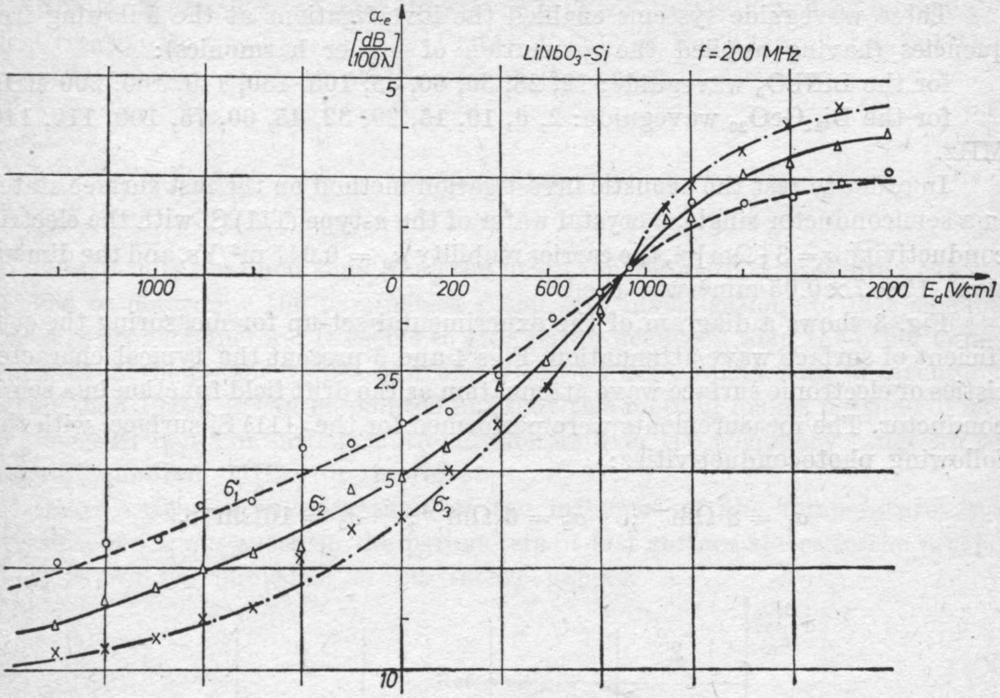

Fig. 4. The electronic attenuation coefficient α_e at 200 MHz

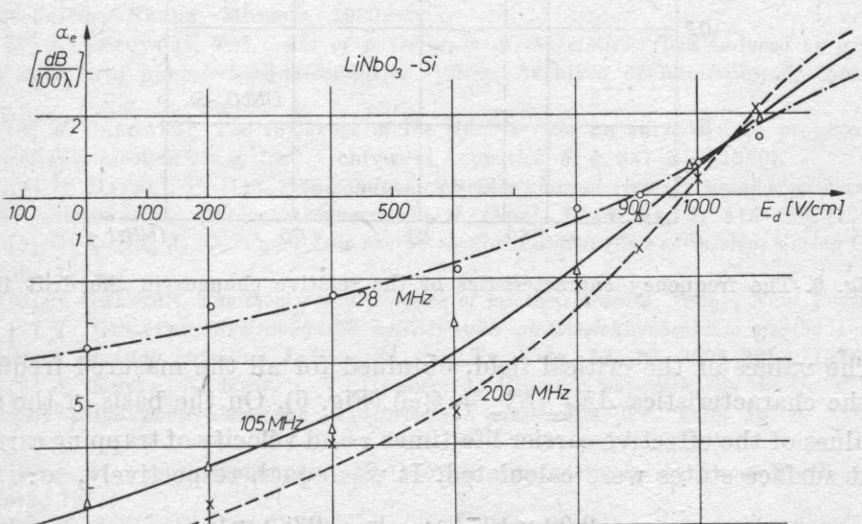

Fig. 5. The characteristics of the electronic attenuation coefficient $\alpha_e = f(E_d)$ for the $LiNbO_3-Si$ system

These waveguide systems enabled the investigations at the following frequencies (having applied the generation of higher harmonics):

for the $LiNbO_3$ waveguide: 12, 28, 36, 60, 85, 105, 130, 140, 160, 200 MHz

for the $Bi_{12}GeO_{20}$ waveguide: 2, 6, 10, 15, 20, 32, 45, 60, 75, 100, 110, 140 MHz.

In order to test the acoustic investigation method on the fast surface states in a semiconductor single, a crystal wafer of the n-type (111) Si with the electric conductivity $\sigma = 3\ [\Omega m]^{-1}$, the carrier mobility $\mu_0 = 0.047\ m^2/Vs$, and the dimensions $12 \times 7 \times 0.05\ mm^3$ was used.

Fig. 3 shows a diagram of the experimental set-up for measuring the coefficient of surface wave attenuation. Figs 4 and 5 present the typical characteristics of electronic surface wave attenuation as the drift field function in a semiconductor. The measurements were performed for the (111) Si surface, with the following photoconductivities:

$$\sigma_1 = 3\ \Omega m^{-1}; \quad \sigma_2 = 5\ \Omega m^{-1}; \quad \sigma_3 = 10 \Omega m^{-1}.$$

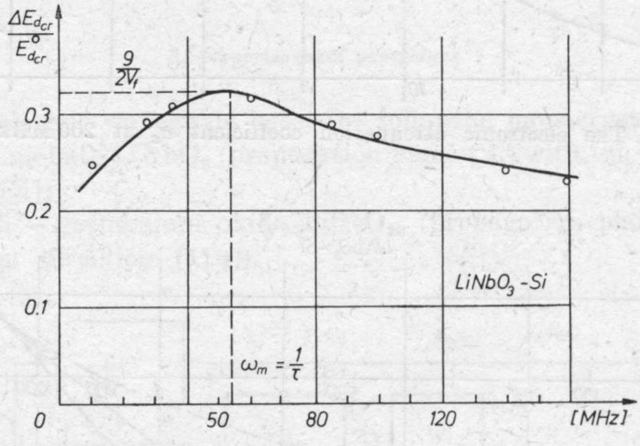

Fig. 6. The frequency characteristics of the relative changes in the drift field

The values of the critical field, obtained for all the masured frequencies, give the characteristics $\Delta E_{d_{cr}}/E^0_{d_{cr}} = f(\omega)$ (Fig. 6). On the basis of the results, the values of the effective carrier life-timee τ and velocity of trapping carriers, g, in fast surface states were calculated. It was equal, respectively, to:

$$\tau = 2.92 \times 10^{-9}\ s; \quad g = 2360\ m/s.$$

The accuracy of determining τ and g was:

$$\frac{\delta\tau}{\tau} = 9.3\,\% \quad \text{and} \quad \frac{\delta g}{g} = 9.1\,\%.$$

Similar values of τ and g for the n-type (111) Si surface, prepared by mechanical treatment, was obtained by RZHANOV [14] as less than 10^{-8} s, but the trapping velocity of those states was of the order of 10^3 m/s.

4. Conclusions

The results obtained show that the new acoustic method presented can be applied to determine the parameters τ and g in investigations of fast surface states in semiconductors. It seems to give better accuracy than the other experimental methods (the values of τ and g can be determined with an accuracy better than 10%). It can be pointed out that this method makes possible dynamic measurements of surface state parameters over the frequency range up to several hundred MHz (or more).

More extensive investigations of the influence of the temperature and pressure of various gases on the parameters of fast surface states in the n-type (111) Si will be published in the future papers.

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ULTRASONIC STUDIES ON HYDRATION OF CARBOXYLIC ACIDS, AMINO ACIDS AND PEPTIDES IN AQUEOUS ETHANOLIC SOLUTIONS*

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Hydration numbers of the simplest carboxylic acids, amino acids and di- and tripeptides were determined by measurements of ultrasonic velocity in the ethanolic-aqueous solutions. Hydration numbers of the functional groups present in the amino acids and peptides were also determined.

1. Introduction

Understanding of the nature of interactions between biologically active substances, such as amino acids, peptides, proteins or nucleic acids and water is, according to many investigators, the key to solution of numerous problems connected with the role and interaction of these substances in the living organisms. Hence, the ample literature comprises both theoretical and experimental works with the application of various techniques [1–10].

The investigations of the problem of hydration of amino acids and peptides are presented in this paper. The experiments consisted of measurements of the hydration numbers of carboxylic acids, amino acids and di- and tripeptides at different temperatures by using the ultrasonic method proposed by Yasunaga *et al.* [11, 12]. The purpose of these investigations was, besides the determination of the hydration numbers of various types of compounds, to calculate the contribution of individual functional groups present in the tested compounds in the overall hydration and, also, the determination of hydration of alkyl groups.

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2. Experiment

In all experiments the following pure or chemically pure substances were used: glycine, α- and β-alanine, α-aminobutyric acid, diglycine, glycylalanine and glycylvaline produced by Reanal (Hungary), glycylproline produced by Koch Light Laboratories (England), alanylglycine made by Fluka (Germany) and alanylalanine made by Janssen (Belgium). Other substances, such as acetic acid, propionic acid, n-butyric acid, triglycine and glycylalanylglycine were produced in Poland. Triple-distilled water was used throughout. The second distillation of water was carried out from diluted KOH and $KMnO_4$ solution. Ethyl alcohol (99.8 %), pure for analysis, added to aqueous solutions of substances under investigations, was from POCh, Gliwice, Poland. Water content in the alcohol was checked by means of the Karl Fischer method. The water content determined was in agreement with that given by the manufacturer within the limits of $\pm 0.1\%$ error.

The measurement method was described in detail previously [13, 14]. Hydration was determined from the following relation:

$$W_x = W_0 - \frac{A_1 W_1}{A_0}, \tag{1}$$

where W_x is the amount of water bound by the solute, A_0 and W_0 are the amounts of alcohol and water at the maximum of ultrasound velocity for the ethanol-water system, and A_1 and W_1 are the amounts of alcohol and water at the maximum velocity for ethanolic-aqueous solutions, containing a known amount of the solute.

The amount of water moles per 1 mole of the solute was calculated from the formula:

$$n_t = W_x M d_0 / M_0 m, \tag{2}$$

where d_0 is the density of water, m is the mass concentration of the solute, M_0 is the molecular weight of water and M is the molecular weight of the solute. The concentrations of the solutes were within the range 0.1–1 mole per kG H_2O, depending on their solubility.

The results of experiments are shown in Tables 1–4 and Figs 1–3. The results given in Tables are mean from 4–6 measurements. The hydration numbers quoted in the literature and obtained by other methods were also given for comparison.

3. Results and discussion

The temperature dependence of the n_t values given in the tables can be expressed by the relation of the same type as the one obtained previously for

Table 1

	n	n_t							error	literature data	
		°C	10	15	20	25	30	35	$\pm\delta$	[21]	[22]
CH_3COOH	3,0		3.6	4.0	4.4	4.8	5.4	6.0	0.2	3.0	2.0
C_2H_5COOH	6.0		6.7	7.1	7.5	8.0	8.5	9.0	0.2	3.0	3.0
C_3H_7COOH	8.0		8.6	9.0	9.4	9.8	10.4	10.9	0.4	4.0	4.0

Table 2

	n	n_t							error	literature
		°C	10	15	20	25	30	35	$\pm\delta$	data
glycine	4.0		4.5	4.9	5.3	5.7	6.4	7.0	0.2	6.0 [21]; 3.3 [24]; 8.2 [30];
α-alanine	6.0		6.6	7.0	7.4	7.8	8.3	8.9	0.2	7.6 [21]; 3.3 [24]; 2.6 [30];
β-alanine	5.0					6.8	7.2	7.7	0.4	
dl-α-amino-butyric acid	8.0		8.5	8.9	9.4	9.9	10.5	11.0	0.4	4.1$^{(a)}$[25]
dl-valine	12.0					13.6	14.0	14.5	0.6	4.3$^{(a)}$[29]
dl-lysine	11.0		11.7		12.4	12.8		13.9	0.6	
dl-proline	6.0			7.0		7.9		8.9	0.4	

(*a*) – the mean number of moles of water per mole of different amino acids.

Table 3

	n	n_t					error	literature data
		°C	20	25	30	35	$\pm\delta$	[24]
diglycine	7.0		8.5	8.9	9.3	9.8	0.5	4.5 25°C; 6.0$^{(a)}$
triglycine	11.0		12.4	12.8	13.2	13.7	1.0	5.5 25°C; 7.5$^{(a)}$
glycyl-l-α-alanine	9.0		10.6	11.0		12.0	0.5	
glycyl-dl-α-alanylglycine	12.0			13.5	14.0	14.5	1.0	
dl-alanyl-dl-alanine	11.0		12.5	12.8		13.9	0.5	
l-alanylglycine	9.0			10.8		11.9	0.5	
glycyl-l-proline	9.0			10.7		11.8	0.5	
glycyl-l-valine	16.0			17.6		18.8	1.0	

(*a*) – obtained by extrapolation to 0°C.

other compounds [13–20]:

$$n_t = n + At + Bt^2, \tag{3}$$

where n is the number of water moles per 1 mole of the solute at 0°C, A and B are experimental coefficients equal, respectively, to 3.83×10^{-2} and 1.3×10^{-3}, and t is temperature in °C.

Assuming that at 0 °C water molecules are in the ice-like structure, one can suggest that the number n ilustrates the interaction between the solutes and the water lattice.

The further terms of the equation, i.e. At and Bt^2, are related to the properties of water itself, independent of the type of the solute, and they determine the population of "free" water at different temperatures; at 25°C, $At+Bt^2 = 1.8$.

Similar relationships between n_t and temperature, obtained for the different types of compounds, suggest a similar mechanism of the hydration of these substances: a certain ice-like structure of considerable stability is formed around solute molecules. At the concentration of alcohol corresponding to the maximum of ultrasonic velocity, a structure, composed of quasi crystalline hydrates of the examined substances, an aqueous alcoholic structure, similar to those above and to that of "free" water, whose molecules do not build the ice-like skeleton, is formed.

Comparison of the results obtained for the individual groups of chemical compounds allows formulation of some relationships between hydration numbers and structure of these compounds:

1) the hydration numbers increase with the growth of the hydrocarbon chain, the mean number of water molecules per $-CH_2-$ group is 2.

2) the hydration numbers of di- and tripeptides are, respectively, smaller by 1 or 2 than the sum of the hydration numbers of amino acids composing the given peptide. Glycylvaline with the hydration number equal to the sum of the hydration numbers of glycine and valine is an exception to this rule.

3) the shift of the amine group into the β-position of the alkyl chain (β-alanine) or the introduction of an additional amine group into the ε-position (lysine) causes a decrease in the hydration number by 1 as compared with the respective α-amino acids.

The results obtained allow some conclusions to be drawn regarding the mode of binding water molecules by the different groups present in the substances tested.

Taking into account the low degree of dissociation of carboxylic acids in aqueous solutions, the presence of ions may be neglected and such solutes may be treated as polar molecules. The binding of water by these molecules will take place mainly by free electron pairs of oxygen atoms and with protons in carboxylic groups. The alkyl groups of acids will probably be hydrated in the same way as alkyl groups of non-electrolyte molecules.

The situation is slightly different in the case of amino acids and peptides.

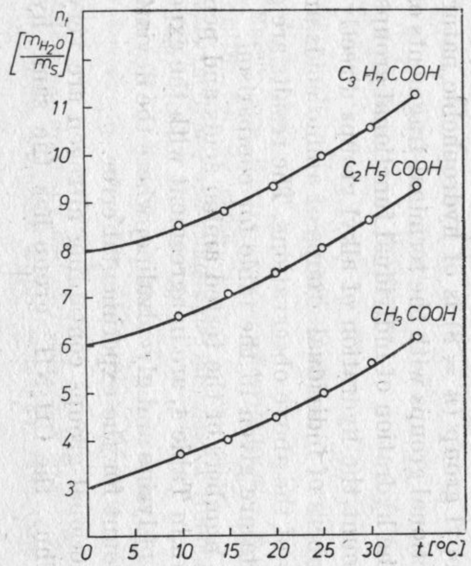

Fig. 1. Dependence of the hydration numbers n_t of carboxylic acids on temperature

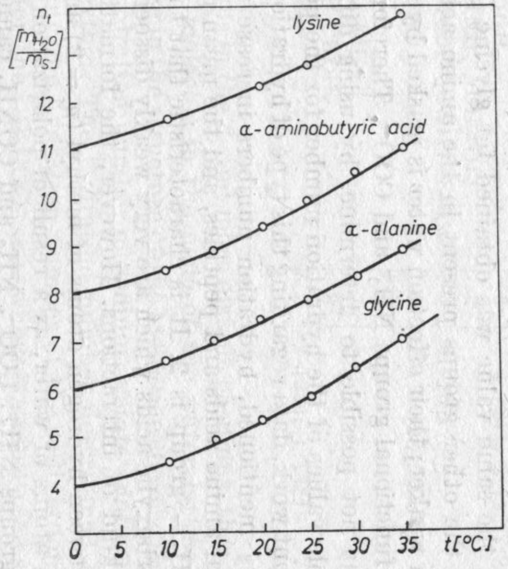

Fig. 2. Dependence of the hydration numbers n_t of amino acids on temperature

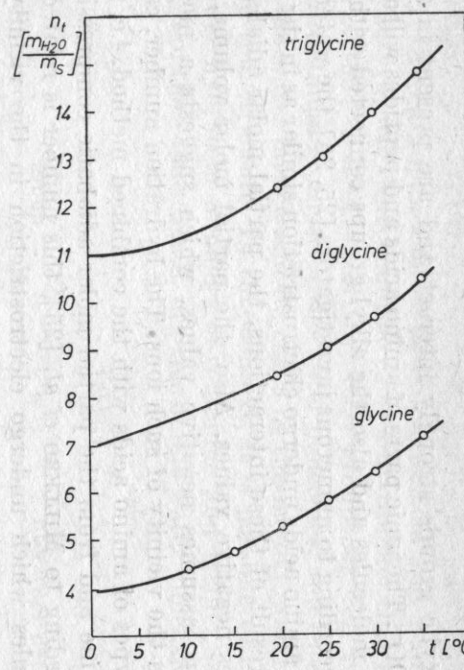

Fig. 3. Dependence of the hydration numbers n_t of glycine oligopeptides on temperature

Amine and carboxylic groups strongly interact and are present in the ionic forms NH_3^+ and COO^-. The ionic parts of amino acids and peptides will affect the surrounding water molecules and also the alkyl groups connected with them in a different way. According to numerous investigators [25, 26], the water molecules which surround amino acids undergo electrostriction similar as in the presence of ions, and, as a result of these interactions, the partial molar adiabatic compressibility assumes negative values. Also, the partial molar volume, affected and electrostriction, assumes negative values, which suggests a more dense packing of water in the vicinity of such ions. The hydration number, calculated for the different types of amino acids with the combined method, i.e. from the partial molar volume and from the partial molar adiabatic compressibility, is about 4 and, according to MILLERO *et al.* [25], this number is related only to such water molecules which undergo electrostriction in the vicinity of the $NH_3^+CHCOO^-$ group.

In this paper, the same value was obtained for glycine ($NH_3^+CH_2COO^-$). The interaction of the other groups present in the amino acids and peptides with water is much weaker; their effect on water is masked by the strong interactions of charged functional groups NH_3^+ and COO^-. Therefore, in the former experiments, it was not possible to determine, by using different detecting methods, the reliable values of the hydration number for the peptide and alkyl groups. In the present work, data regarding this type of hydration were obtained.

As was already mentioned, hydration numbers increase with the length of the alkyl chain of amino acids and peptides, and the mean number of water molecules per $-CH_2-$ group is 2. It is characteristic that the same result is obtained for the carboxylic acids which are very weakly dissociated. This could suggest the same kind of interactions. However, the formation of the weak hydrogen bonds between hydrogen atoms of methyl ($n = 2$) and ethyl ($n = 4$) groups and oxygen atoms of water, as a result of polarization of these groups by the functional groups NH_3^+, COO^-, NH_2 and CONH, cannot be excluded. This hydration would be of hydrophilic nature. On the other hand, it seems that hydration of isopropyl group ($n = 8$) is of hydrophobic nature due to weaker interactions of functional groups with the terminal fragments of the alkyl chain. Determination of the hydration of individual functional groups should be made by taking into account the hydration of alkyl groups directly bound to them. The hydration numbers of individual groups of amino acids and peptides were determined in view of the above observations. The results are given in Table 4. Some literature data are given in the table for comparison.

The hydration numbers of the tested amino acids and peptides, calculated from the data shown in Table 4, are in agreement with the experimental values, with the exception of lysine and glycylvaline, where the deviations of one water molecule could account for the experimental error.

Generally, functional groups containing nitrogen are very weakly, or not at all, hydrated. Thus, the $CH_2NH_3^+$ group has the same hydration number as the $CH_2(CH_3)$ group, α-alanine as propionic acid and α-aminobutyric acid as that of *n*-butyric acid. This could be caused by the fact that the dimensions and geometry of the $-NH-$, $-NH_2$ and NH_3^+ groups, as well as those of the NH_4^+ ion [16], are similar to those of the water molecules, and these can replace both nodes of the water lattice and its cages in the ice-like water structure without disturbing this structure. In this context, it is possible to clarify the problem of the lower hydration numbers of β-alanine and lysine, as in the structures of hydrates of these substances, in place of one water molecule found in the vicinity of alkyl groups in the β- and more distant positions, there occurs a fragment of the hydration molecule in the node of the water lattice and this does not lead to any change in the structure of the hydration sheath. The results of measurements of the hydration number of sodium acetate confirm the above assumption, to some extent. The hydration number determined for this compound is $n = 8$. Assuming the hydration number of the sodium ion as 5 [16], a value of 3 is obtained for the CH_3COO^- ion, which is exactly the same as the hydration number of the CH_2COO^- group.

Table 4

group	n	literature data
$CHCOO^-$, CH_2COO^-	3	
COOH	3	3–4 [21]; 2 [22]; 2 [28]
$CHNH_3^+$, $CH_2NH_3^+$	2	
$NH_3^+CHCOO^-$, $NH_3^+CH_2COO^-$	4	4 [25]
CONH	2	1–1.5 [28]; 3 [27]
CH_3	2	
CH_3CH_2	4	
CH_3CHCH_3	8	
CH_2	2	2 [23]; 1 [22]

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INVESTIGATION OF THE ULTRASONIC WAVE PROPAGATION ALONG THE BOUNDARY OF TWO HALF-SPACES: THE ELASTIC ONE OF A SOLID AND THE VISCOELASTIC ONE OF A LIQUID

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By considering the problem of the travelling wave propagation along two half-spaces: the ideally elastic (solid) and the viscoelastic (liquid), with bulk viscosity, as a result of solving the wave equations and taking into account the boundary conditions, the complex characteristic equation was obtained.

The characteristic equation was solved numerically for a frequency of 2.5 MHz for two different viscoelastic bodies, for biological tissue and the acetic acid CH_3COOH, bordering on an elastic medium, steel.

The wave velocity was sought close to the longitudinal wave velocity characteristic of the given media. It was shown that the wave could propagate at a velocity only slightly less than that of longitudinal waves, but with attenuation being slightly larger than that in an unbounded medium.

It follows from the representations obtained of the displacement potentials that, apart from the wave propagation along the boundary of the media, there is also wave propagation towards the liquid damping medium. This phenomenon did not occur in considering the ideal liquid medium.

In both cases, the distributions of the normal and tangential stresses and of the partial displacements were obtained. The wave decays exponentially as the distance from the boundary increases (on both sides).

The distributions are close in character to those of stresses and displacements obtained in the previous paper of the author, where a similar, but a lossless, model was considered.

The acoustic impedance in a viscoelastic medium was also found for the wave type propagating along and across the boundary.

1. Introduction

The investigations of the ultrasonic wave propagation along the boundary of two half-spaces: a viscoelastic liquid and an ideally elastic solid, involve a phenomenon observed during biopsy controlled by ultrasound. In specific physical conditions, there emerges a wave, which propagates along the needle, reaches its end and returns, giving an image of the needle end on the oscilloscope screen. This problem was already considered theoretically with specific physical restrictions in papers [1–3]. These papers showed that the velocity of the propagating wave is close to that in the biological medium surrounding the needle. The previous investigations have dealt with the wave propagation in ideally elastic media.

At present, it assumed that the biological medium surrounding the needle is a viscoelastic liquid, as the biological structures, such as muscle, kidney, liver, on which biopsy is performed, show viscous properties. The needle used in the puncture of a given biological structure is reduced to the infinitely long half-space of an ideally elastic solid. Thus, the wave reflected from needle end will not be considered; the wave analysed will be a travelling one. It is also assumed that the viscoelastic biological medium is unilaterally unbounded. These simplifications will ensure better knowledge of the phenomenon of the wave propagation itself along the boundary of the two media.

The coordinate system was chosen in the way shown in Fig. 1. The axis x coincides with the boundary of the two half-spaces and is parallel to the direction of the wave propagation. The axis z is directed vertically upwards. The ideally elastic solid medium is a homogeneous, isotropic material with the density ϱ_s and the Lamé constants λ_s and μ_s. Here, the velocities of the longitudinal and transverse waves are, respectively, c_d and c_t. The ideally elastic medium borders on a viscoelastic isotropic medium with the density ϱ_c and the viscoelastic constants λ_c and μ_c, defined as

$$\lambda_c = \lambda' + j\omega\lambda'', \quad \mu_c = \mu' + j\omega\mu'',$$

where λ' and μ' are the elastic constants, λ'' and μ'' are the viscous constants, $\omega = 2\pi f$; f = frequency; $j^2 = -1$.

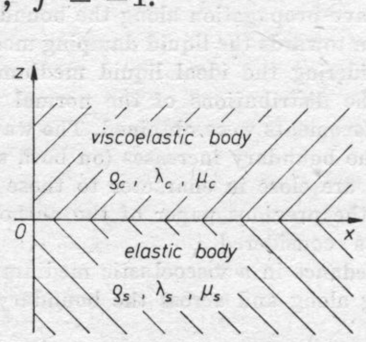

Fig. 1. The system of the media considered

The purpose of the investigations is to determine the parameters characterizing the wave motion propagating in the direction x and the approximate magnitude of the velocity and attenuation of the wave propagating along the boundary of the two half-spaces.

Further on in this paper, the biological medium will be defined as a viscoelastic liquid, where the propagating transverse wave is so rapidly, compared with the longitudinal wave propagation, attenuated that it can be neglected.

2. Initial formulae

In elasticity theory, it is assumed that the components of the stress tensor are linear functions of the components of the strain tensor. These assumptions (the Hook law) are valid only when the purely elastic forces are much stronger than those depending on the strain velocities (the viscous forces). When these forces are comparable and the stress components are also linear functions of the strain velocities, it is said that a given body also has viscous properties (a Voigt body). This body model will be assumed as an approximation of the biological medium. When isotropic, such a body is characterized by four material constants: λ', μ', λ'' and μ'', where λ' and μ' define the elastic properties and λ'' and μ'' the viscous properties of the body.

Then, the constitutive equation of the viscoelastic body becomes

$$\tau_{ij} = \left(2\mu' + 2\mu'' \frac{\partial}{\partial t}\right) \varepsilon_{ij} + \left(\lambda' + \lambda'' \frac{\partial}{\partial t}\right) \varepsilon_{ij}\delta_{ij}, \qquad (i, j = x, y, z), \tag{1}$$

where τ and ε are, respectively the stress and the strain. Substitution of (1) into the motion equations

$$\varrho_c \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

gives the equation of the displacements of the isotropic viscoelastic body

$$\varrho_c \frac{\partial^2 \overline{u}}{\partial t^2} = \left[(\lambda' + \mu') + (\lambda'' + \mu'')\frac{\partial}{\partial t}\right] \operatorname{grad}\operatorname{div}\overline{u} + \left(\mu' + \mu'' \frac{\partial}{\partial t}\right)\nabla^2 \overline{u}. \tag{3}$$

In the case of harmonic motion with the frequency $f = \omega/2\pi$, which is assumed in this paper,

$$\overline{u}(x, y, z, t) = \overline{u}(x, y, z)\exp(j\omega t)$$

and, after using equation (3),

$$-\varrho_c\omega^2\overline{u} = (\lambda_c + \mu_c)\operatorname{grad}\operatorname{div}\overline{u} + \mu_c\nabla^2\overline{u}, \tag{4}$$

where

$$\left.\begin{aligned} \lambda_c &= \lambda' + j\omega\lambda'' \\ \omega &= 2\pi f \\ \mu_c &= \mu' + j\omega\mu'' \end{aligned}\right\}. \tag{5}$$

The displacement equation (4) has formally the same shape as that in elasticity theory. The only difference involves the coefficients λ_c and μ_c which are at present complex and depend on the frequency, according to dependence (5), whereas in the case of the wave propagation in an ideally elastic medium the coefficients were real quantities. Thus, the ideally elastic isotropic body is characterized by two constants, the Lame constants; the viscoelastic isotropic body, by four constants. λ' and μ' define, respectively, the bulk and structural elasticity, whereas λ'' and μ'' are, respectively, the coefficients of the bulk and tangential viscosity. Equation (4) is solved in the same way as in elasticity theory [7].

For the viscoelastic medium, in order to solve equation (4), the displacement vector $\bar{u}$ is respresented in the form

$$\left.\begin{aligned} \bar{u}^c &= (\bar{v}^c + w^c)\exp(j\omega t) \\ \text{with the condition}\ \operatorname{rot}\bar{v}^c &= 0\ \text{and}\ \operatorname{div} w^c = 0 \end{aligned}\right\}. \tag{6}$$

Here, the vector is respresented in the form of the sum of the scalar potential gradient ϕ^c and the rotation of the vector potential ψ^c with the coordinates ψ_x^c, ψ_y^c and ψ_z^c.

The vector rot $\bar{\psi}^c$ has components of the form

$$\operatorname{rot}\bar{\psi}^c = \left[\frac{\partial \psi_z^c}{\partial y} - \frac{\partial \psi_y^c}{\partial z}, -\left(\frac{\partial \psi_z^c}{\partial x} - \frac{\partial \psi_x^c}{\partial z}\right), \frac{\partial \psi_y^c}{\partial x} - \frac{\partial \psi_x^c}{\partial y}\right]. \tag{7}$$

In view of the twodimensional character of the problem in expression (7), only one component of the vector $\bar{\psi}^c$ occurs, i.e. ψ_y^c, while the vector rot $\bar{\psi}^c$ has the components

$$\operatorname{rot}\bar{\psi}^c = \left[-\frac{\partial \psi_y^c}{\partial z}, 0, \frac{\partial \psi_y^c}{\partial x}\right]. \tag{7a}$$

Therefore, the displacement vector $\bar{u}^c$ has the form

$$\bar{u}^c(x, z, t) = [\operatorname{grad}\phi^c(x, z) + \operatorname{rot}\psi_y^c(x, z)]\exp(j\omega t), \tag{8}$$

and, after breaking it into the components u^c and w^c, they have the form

$$\left.\begin{aligned} u^c &= \left(\frac{\partial \phi^c}{\partial x} - \frac{\partial \psi_y^c}{\partial z}\right)\exp(j\omega t) \\ w^c &= \left(\frac{\partial \phi^c}{\partial z} + \frac{\partial \psi_y^c}{\partial x}\right)\exp(j\omega t) \\ \bar{u} &= (u, w). \end{aligned}\right\} \tag{8a}$$

The potentials ϕ^c and ψ_y^c satisfy the equations

$$\left.\begin{aligned} \nabla^2\phi^c &= \frac{-\varrho_c\omega^2}{\lambda_c+2\mu_c}\,\phi^c \\ \nabla^2\psi_y^c &= \frac{-\varrho_c\omega^2}{\mu_c}\,\psi_y^c \end{aligned}\right\}, \tag{9}$$

where $\lambda_c = \lambda' + j\omega\lambda''$, $\mu_c = \mu' + j\omega\mu''$ and $\omega = 2\pi f$.

Equations (9) result from the application of dependence (8) in the displacement equation (4), i.e.

$$(\lambda_c+\mu_c)\,\mathrm{grad}\,\mathrm{div}(\mathrm{grad}\,\phi^c + \mathrm{rot}\,\psi_y^c) + \mu_c\nabla^2(\mathrm{grad}\,\phi^c+\mathrm{rot}\,\psi_y^c) = -\varrho_c\omega^2(\mathrm{grad}\,\phi^c+\mathrm{rot}\,\psi_y^c),$$

but

$$\mathrm{div}\,\mathrm{grad}\,\phi^c = \nabla^2\phi^c,$$

$$\mathrm{div}\,\mathrm{rot}\,\psi_y^c = 0,$$

$$(\lambda_c+\mu_c)\,\mathrm{grad}\,\nabla^2\phi^c + \mu_c\nabla^2\phi^c + \mu_c\nabla^2\mathrm{rot}\,\psi_y^c = -\varrho_c\omega^2(\mathrm{grad}\,\phi^c+\mathrm{rot}\,\psi_y^c),$$

$$\mathrm{grad}\,[(\lambda_c+2\mu_c)\nabla^2\phi^c + \varrho_c\omega^2\phi^c] + \mathrm{rot}\,[\mu_c\nabla^2\psi_y^c + \varrho_c\omega^2\psi_y^c] = 0,$$

hence, (9) follows.

The solution of system (9) (by the classical method of separation of variables) leads to the form

$$\begin{aligned} \phi^c(x,z) &= \big(D\exp(-jl_d z) + D_1\exp(jl_d z)\big)\exp(-jpx), \\ \psi_y^c(x,z) &= \big(B\exp(-jl_t z) + B_1\exp(jl_t z)\big)\exp(-jpx), \end{aligned} \tag{10}$$

where

$$\left.\begin{aligned} l_d^2 &= \frac{\omega^2\varrho_c}{\lambda_c+2\mu_c} - p^2 \\ l_t^2 &= \frac{\omega^2\varrho_c}{\mu_c} - p^2 \end{aligned}\right\}, \tag{11}$$

p is the sought propagation constant,

$$\left.\begin{aligned} c &= \omega/\mathrm{Re}(p), \quad p = \big(\mathrm{Re}(p), \mathrm{Im}(p)\big) \\ \alpha &= -\mathrm{Im}(p) \end{aligned}\right\}, \tag{12}$$

c is the phase velocity of the wave and α is the attenuation coefficient of the wave.

A damped planar harmonic wave travelling in the direction x is characterized by the factor $\exp(j\omega t)\exp(-jpx)$.

Since the biological medium is bounded only on one side (by the elastic half-space), the wave radiated in the direction z will not be reflected and the term containing the factor $\exp(jl_d z)$ can be neglected (i.e. $D_1 \equiv 0$). Analogously, $B_1 \equiv 0$.

Finally, formulae (10) become

$$\begin{aligned} \phi^c(x, z) &= D\exp(-jl_d z)\exp(-jpx), \\ \psi_y^c(x, z) &= B\exp(-jl_t z)\exp(-jpx). \end{aligned} \tag{13}$$

Then, the normal and tangential stresses, expressed by the displacement components, u^c and w^c, according to the formulae

$$\begin{aligned} \tau_{zz}^c &= \lambda_c\left(\frac{\partial u^c}{\partial x} + \frac{\partial w^c}{\partial z}\right) + 2\mu_c \frac{\partial w^c}{\partial z}, \\ \tau_{xz}^c &= \mu_c\left(\frac{\partial w^c}{\partial x} + \frac{\partial u^c}{\partial z}\right), \end{aligned} \tag{14}$$

where

$$\begin{aligned} u^c &= \big(-pjD\exp(-jl_d z) + jl_t B\exp(-jl_t z)\big)\exp(-jpx), \\ w^c &= \big(-jl_d D\exp(-jl_d z) + jl_t B\exp(-jl_t z)\big)\exp(-jpx), \end{aligned} \tag{15}$$

and defined by representations (8) and (13), become

$$\begin{aligned} \tau_{zz}^c &= [-D\exp(-jl_d z)(\lambda_c p^2 + \lambda_c l_d^2 + 2\mu_c l_d^2) + B\exp(-jl_t z) \times \\ &\qquad \times 2\mu_c p l_t]\exp(-jpx + j\omega t), \\ \tau_{xz}^c &= \mu_c[-2pl_d D\exp(-jl_d z) + (l_t^2 - p^2)B\exp(-jl_t z)] \times \\ &\qquad \times \exp(-jpx + j\omega t). \end{aligned} \tag{16}$$

The constants l_d, l_t and p are complex conjugate quantities, related by formulae (11). The propagation constant p is related to the wave number k and the wavelength λ by the formula

$$\mathrm{Re}(p) = k = \frac{\omega}{c} = 2\pi/\lambda. \tag{17}$$

In general, the propagation constant has the form $p = \omega/c - j\alpha$, where c denotes the phase velocity of the wave propagation in the system and α is the coefficient of the wave attenuation.

3. Viscoelastic liquid

Formulae (13) describe the displacement potentials in the viscoelastic body, where longitudinal and transverse waves can propagate. This body is characterized by the density ϱ_c, the Lamé elastic constants λ' and μ' and by the coefficients of the bulk and structural viscosity, λ'' and μ'', respectively.

The determination of the specific values of the material constants λ', λ'', μ' and μ'' requires the solution of the following equations:

$$\left.\begin{aligned} c_d &= \omega/\mathrm{Re}(h) \\ a_d &= -\mathrm{Im}(h) \end{aligned} \quad \text{where } h = \left[\frac{\varrho_c\omega^2}{\lambda_c+2\mu_c}\right]^{1/2} \atop \begin{aligned} c_t &= \omega/\mathrm{Re}(l) \\ a_t &= -\mathrm{Im}(l) \end{aligned} \quad \text{where } l = \left[\frac{\varrho_c\omega^2}{\mu_c}\right]^{1/2}\right\}. \tag{18}$$

These dependencies relate the material constants to the longitudinal and transverse wave velocities in tissue, c_d and c_t, and to the attenuation coefficients a_d and a_t, corresponding to the propagation of these waves for given frequencies. It is assumed, after [4], that

$$c_d = 1.5\times10^5\ \mathrm{cm/s}, \qquad c_t = 3\times10^3\ \mathrm{cm/s},$$

$$a_d = 0.37\ \mathrm{cm}^{-1}, \qquad a_t = 2\times10^3\ \mathrm{cm}^{-1},$$

where a_d is the attenuation coefficient of the longitudinal wave propagating along the muscle. With these assumptions and the frequency $f = 2.5$ MHz, the values of the material constants of biological tissue, determined from relations (18), are

$$\lambda' = 2.27\times10^{10}\ \mathrm{dyne/cm^2} = 2.27\times10^9\ \mathrm{N/m^2},$$

$$\mu' = 5.9\times10^6\ \mathrm{dyne/cm^2} = 5.9\times10^5\ \mathrm{N/m^2}, \tag{19}$$

$$\lambda'' = 10.23\ \mathrm{dyne\ s/cm^2} = 1.023\ \mathrm{Ns/m^2}, \qquad \mu'' = 0.33\ \mathrm{dyne\ s/cm^2} = 0.033\ \mathrm{Ns/m^2}.$$

It is seen that the coefficient of the bulk viscosity λ'' is larger by almost 2 orders of magnitude than μ''. In paper [12] O'Brien showed that μ'' has the same value for tissue as that for water (soft tissue contains 70 % of water) and, subsequently, made the assumption $\mu'' < \lambda''$ for water. The same assumption can be made here for tissue. Subsequently, comparison of the elastic coefficients λ' and μ' in (9) shows that μ' is lower by 4 orders of magnitude than λ'. Therefore, it is assumed that $\mu' \ll \lambda'$.

In summing up the above assumptions, tissue is defined as a liquid with the coefficients of bulk viscosity $\lambda'' = 10.23$ dyne s/cm² and of bulk viscosity $\lambda' = 2.25\times10^{10}$ dyne/cm². In this liquid only the longitudinal wave propagates, since, as Frizzell showed in paper [4], the attenuation of the transverse wave in tissue is 1000 times as large as that of the longitudinal wave.

Thus, the displacement potential has the form

$$\phi^c(x,z) = D\exp(-jl_d z)\exp(-jpx), \quad l_d^c = \frac{\omega^2 \varrho_c}{\lambda_c} - p^2. \tag{20}$$

The displacement $\bar{u}$ is, when broken into components,

$$\left.\begin{aligned} u^c &= -jpD\exp(-jl_d z)\exp(-jpx)\exp(j\omega t) \\ w^c &= -jl_d D\exp(-jl_d z)\exp(-jpx)\exp(j\omega t) \end{aligned}\right\}. \tag{21}$$

The stresses have the form

$$\left.\begin{aligned} \tau_{zz}^c &= \tau_{xx}^c = -D\exp(-jl_d z)\lambda_c(p^2+l_d^2)\exp(-jpx)\exp(j\omega t) \\ \tau_{xz} &= 0. \end{aligned}\right\}. \tag{22}$$

The propagation constant p is common to the potential ϕ^c and the potentials ϕ^s and ψ_y^s, defined below, in the ideally elastic half-space of the solid. These (displacement) potentials can be given in the following form (considering, analogously to formulae (13), only the possibility of the wave propagation away from the boundary, i.e. in the direction $-z$):

$$\left.\begin{aligned} \phi^s(x,z,t) &= A\exp(jk_d z)\exp(-jpx)\exp(j\omega t) \\ \psi_y^s(x,z,t) &= E\exp(jk_t z)\exp(-jpx)\exp(j\omega t) \end{aligned}\right\}, \tag{23}$$

where

$$k_d^2 = \frac{\omega^2}{c_d^2} - p^2, \quad k_t^2 = \frac{\omega^2}{c_t^2} - p^2. \tag{24}$$

The components of the displacement vector, u^s and w^s, and the normal and tangential stresses, calculated from formulae (16) and expressed by potentials (23), have the form

$$\left.\begin{aligned} u^s &= [-Ajp\exp(jk_d z) - jk_t\exp(jk_t z)E]\exp(-jpx+j\omega t) \\ w^s &= [jk_d A\exp(jk_d z) - jpE\exp(jk_t z)]\exp(-jpx+j\omega t) \end{aligned}\right\}; \tag{25}$$

$$\left.\begin{aligned} \tau_{zz}^s &= [-(\lambda_s p^2+\lambda_s k_d^2+2\mu_s k_d^2)A\exp(jk_t z)+2\mu_s pk_t E\exp(jk_t z)]\exp(-jpx+j\omega t) \\ \tau_{xz}^s &= [2A\exp(jk_d z)k_d p + E\exp jk_t z(k_t^2-p^2)]\mu_s\exp(-jpx+j\omega t)] \end{aligned}\right\}. \tag{26}$$

4. Boundary conditions

On the boundary of the half-space $z = 0$, the normal and tangential stresses, and the normal components of the displacement vector, must be continuous, i.e. the following conditions should be statisfied:

$$\left.\begin{aligned} \tau_{zz}^s &= \tau_{zz}^c \\ \tau_{xz}^s &= 0 \\ w^s &= w^c \end{aligned}\right\}. \tag{27}$$

Substitution of dependences (8a), (21), (22), (25) and (26) in the boundary conditions (27) gives a system of three homogeneous equations with the unknons A, E and D and the coefficients a_{ij}; $i, j = 1, 2, 3$. The coefficients include the material constants of the elastic half-space and the viscoelastic biological medium, and the wave numbers k_d, k_t and l_d and the sought propagation constant $p = (\omega/c) - j\alpha$. The determinant formed from conditions (27), after substituting the previously determined displacements ($8a$) and (25), and stresses (22) and (26), has the form

$$|a_{ij}| = \begin{vmatrix} 2\mu_s p^2 - \omega^2 \varrho_s & 2\mu_s p k_t & \omega^2 \varrho_c \\ 2\mu_s p k_d & \mu_s(k_t^2 - p^2) & 0 \\ jk_d & -jp & -jl_d \end{vmatrix}. \tag{28}$$

The characteristic equation

$$|a_{ij}| = 0 \quad (i, j = 1, 2, 3) \tag{29}$$

signifies that there exists a nontrivial solution of system (27). The characteristic equation is an algebraic equation with complex conjugate terms and the complex conjugate unknown p. The propagation constant p occurs explicitly and is contained in the terms k_d, k_t and l_d, defined by relationships (11) and (24). It is impossible to transform equation (29) to achieve an analytical solution. Therefore, equation (29) will be solved numerically for the characteristic parameters of the biological medium when biopsy is performed. Subsequently, the results obtained will be used in another model, providing clues as to in what ranges the propagation constant p and other parameters, characteristic of the wave propagating along a hollow elastic cylinder immersed in a viscoelastic liquid, should be sought. This problem will be considered in another paper.

The characteristic equation (29) was solved numerically by the method of successive approximations. The aim was to find a complex conjugate solution whose real part lies close to the longitudinal wave velocity in tissue (close to 1.5×10^5 cm/s) and whose imaginary part is close to the value of the longitudinal wave attenuation in tissue (close to 0.370 cm^{-1}). The signs of k_d, k_t and l_d from formulae ($13a$) and (24) were chosen in such a way that the wave decayed with increasing distance from the boundary of the two media. The solution of the complex conjugate characteristic equation gave zero for the velocity of the wave sought $c_x = 1.499593 \times 10^5$ cm/s, i.e. slightly lower than the longitudinal wave velocity assumed in the unbounded viscoelastic liquid $c = 1.5 \times 10^5$ cm/s. The value of the attenuation coefficient obtained was $\alpha_x = 0.3734$ cm^{-1}, i.e. higher than the attenuation coefficient of the longitudinal wave in an unbounded viscoelastic medium assumed as $\alpha = 0.370$ cm^{-1}.

As a result of solving the equation, the following values of the wave numbers k_d, k_t and l_d were obtained:

$$k_d = -0.39 - j101,$$
$$k_t = -0.42 - j92.8, \tag{30}$$
$$l_d = 0.013 - j2.59,$$

and the following values of the displacement potential amplitudes:

$$E = 0.00067 - j1.08,$$
$$D = 4.85 - j0.047, \tag{31}$$

for the assumed value of the amplitude $A = 1 + j0$.

Subsequently, in order to verify whether the phenomenon is similar for a highly damping liquid, the acetic acid CH_3COOH was assumed as the viscoelastic liquid. This is a medium which shows 10 times as much attenuation as that in biological tissue. Namely, according to [9] the measured attenuation coefficient is

$$\frac{\alpha_d}{f^2} \times 10^{17} \frac{s^2}{\text{cm}} = 90{,}000. \tag{32}$$

Then for the frequency $f = 2$ MHz the attenuation $\alpha_d = 5.625$ cm^{-1}. The other characteristic parameters of the acetic acid are: the longitudinal wave velocity $c_d = 1.15 \times 10^5$ cm/s, the density $\varrho = 1.049$ g/cm^3, the coefficients of elasticity and bulk viscosity λ' and λ'', respectively (from formulae(18)): $\lambda' = 1.38 \times 10^{10}$ dyne/cm^2 $= 1.38 \times 10^9$ N/m^2, $\lambda'' = 72.5$ dyne s/cm^2 $= 7.25$ Ns/m^2. Then, the solution of the characteristic equation (29) by the method of successive approximations gives the sought velocity of the wave guided along the boundary, $c_x = 1.14913 \times 10^5$ m/s and the attenuation of this wave $\alpha_x = 5.635$ 1/cm.

Analogously to the first case considered (biological tissue), the velocity of the sought wave was found to be slightly lower than the longitudinal wave velocity in the medium and the attenuation slightly higher than the wave attenuation in an unbounded medium. By assuming the displacement amplitude $A = 1 + j0$, the remaining displacements amplitudes D and E and the wave displacements and stresses in the system considered were calculated. For the velocity c_x and the attenuation α_x determined numerically, the calculated numbers k_d, k_t and l_d and the displacement amplitudes E and D are

$$\left.\begin{aligned} k_d &= -5.74 - j134 \\ k_t &= -6.03 - j128 \\ l_d &= 0.0937 - j1.86 \end{aligned}\right\}, \tag{33}$$

$$\left.\begin{aligned} E &= 0.00411 - j1.047 \\ D &= 4.863 - j\,0.0256 \end{aligned}\right\}. \tag{34}$$

Consideration of the numerical results of (30), (31), (33) and (34) gives the displacement potentials in the form:

a) biological tissue/steel:

$$\phi^c = D\exp(-jz0.013)\exp(-2.59z)\exp(-jx104.75 - 0.3734x) \quad \text{tissue}$$

$$\left.\begin{aligned} \phi^s &= A\exp(-jz0.39)\exp(101z)\exp(-jx104.75 - 0.3734x) \\ & \qquad\qquad \text{steel} \\ \psi_y^s &= E\exp(-jz0.42)\exp(93z)\exp(-jx104.75 - 0.3734x) \end{aligned}\right\} \tag{35}$$

b) acetic acid/steel:

$$\phi^c = D\exp(-jz0.009)\exp(-1.86z)\exp(-jx136.69 - 5.635x) \quad \text{acetic acid}$$

$$\left\{\begin{aligned} \phi^s &= A\exp(-jz5.74)\exp(134z)\exp(-jx136.69 - 5.635x) \\ & \qquad\qquad \text{steel} \\ \psi_y^s &= E\exp(-jz6.03)\exp(128z)\exp(-jx136.69 - 5.635x) \end{aligned}\right. \tag{36}$$

It follows from the form of ϕ^c, ϕ^s and ψ_y^v that the wave propagates and is attenuated in the direction x and z; from the solid to the viscoelastic liquid. The first exponential factor did not occur when the liquid medium was considered without attenuation [1].

Moreover, the wave is strongly attenuated with increasing distances from the boundary $z = 0$ in both directions.

5. Acoustic impedance in the viscoelastic liquid

Let us now calculate the impedance in the unbounded viscoelastic medium and the impedance of the half-space of the viscoelastic liquid for the wave propagating along the boundary of the two half-spaces.

The impedance in the unbounded medium, Z_{bulk}, of the viscoelastic liquid, for the planar wave propagating in the direction x, is given by the formula

$$Z_{\text{bulk}} = \frac{p'}{v} = \varrho_c c = \frac{\lambda_c + 2\mu_c}{c} = \frac{\lambda_c}{c} = \lambda_c \operatorname{Re}\left(\sqrt{\frac{\varrho_c}{\lambda}}\right), \tag{37}$$

where p' is the pressure of the wave and c is its velocity. In the case of a bounded medium the components of the vector of the impedance of the medium in the direction i ($i = x, y, z$) are defined, according to [8, 10], as

$$Z_i^c = \frac{\tau_i^c}{v_i^c}, \tag{38}$$

where

$$\tau_i^c = \tau_{xi}^c + \tau_{yi}^c + \tau_{zi}^c \quad (i = x, y, z),$$

$$\bar{v}^c = \left[\frac{du^c}{dt}, \frac{dv^c}{dt}, \frac{dw^c}{dt}\right] = [v_x^c, v_y^c, v_z^c].$$

Then for the half-space of the viscoelastic liquid, from formulae (14) (15) and (22),

$$\begin{aligned} Z_x^c &= \frac{\tau_{xx}^c}{v_x^c} = \frac{\omega\varrho_c}{p}, \\ Z_z^c &= \frac{\tau_{zz}^c}{l_d} = \frac{\omega\varrho_c}{l_d}, \end{aligned} \tag{39}$$

giving the following values of the components of the impedance

a) for tissue:

$$\begin{cases} |Z_x| = 1.5 \times 10^5 \text{ g/scm}^2, \text{ since } Z_x = 1.4995 \times 10^5 + 5.35 \times 10^2 j \\ |Z_z| = 6.2 \times 10^6 \text{ g/scm}^2, \text{ since } Z_z = 3.216 \times 10^4 + 6.234 \times 10^6 j \end{cases} \tag{40}$$

b) for acetic acid CH_3COOH:

$$\begin{cases} |Z_x| = 1.2 \times 10^5 \text{ g/scm}^2, \text{ since } Z_x = 1.2 \times 10^5 + 4.96 \times 10^3 j \\ |Z_z| = 8.8 \times 10^6 \text{ g/scm}^2, \text{ since } Z_z = 4.44 \times 10^5 + 8.82 \times 10^6 j \end{cases} \tag{41}$$

weheras the characteristic impedance for the wave in an unbounded viscoelastic medium is:

a) for tissue

$$|Z_{\text{bulk}}^c| = 1.5 \times 10^5 \text{ g/scm}^2, \text{ since } Z_{\text{bulk}} = 1.49 \times 10^5 + 5.7 \times 10^2 j;$$

b) for acetic acid CH_3COOH: (42)

$$|Z_{\text{bulk}}^c| = 1.2 \times 10^5 \text{ g/scm}^2, \text{ since } Z_{\text{bulk}} = 1.2 \times 10^5 + 9.88 \times 10^3 j.$$

It can be seen that the modulus of the component Z_x of the impedance vector for the liquid half-space (formulae (40) and (41)) is equal to the modulus of the characteristic impedance of the wave in the unbounded medium (formula (42)). In turn, the component Z_z of the impedance (perpendicular to the boundary of the medium) is in both cases distinctly larger (more than ten times). Its imaginary part is larger by one or two orders of magnitude than the real one, which results from the very weak attenuation of this component, propagating from the elastic medium to the damping liquid, perpendicularly across the boundary of the two media. For an undamped propagating wave the impedance is a real quantity [13].

6. Discussion and results

It has been shown that in a planar system of a viscoelastic half-space (biological tissue), bordering on an ideally elastic half-space (steel), a boundary wave can propagate with a velocity slightly lower ($c_x = 1.499593 \times 10^5$ cm/s) than that of the longitudinal wave, assumed for an unbounded viscoelastic medium ($c = 1.5 \times 10^5$ cm/s). In view of the properties of biological tissue, it has been assumed that it only exhibits elasticity and bulk viscosity (damping liquid).

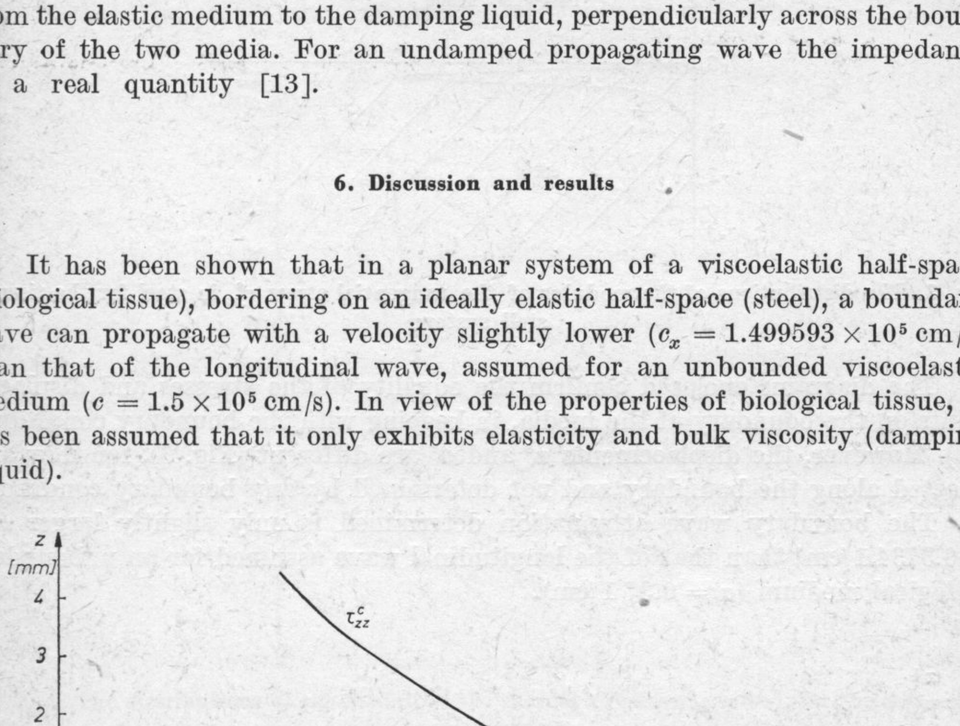

Fig. 2. The distribution of the moduli of the normal stresses τ_{zz}^s and τ_{zz}^c for the tissue-steel system

The boundary wave analysed propagates only in the boundary conditions: the thickness of this layer in steel is smaller by an order of magnitude than that in biological tissue. In turn, the thickness of the boundary layer in biological tissue is of the order of 10 wavelengths. This results from the displacement distributions (Fig. 4) determined for a frequency of 2.5 MHz. The stress distributions (Figs. 2, 5, 7), determined in biological tissue and acetic acid also confirm this character of bilateral decay of the wave across the boundary.

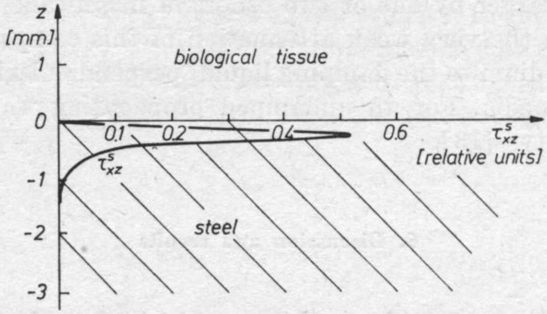

Fig. 3. The distributions of the modulus of the tangential stress τ^s_{xz} in steel for the tissue-stell system

The diagrams enclosed confirm the equality of the stresses and displacements on the boundary of the media, in keeping with the boundary conditions (27). However, the displacements u^s and u^c are different (Fig. 8), for they are directed along the boundary and not determined by any boundary condition.

The boundary wave attenuation determined is only slightly larger ($\alpha_x = 0.3734$ 1/cm) than that of the longitudinal wave assumed for an unbounded biological medium ($\alpha = 0.37$ 1/cm).

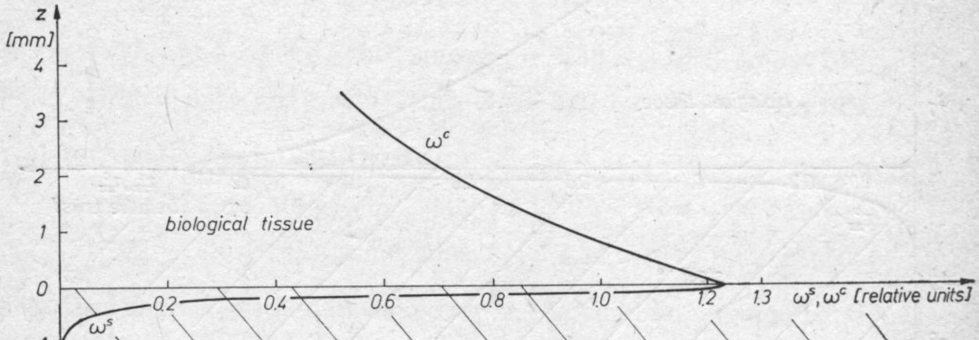

Fig. 4. The distributions of the moduli of the displacement components w^c and w^s for the tissue-steel system

It has been observed that the wave propagates in the directions x and z; from the boundary layer of the solid medium to the boundary layer of the viscoelastic liquid (see formulae (35) and (36)). In a previous paper of the author, where two elastic media were considered, the boundary wave was not observed to propagate across the boundary.

Physically, this phenomenon can be explained by energy flow from the boundary layer to the viscoelastic liquid. Without this energy flow, as a result of absorption, the amplitude (and energy) of the wave in the boundary layer of

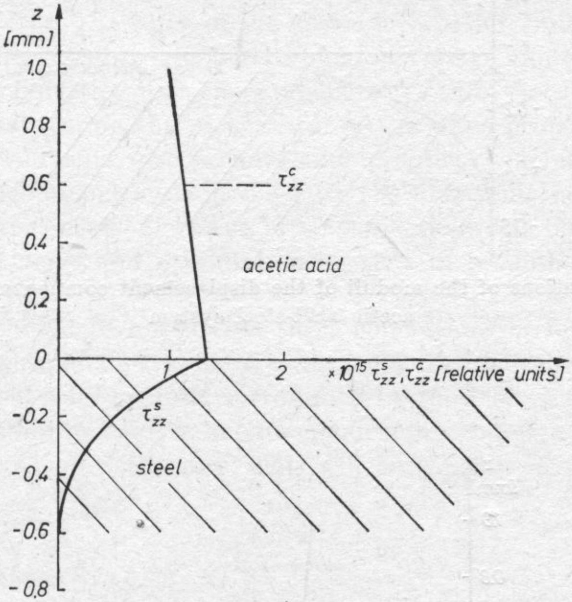

Fig. 5. The distributions of the moduli of the normal stresses τ_{zz}^{s} and τ_{zz}^{c} for the acetic acid-steel system

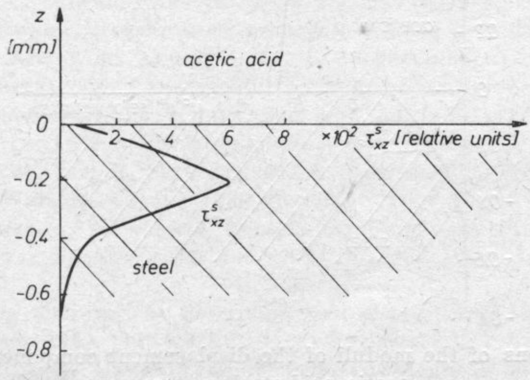

Fig. 6. The distribution of the modulus of the tangential stress τ_{xz}^{s} in steel for the acetic acid-steel system

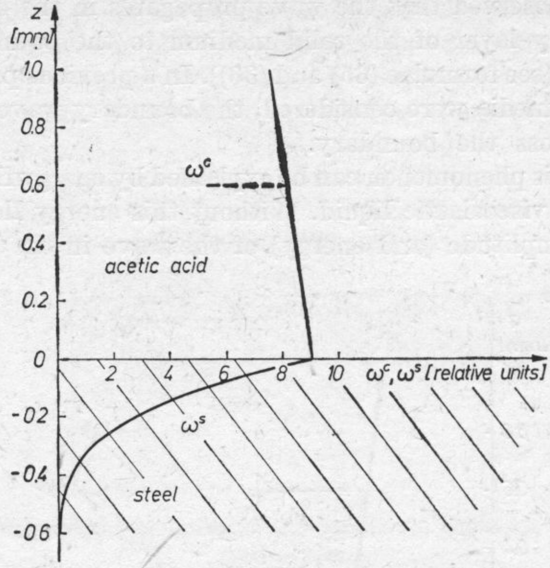

Fig. 7. The distributions of the moduli of the displacement components w^c and w^s for the acetic acid-steel system

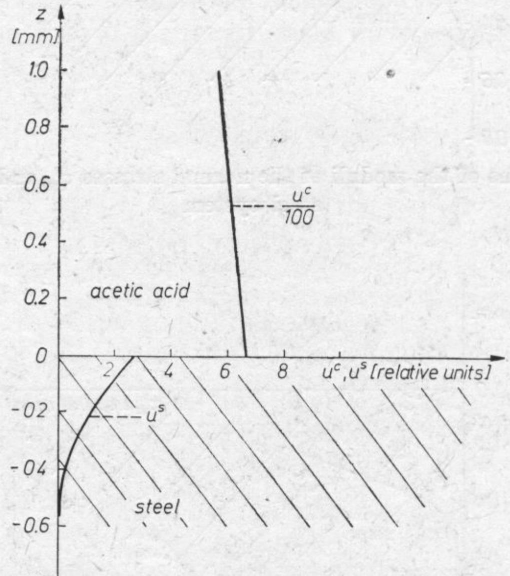

Fig. 8. The distributions of the moduli of the displacement components u^c and u^s for the acetic acid-steel system

the viscoelastic liquid would decrease as the wave would propagate in the direction x. It would, however, remain constant in the boundary layer of the ideally elastic solid medium. Therefore, after covering some distance x, it could not satisfy the boundary conditions of the equality of the stresses and displacements on both sides of the boundary. Thus, there must occur energy flow across the boundary, to increase the wave amplitude in the viscoelastic liquid and decrease it in the elastic one; and, by doing so, satisfy the boundary conditions, irrespective of the distance x.

The conclusions that there is energy flow across the boundary of the media can also be drawn from the value of the impedance Z_z determined for the viscoelastic liquid. It has a real component, which, in view of the wave propagation in the direction z, indicates that energy penetrates into the viscoelastic liquid.

The above analysis, on the mechanism of the wave propagation along the boundary of the two media, also permits some practical conclusions to be drawn for the performance of biopsy controlled by the ultrasonic beam, since it can be assumed that the ultrasonic wave propagates along the needle with practically the same velocity and attenuation as that in an unbounded biological medium.

However, it should be noted that these conclusions have been formulated for a very simplified planar system of two media. In reality, in biopsy, there is a layered cylindrical solid medium surrounded by the biological one. Therefore, it seems indispensible to analyse such a much more complex case, in order to solve the problem in an exact way. This will be considered in another paper.

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DIRECTIONAL CHARACTERISTIC OF A CIRCULAR MEMBRANE VIBRATING UNDER THE EFFECT OF A FORCE WITH UNIFORM SURFACE DISTRIBUTION

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In this paper, the acoustic pressure of a circular membrane is analysed on the assumption that the distance between the field point and the membrane is much longer, both in terms of its linear dimensions and the wavelengths radiated. It was assumed that the membrane was excited to induced harmonic vibration – including nonresonance one – by a force with uniform surface distribution. The membrane was placed in a rigid, planar baffle, and the gas medium, into which it radiated, was lossless. Numerical examples of the directional characteristic were represented graphically.

1. Notation

a – membrane radius
a_0, b – radii of the annular surface of the membrane, on which the normal component of the force inducing vibration, different from zero, acts
c_M – wave propagation velocity on the membrane
f – surface density of the force inducing the vibration
f_0 – constant density, independent of time, of the force inducing vibration (1)
J_m – Bessel function of the mth order
N_m – Neumann function of the mth order
$k = \omega \sqrt{\eta/T}$
$k_0 = 2\pi/\lambda$
K – directionality coefficient (17)
K' – directionality coefficient (25)
p – acoustic pressure (10)
p' – acoustic pressure in the main direction (23)
p_0 – acoustic pressure in the main direction (22)
R – radial variable of the field point in the spherical coordinate system

r, r_0 — radial variable of the point of the membrane surface in the polar coordinate system
T — force stretching the membrane, referred to unit length
t — time
v — normal component of the vibration velocity of points of the membrane surface
β_{0n} — nth root of the equation $J_0(\beta_{0n}) = 0$
ξ — transverse displacement of the points of the membrane surface
η — surface density of the membrane
λ — wavelength in a gaseous medium
ϱ_0 — rest density of the gaseous medium
σ_0 — membrane surface area (circular field)
ω — angular frequency of the force inducing vibration

2. Introduction

In considering practical applications, membranes being sources or receivers of acoustic energy, excited to resonance vibration, are most often analysed. In order to investigate fully and in detail the acoustic properties of such vibrating systems, investigations should also be carried out for nonresonance frequencies.

In the case of nonresonance vibration, the velocity distribution is much more complex than that for resonance vibration and depends significantly on the factor forcing the vibration, e.g. on the distribution of the inducing force [1], [2].

In paper [2], analysing the forced vibration of the circular membrane, expressions were given for the vibration velocity in the form of the expansion into a Fourier series, and the distribution of the force inducing the vibration and the distribution of deviations, as the resultants of the series of sinusoidal vibrations with frequencies equal to the eigenfrequencies of the membrane, were given.

Two methods for the calculation of the vibration velocity distribution of the membrane were given in paper [1]. The first of these methods is based on the use of the eigenfunctions for a circular membrane performing free vibration. This method is convenient for the analysis of the physical properties of the vibrating membrane, but hardly useful for numerical results to be obtained, since the solutions given in it are slowly converging series. The other method leads to the establishment of the vibration distribution in the form of the sum of the general solution of a homogeneous vibration equation and of the specific solution for a heterogeneous vibration equation. This method was used by HAJASAKA to analyse theoretically the forced vibration of the circular membrane, induced to harmonic vibration by an electric force, by means of two circular electrodes parallel to the surface of the membrane.

The directional characteristic of the circular membrane, strained with the same force over the circumference, excited to resonance vibration, is known, e.g. from SKUDRZYK'S papers [4], [5].

Referring to communique [3], the present paper also considered the directional characteristic of the circular membrane, however, on the assumption that it is excited to forced vibration — including nonresonance one — by a force with uniform surface distribution. The use was made of the expression for the vibration velocity, obtained by solving a heterogeneous vibration equation for undamped phenomena harmonic in time. The vibration distribution was given in the form of the sum of the general solution of the homogeneous equation and the specific solution of the heterogeneous vibration equation. It was also assumed that the membrane was placed in an ideal rigid, planar baffle, and the baffle — into which it radiated — was lossless. An expression was obtained for the directionality coefficient in a form convenient for numerical calculations, which were represented graphically.

3. Vibration velocity

On a plane, which is an ideal rigid baffle, there is a circular membrane stretched by the same force round the circumference with the radius a. The membrane is induced to transverse vibration under the effect of an axially-symmetric inducing force, e.g. by means of two planar annular electrodes parallel

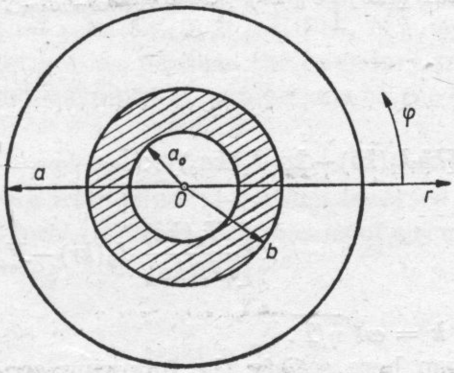

Fig. 1. The vibrating system: a – membrane radius; a_0, b – radii of the annular surface of the membrane on which the inducing force, different from zero, acts; $\{a \leqslant r < \infty,\ 0 \leqslant \varphi \leqslant 2\pi\}$ – the region of the rigid baffle

to the surface of the membrane, with the external radii b and the internal ones a_0 (Fig. 1). In this case, the factor inducing harmonic vibration can be an electric force with the surface density

$$f(r,t) = \begin{cases} 0 & \text{for } 0 < r < a_0 \\ f_0 \exp(i\omega t) & \text{for } a_0 < r < b \\ 0 & \text{for } b < r < a. \end{cases} \tag{1}$$

The vibration equation [2] of the circular membrane under the effect of an axially symmetric inducing force, is the following:

$$T\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\xi(r,t)}{\partial r}\right)-\frac{\partial^2\xi(r,t)}{\partial t^2} = -f(r,t), \tag{2}$$

where $T = c_M^2\eta$.

The solution of equation (2) for a membrane excited to forced vibration by force (1) has the form

$$\xi_1(r,t) = \frac{\pi}{2}\frac{f_0}{\eta\omega^2}\left\{\frac{N_0(ka)}{J_0(ka)}[kbJ_1(kb)-ka_0J_1(ka_0)]- -kbN_1(kb)+ka_0N_1(ka_0)\right\}J_0(kr)\exp(i\omega t) \tag{3}$$

for $0 < r < a_0$;

$$\xi_2(r,t) = \frac{\pi}{2}\frac{f_0}{\eta\omega^2}\left\{\left[\frac{N_0(ka)}{J_0(ka)}\big(kbJ_1(kb)-ka_0J_1(ka_0)\big)- -kbN_1(kb)\right]J_0(kr)+ka_0J_1(ka_0)N_0(kr)-\frac{2}{\pi}\right\}\exp(i\omega t) \tag{4}$$

for $a_0 < r < b$; and

$$\xi_3(r,t) = \frac{\pi}{2}\frac{f_0}{\eta\omega^2}[kbJ_1(kb)-ka_0J_1(ka_0)]\times \times\left[\frac{N_0(ka)}{J_0(ka)}J_0(kr)-N_0(kr)\right]\exp(i\omega t) \tag{5}$$

for $b < r < a$, where $k = \omega\sqrt{\eta/T}$.

The solutions given here satisfy the following conditions:

a) The functions $\xi_1(r,t)$, $\xi_2(r,t)$ and $\xi_3(r,t)$ take finite values in the respective regions: $\{0 \leqslant r \leqslant a_0,\ 0 \leqslant \varphi \leqslant 2\pi\}$; $\{a_0 \leqslant r \leqslant b,\ 0 \leqslant \varphi \leqslant 2\pi\}$ and $\{b \leqslant r \leqslant a,\ 0 \leqslant \varphi \leqslant 2\pi\}$, and, thus, the solution of $\xi_1(r,t)$ also has a finite value for $r = 0$.

b) The boundary condition $\xi_3(r,t) = 0$ for $r = a$.

c) The agreement conditions

$$\xi_1(r,t) = \xi_2(r,t), \quad \partial\xi_1(r,t)/\partial r = \partial\xi_2(r,t)/\partial r \quad \text{for } r = a_0$$

and

$$\xi_2(r,t) = \xi_3(r,t), \quad \partial\xi_2(r,t)/\partial r = \partial\xi_3(r,t)/\partial r \quad \text{for } r = b.$$

The normal component of the vibration velocity of the points of the membrane surface, is obtained after taking into account that $v(r,t) = \partial\xi(r,t)/\partial t$, where $\xi(r,t) = \xi_0(r)\exp(i\omega t)$.

In the boundary case, when the membrane is excited to transverse vibration by the force

$$f'(r,t) = \begin{cases} f_0 \exp(i\omega t) & \text{for } 0 < r < b; \\ 0 & \text{for } b < r < a, \end{cases} \tag{6}$$

solutions (3), (4) and (5) are replaced, after assuming previously that $a_0 = 0$, by

$$\xi_2'(r,t) = \frac{f_0}{\eta\omega^2}\left\{\frac{\pi kb}{2}\left[\frac{N_0(ka)}{J_0(ka)}J_1(kb) - N_1(kb)\right]J_0(kr) - 1\right\}\exp(i\omega t) \tag{7}$$

for $0 < r < b$;

$$\xi_3'(r,t) = \frac{f_0}{\eta\omega^2}\frac{\pi kb}{2}J_1(kb)\left[\frac{N_0(ka)}{J_0(ka)}J_0(kr) - N_0(kr)\right]\exp(i\omega t) \tag{8}$$

for $b < r < a$; and

$$\xi_1'(0,t) = \xi_2'(0,t) = \frac{f_0}{\eta\omega^2}\left\{\frac{\pi kb}{2}\left[\frac{N_0(ka)}{J_1(ka)}J_1(kb) - N_1(kb)\right] - 1\right\}\exp(i\omega t). \tag{9}$$

In order to show that relation (9) is satisfied, it is necessary to assume in solutions (3) and (4) that $r = a_0$, perform the boundary transition $a_0 \to 0$, apply wronskian (14) and the asymptotic expressions $J_0(x) \approx 1$, $N_1(x) \approx -2/\pi x$ with $x \to 0$.

Solutions (7) and (8), which are specific cases of the more general solutions (3), (4) and (5), are known from paper [1], which analysed the membrane vibration under the effect of force inducing it by means of circular electrodes parallel to the surface of the membrane.

4. Acoustic pressure

The acoustic pressure distribution in the far field of a source vibrating in an ideal rigid and planar baffle can be calculated from the dependence [2]

$$p(R,\theta,\varphi,t) = \frac{i\varrho_0\omega}{2\pi}\frac{\exp(-ik_0R)}{R}\times$$
$$\times\int_{\sigma_0} v(r_0,\varphi_0,t)\exp[ik_0r_0\sin\theta\cos(\varphi-\varphi_0)]\,d\sigma_0 \tag{10}$$

for $1/2\ k_0r_0(r_0/R) \ll 1$, where R, θ, φ are the spherical coordinates of a point of the field; r_0 and ϕ_0 are the polar coordinates of a point of the source; $\sigma_0 = \pi a^2$ is the surface area of the circular membrane.

In the case of a circular membrane excited to axially symmetric vibration (3), (4) and (5), the vibration velocity of the points of its surface does not depend on the angular variable φ_0. Consideration also of the integral property [7].

$$\int_0^{2\pi} \exp[\pm ib\cos(\varphi-\varphi_0)]\,d\varphi_0 = 2\pi J_0(b) \tag{11}$$

leads to the following form of the expression for the acoustic pressure (10):

$$p(R,\theta,t) = i\varrho_0\omega\frac{\exp(-ik_0R)}{R}\left\{\int_0^{a_0}\frac{\partial\xi_1(r_0,t)}{\partial t}J_0(k_0r_0\sin\theta)r_0dr_0+\right.$$

$$+\int_{a_0}^{b}\frac{\partial\xi_2(r_0,t)}{\partial t}J_0(k_0r_0\sin\theta)r_0dr_0+$$

$$\left.+\int_{b}^{a}\frac{\partial\xi_3(r_0,t)}{\partial t}J_0(k_0r_0\sin\theta)r_0dr_0\right\}. \tag{12}$$

In calculating the integrals occurring here, the following dependencies can be used [7]:

$$\int wJ_0(hw)Z_0(lw)\,dw = \frac{w}{h^2-l^2}\{hJ_1(hw)Z_0(lw)-lJ_0(hw)Z_1(lw)\}, \tag{13}$$

where Z_m is any cylindrical function of the mth order. Consideration also of the wronskian [7]

$$J_1(x)N_0(x)-J_0(x)N_1(x) = \frac{2}{\pi x} \tag{14}$$

leads to

$$p(R,\theta,t) = \frac{\varrho_0 f_0 b^2}{2\eta}\frac{\exp[i(\omega t-k_0R)]}{R}\frac{1}{1-\left(\frac{k_0}{k}\right)^2\sin^2\theta}\times$$

$$\times\left\{\frac{2J_1(k_0b\sin\theta)}{k_0b\sin\theta}-\left(\frac{a_0}{b}\right)^2\frac{2J_1(k_0a_0\sin\theta)}{k_0a_0\sin\theta}+\right.$$

$$\left.+\frac{2\left(\frac{a_0}{b}\right)J_1(ka_0)-2J_1(kb)}{kbJ_0(ka)}J_0(k_0a\sin\theta)\right\}. \tag{15}$$

In the main direction, i.e. for $\theta = 0$,

$$p_0(R, 0, t) = \frac{\varrho_0 f_0 b^2}{2\eta} \frac{\exp[i(\omega t - k_0 R)]}{R} \left[1 - \left(\frac{a_0}{b}\right)^2 + \right.$$

$$\left. + \frac{2\left(\frac{a_0}{b}\right) J_1(ka_0) - 2J_1(kb)}{kbJ_0(ka)}\right]. \tag{16}$$

The directionality coefficient [2]

$$K(\theta) = \frac{|p|}{|p_0|} \tag{17}$$

for $p_0 \neq 0$. When, in turn,

$$1 - \left(\frac{a_0}{b}\right)^2 + \frac{2\left(\frac{a_0}{b}\right) J_1(ka_0) - 2J_1(kb)}{kb\,J_0(ka)} = 0 \tag{18}$$

the phenomenon of antiresonance occurs, and the directionality coefficient must then be defined in another way. It can be achieved by referring the value of the pressure $p(R, \theta, t)$ to that of the pressure $p'(R, 0, t)$ in such a direction θ where it is maximum.

In the case of resonance vibration, $ka = \beta_{0n}$, where β_{0n} is the nth root of the equation $J_0(\beta_{0n}) = 0$. Then, calculation of the limit

$$\lim_{ka \to \beta_{0n}} K(\theta) = \lim_{ka \to \beta_{0n}} \frac{|p(R, \theta, t)|}{|p_0(R, 0, t)|} \tag{19}$$

gives the dependence

$$K_0(\theta) = \frac{|J_0(k_0 a \sin\theta)|}{\left|1 - \left(\frac{k_0 a}{\beta_{0n}}\right)^2 \sin^2\theta\right|}, \tag{20}$$

which is known, e.g. from papers [4], [5] and [6].

When, in turn, $a_0 = 0$, then instead of expressions (15) and (16), the following formulae are obtained for the acoustic pressure:

$$p(R, \theta, t) = \frac{\varrho_0 f_0 b^2}{2\eta} \frac{\exp[i(\omega t - k_0 R)]}{R} \times$$

$$\times \frac{1}{1 - \left(\frac{k_0}{k}\right)^2 \sin^2\theta} \left[\frac{2J_1(k_0 b \sin\theta)}{k_0 b \sin\theta} - \frac{2J_1(kb)}{kbJ_0(ka)} J_0(k_0 a \sin\theta)\right] \tag{21}$$

and

$$p_0(R, 0, t) = \frac{\varrho_0 f_0 b^2}{2\eta} \frac{\exp[i(\omega t - k_0 R)]}{R} \left[1 - \frac{2J_1(kb)}{kbJ_0(ka)}\right]. \tag{22}$$

In this case, it is also possible to determine the directionality coefficient from formula (17), but on the assumption that $2J_1(kb) \neq kbJ_0(ka)$. When, in turn,

$$2J_1(kb) = kbJ_0(ka) \tag{22a}$$

the phenomenon of antiresonance occurs. Relation (22a) can also be derived by assuming in dependence (18) that $a_0 = 0$.

5. A numerical example and final remarks

Figs 2, 3 and 4 show curves of the directionality coefficient of the radiation of the circular membrane excited to forced vibration. The value $p(R, \theta, t)$ of the acoustic pressure (21) was referred to the value $p'(R, 0, t)$ of pressure (22) on the main axis, where it was assumed that $ka = 2$, $b = a$, i.e.

$$p'(R, 0, t) = \frac{\varrho_0 f_0 a^2}{2\eta} \frac{\exp[i(\omega t - k_0 R)]}{R} \left[1 - \frac{J_1(2)}{J_0(2)}\right]. \tag{23}$$

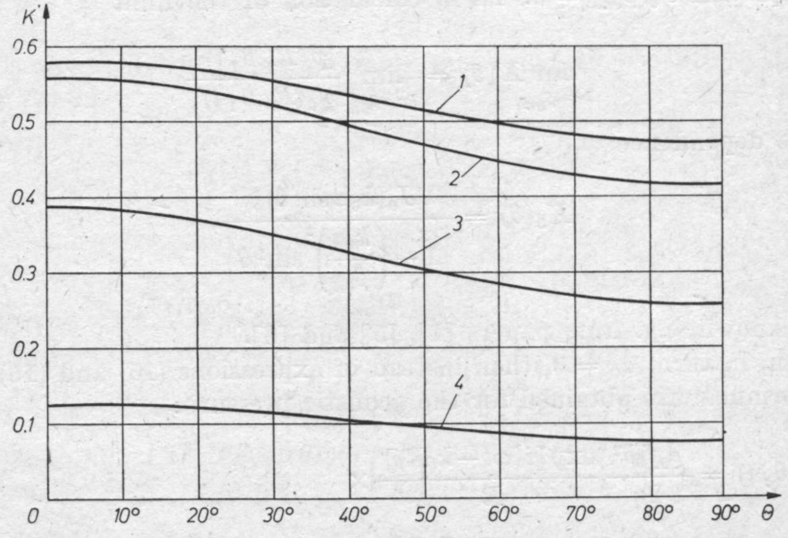

Fig. 2. The directionality coefficient of the radiation of a circular membrane vibrating under the effect of a force with uniform surface distribution, for the different values of b/a. Curve *1* – $b/a = 1$, curve *2* – $b/a = 3/4$, curve *3* – $b/a = 1/2$, curve *4* – $b/a = 1/4$. It was assumed that $ka = 4$, $k_0/k = 1/2$

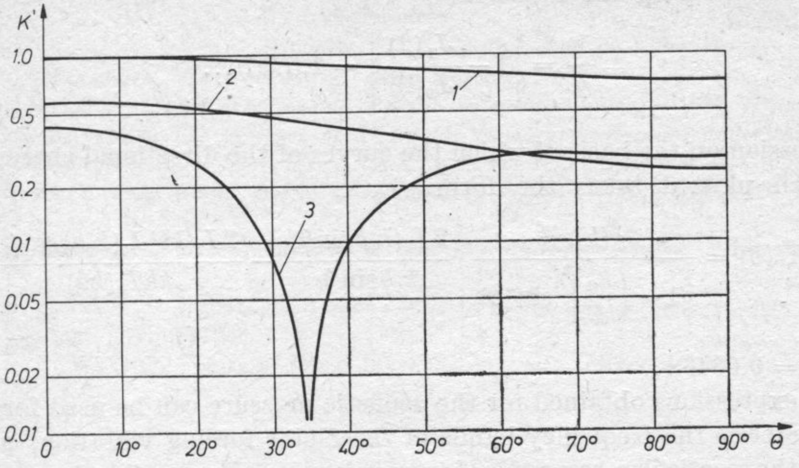

Fig. 3. The directionality coefficient of the radiation of a circular membrane vibrating under the effect of a force with uniform surface distribution, for the different values of the parameter ka. Curve $1 - ka = 2$, curve $2 - ka = 4$, curve $3 - ka = 8$. It was assumed that $b = a$, $k_0/k = 1$

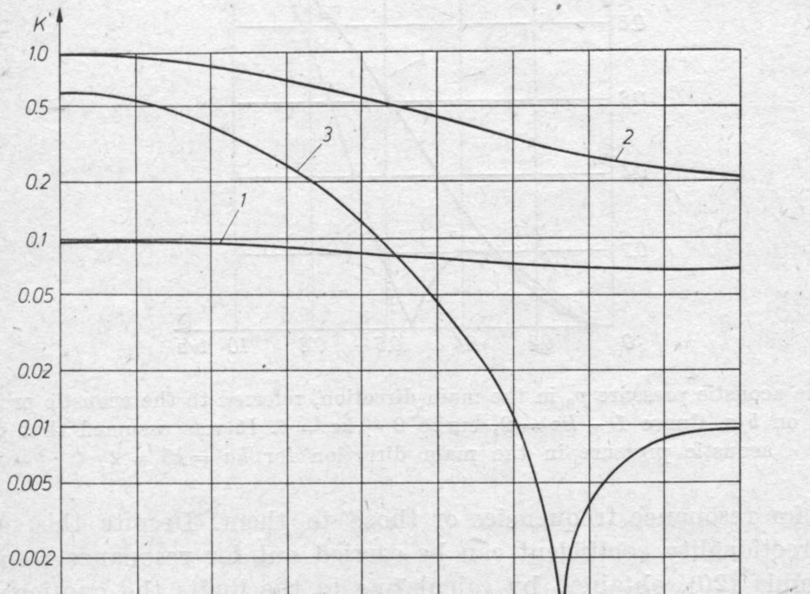

Fig. 4. The directionality coefficient of the radiation of a circular membrane vibrating under the effect of a force with uniform surface distribution, for the different values of the parameter ka. Curve $1 - ka = 1$, curve $2 - ka = 2$, surve $3 - ka = 4$. It was assumed that $b = a$, $k_0/k = 2$

After introducing the notation

$$\frac{1}{\gamma} = \left|1 - \frac{J_1(2)}{J_0(2)}\right| = 1.5757 \ldots \tag{24}$$

the expression on the basis of which the curves of the directional characteristics have been plotted takes the form

$$K'(\theta) = \frac{\gamma (b/a)^2}{\left|1 - \left(\frac{k_0}{k}\right)^2 \sin^2\theta\right|} \left|\frac{2J_1(k_0 b \sin\theta)}{k_0 b \sin\theta} - \frac{2J_1(kb) J_0(k_0 a)\sin\theta}{kb J_0(ka)}\right|, \tag{25}$$

where $\gamma = 0.6346 \ldots$

The expressions obtained for the acoustic prssure can be used for calculating in practice the frequency bands of the factor forcing vibration, contained between the particular resonance frequencies. It is impossible to analyse the

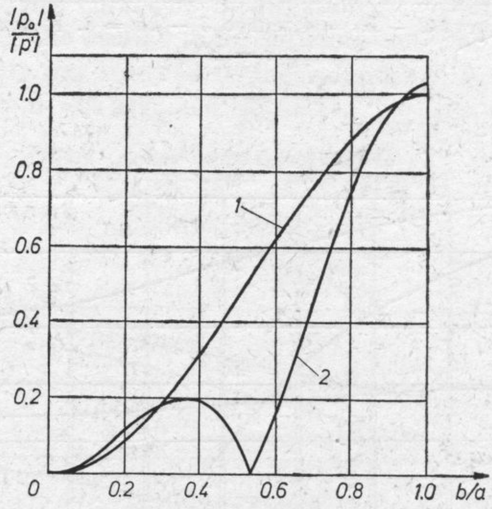

Fig. 5. The acoustic pressure p_0 in the main direction, referred to the acoustic pressure p', depending on b/a. Curve $1 - ka = 2$, curve $2 - ka = 6$. It was assumed that p' is the acoustic pressure in the main direction for $ka = kb = 2$

pressure for resonance frequencies or those to them. Despite this, analysis of the directionality coefficient can be carried out for resonance frequencies from formula (20), obtained by calculating in the limits the quotient of the pressure represented by means of dependencies (15) and (16), which take then infinitely high values.

Expressions (15) and (21) derived for the acoustic pressure can also be used in a more profound analysis of the physical properties of the radiating membrane as a vibrating system, e.g. to calculate the acoustic resistance and reactance.

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DIFFRACTION OF A CYLINDRICAL ACOUSTIC PULSE BY A WEDGE

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In the paper, the diffracted field of a cylindrical pulse, approximating an explosion, at a wedge with the V angle $\alpha = 3/2\pi$, was calculated. This problem was solved on the basis of the Oberhettinger theory. The drop of the acoustic pressure level at the edge of the wedge, depending on the energy of the source, and the drop of the pressure level along the wall of the wedge in the silence zone, were calculated.

1. Introduction

The protection of the environment against noise is becoming increasingly significant. Kinds of noise sources and the means of protection against noise were described synthetically in paper [2] and the bibliography given in it. Apart from the means of protection described in [1], the problem of planner-designed protection against sounds is of particular significance; this is the method of situating buildings with respect to the noise sources. The theoretical problem consists in the calculation, in the acoustical shadow zone, of the so-called diffracted field at the corner of the building. A large number of papers has so far been devoted to this problem (see [8] and the list of references given here), but they take into account the diffraction of a harmonic wave, while pulses, and among them explosion, are the most annoying forms of noise.

In the present paper, the diffracted field of a cylindrical pulse, approximating an explosion, was calculated. The diffraction of the pulse of a planar-type explosion was described in paper [9], whereas a paper on the diffraction of a spherical pulse of the same type, will be published in the near future.

The problem of pulse diffraction was considered by SOMMERFELD [6], FRIEDLANDER [2], OBERHETTINGER [4], [5] and others (see the bibliography given in [5]).

In this paper, the theoretical considerations were based on the general Oberhettinger theory [5], [7], OBERHETTINGER solved the problem of the diffraction of unitary pulses; a plane one on a wedge, and cylindrical and spherical ones on a half-plane. The problems solved are not of any greater practical significance. The subject of the present paper seems to be more practical and more general.

The theory given by OBERHETTINGER describes a linear physical phenomenon. Its application to describe the explosion-type diffraction, can raise some doubts. However, at a sufficiently long distance from the source, this assumption appears to be valid.

2. Basic assumptions

In the present paper, as shape of the pulse $f(t^*)$ (Fig. 1) was chosen, which describes the explosion with the good approximation. Physically, it describes the time distribution of the velocity potential of the acoustic field [3].

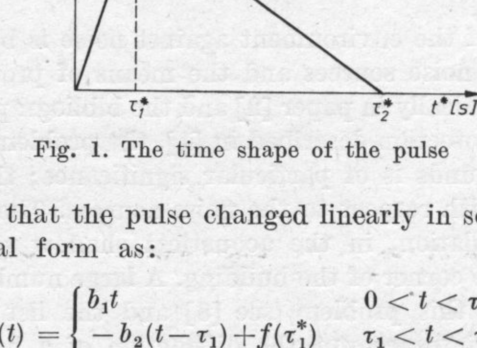

Fig. 1. The time shape of the pulse

It was assumed that the pulse changed linearly in sections, which can be written in analytical form as:

$$f(t) = \begin{cases} b_1 t & 0 < t < \tau_1 \\ -b_2(t-\tau_1)+f(\tau_1^*) & \tau_1 < t < \tau_2^* \\ 0 & \text{other } t \end{cases} \tag{1}$$

where t[m] is the reduced current time, $t = t^*c$, t^* [s]; c [m/s] is the sound velocity, $b_1 = f(\tau_1^*)/\tau_1^*$, $b_2 = -[f(\tau_1^*)/\tau_2 - \tau_1^*]$.

The geometrical aspect of the problem is shown in Fig. 2. The diffraction phenomenon occurs at a corner, i.e. on the structural element of the building.

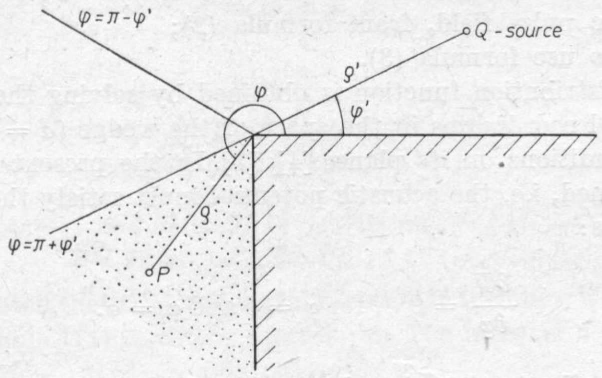

Fig. 2. The geometry of the problem: wave diffraction at a corner

The source Q was located with reference to the corner in such a way as to form a acoustical shadow zone. It was also assumed that a cylindrical wave of the zeroth order, $H_0^{(2)}(kr)$, was diffracted. This assumption seems to be valid, since the source is at some distance from the edge, and higher-order cylindrical waves are damped.

3. General theory of pulse diffraction at a wedge according to Oberhettinger

The problem was solved by applying the Laplace's transform and the diffraction problem solved for harmonic waves by OBERHETTINGER [4], [7]. According to this theory, for a harmonic source, the field diffracted at a wedge is the product of the field distribution function $U(x, y, z, \gamma) = U$ and the harmonic function $\exp(\gamma ct)$, $(\gamma = ik)$.

OBERHETTINGER proposed a similar approach to the pulse. First, the function of the pulse $f(t)$ is resolved into the sum (integral) of harmonic components (on the basis of the simple Laplace's transform), subsequently the diffracted field of each harmonic component is calculated, and these fields are summed up (integrated on the basis of the inverse Laplace's transform):

$$\Phi(x, y, z, \gamma) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \left[U \exp(\gamma ct) \int_0^\infty f(\tau) \exp(-\gamma c\tau)\, d\tau \right] d(\gamma c). \tag{2}$$

Formula (2) can be given in the form

$$\Phi(x, y, z, \gamma) = \int_0^\infty f(\tau) \Phi_D(t-\tau)\, d\tau, \tag{3}$$

where $\Phi_D(t-\tau)$ is the field of the Dirac pulse, calculated from formula (2), when $f(t)$ is taken to be the distribution of δ.

In order to find the field of any pulse in the region of the wedge, it is necessary to calculate:

a. the field distribution function $U(x, y, z, \gamma) = U$;

b. the Dirac pulse field, from formula (2);

c. finally, to use formula (3),

The field distribution function is obtained by solving the wave equation in the cylindrical coordinates in the space of the wedge ($\alpha = 3/2\pi$), with the predescribed conditions on its planes [4], [7]. In the present case, ideal rigid walls were assumed, i.e. the acoustic potential must satisfy the following boundary conditions:

$$\frac{\partial \Phi}{\partial \varphi} = 0 \quad \text{for } \varphi = 0 \text{ and } \varphi = \alpha. \tag{4}$$

The field distribution function obtained can be given by the formula [4], [7]

$$U = \sum_{v=1}^{2}\Big[\sum_{r=r_1}^{r_2} H_0^{(2)}(kR_v) + \int_0^\infty H_0^{(2)}(kR_x)G(x, \theta_v)\,dx\Big], \tag{5}$$

where

$$R_v^2 = \varrho^2 + \varrho'^2 - 2\varrho\varrho'\cos(3\pi r + \theta_v),\; R_x^2 = \varrho^2 + \varrho'^2 + 2\varrho\varrho'\cosh x; \tag{6}$$

$$G(x, \theta_v) = -\frac{1}{3\pi}\sum_{p=1}^{2}\frac{s_{vp}}{\cosh(2/3\pi) - c_{vp}}, \quad S_{vp} = \sin\left(\frac{3}{2}\pi \pm \theta_v\right),$$

$$C_{vp} = \cos\left(\frac{3}{2}\pi \pm \theta_v\right), \quad \theta_{1,2} = \varphi \pm \varphi'. \tag{7}$$

The symbols r_1, r_2 are given by: $r_1 = [-2(\pi+\theta)/3\pi]$, $r_2 = [2(\pi-\theta)/3\pi]$, where the symbol $[2(\pi \pm \theta)/3\pi]$, denotes the highest integer which is less than the symbol given in the bracket. The sum $\sum_{r=r_1}^{r_2}$ is zero when $r_1 > r_2$.

The field of the Dirac pulse is calculated from formula (2), if $f(t)$ is replaced by the distribution δ [4], [5], [7]:

$$\Phi_D(t-\tau) = \frac{2i}{\pi}\sum_{v=1}^{2}\Big\{\sum_{r=r_1}^{r_2}[(t-\tau)^2 - R_v^2]^{-1/2} + \int_0^\infty [(t-\tau)^2 - R_x^2]^{-1/2} G(x, \theta_v)\,dx\Big\}, \tag{8}$$

where $\Phi_D(t-\tau)$ is different from zero for $(t-\tau)^2 > R_v^2$ and $(t-\tau)^2 > R_x$. For the other values of $(t-\tau)$, $\Phi_D(t-\tau) = 0$.

4. Field of the pulse approximating the explosion

The field potential of the pulse $f(t)$ is calculated from formula (3). In view of the form of $\Phi_D(t-\tau)$, integral (3) can be given in the form of the sum

$$\Phi = \Phi_1 + \Phi_2, \tag{9}$$

where

$$\Phi_1 = \frac{2i}{\pi} \sum_{v=1}^{2} \sum_{r=r_1}^{r_2} \int_0^{\infty} f(\tau)[(t-\tau)^2 - R_v^2]^{-1/2} d\tau, \tag{10}$$

$$\Phi_2 = \frac{2i}{\pi} \sum_{v=1}^{2} \int_0^{\infty} G(x, \theta_v) \left\{ \int_0^{\infty} f(\tau)[(t-\tau)^2 - R_x^2]^{-1/2} d\tau \right\} dx. \tag{11}$$

It can be noted that the subintegral function in formula (10) and the internal integral in formula (11) have the same form. The integral Φ_1 has the solution

$$\Phi_1 = \Phi_{1a} = \frac{2i}{\pi} \sum_{v=1}^{2} \sum_{r=r_1}^{r_2} W_a, \quad 0 < t_{01} < \tau_1;$$

$$\Phi_1 = \Phi_{1b} = \frac{2i}{\pi} \sum_{v=1}^{2} \sum_{r=r_1}^{r_2} W_b, \quad \tau_1 < t_{01} < \tau_2; \tag{12}$$

$$\Phi_1 = 0 \quad \text{other } t_{01},$$

where $W_a = b_1 I_1$, $W_b = -b_2 I_1 + [b_2 \tau_2 + f(\tau_1)] I_2$, $t_{01} = t - R_v$,

$$I_1 = \int \frac{\tau}{\sqrt{(t-\tau)^2 - R_v^2}} d\tau, \quad I_2 = \int \frac{1}{\sqrt{(t-\tau)^2 - R_v^2}} d\tau.$$

The integrals I_1 and I_2 are simple inexchangable integrals. In these integrals, the integration limits are determined from the conditions $\tau < t - R_v$, $0 < \tau < \tau_1$ or $\tau < t - R_v$, $\tau_1 < \tau < \tau_2$ with R_v given by formula (6).

In order to calculate the expression Φ_2, the internal integral was first calculated in the same way as the integral Φ_1 was, whose solution is given by the symbol W_a, W_b (12), with the additional fact that the quantity t_{02} replaced t_{01}, and the quantity R_x ($t_{02} = t - R_x$) replaced R_v.

The solution of integral (11) can be given in the form

$$\Phi_2 = \Phi_{2a} = \frac{1}{3\pi} \sum_{v=1}^{2} \sum_{p=1}^{2} s_{vp} Z_a, \quad 0 < t_{02} < \tau_1;$$

$$\Phi_2 = \Phi_{2b} = \frac{1}{3\pi} \sum_{v=1}^{2} \sum_{p=1}^{2} s_{vp} Z_b, \quad \tau_1 < t_{02} < \tau_2; \tag{13}$$

$$\Phi_2 = 0 \quad \text{other } t_{02},$$

where $Z_a = b_1(tI_3 - tI_4 - I_5)$, $Z_b = [b_2(\tau_1 - t) + f(\tau_1)](I_3^* - I_4) + b_2 I_5$; for s_{vp} see formula (7). I_3, I_4, I_5 are the symbols of definite integrals (the integration limits are determined from the conditions imposed on t_{02}) in the form

$$I_3 = \int \frac{\ln|t + \sqrt{t^2 - R_x^2}|}{M(x)} dx, \quad I_4 = \int \frac{\ln R_x}{M(x)} dx, \quad I_5 = \int \frac{\sqrt{t^2 - R_x^2}}{M(x)} dx, \tag{14}$$

where $M(x) = \cosh(2/3x) - c_{vp}$ (for c_{vp} see formula (7)). The integrals I_3 and I_5 have the respective form of I_3 and I_5, except that t should be replaced by $t - \tau_1$ in formulae (14).

After some calculations, the integrals I_3, I_4 and I_5 are reduced to hyperelliptic ones, and these, in turn, cannot be expressed by elementary functions. Therefore, numerical integration remains.

The final solution has the form:

$$\begin{aligned} \Phi &= \Phi_{1a} + \Phi_{2a}, \quad 0 < t_{01}, t_{02} < \tau_1; \\ \Phi &= \Phi_{1b} + \Phi_{2b}, \quad \tau_1 < t_{01}, t_{02} < \tau_2; \\ \Phi &= 0 \quad \text{for other } t_{01}, t_{02}. \end{aligned} \tag{15}$$

5. Numerical calculations and conclusions

It is purposeful, from the practical point of view, to calculate the drop in the pressure level at the edge of the wedge for the different maximum values of the field potential $f(\tau_1^*)$ close to the source. Since the relative value of the drop in the sound level is of interest, the point A_1 was assumed to be in the acoustical shadow zone, while the reference point B was localised in the sonicated zone (Fig. 3).

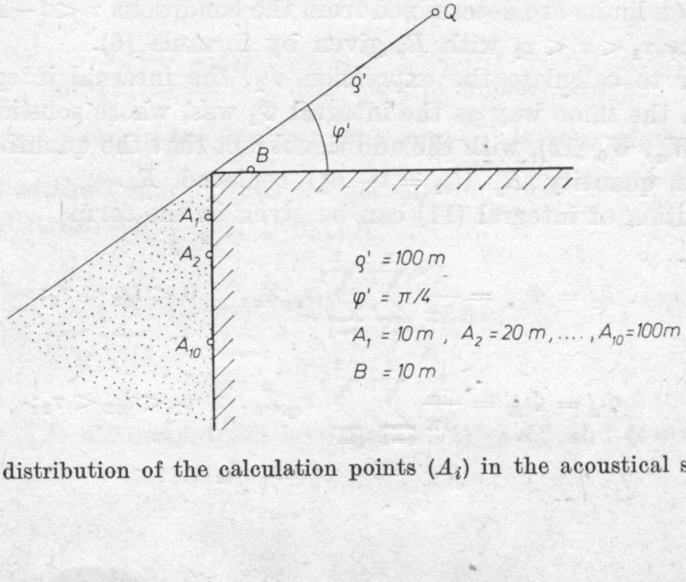

Fig. 3. The distribution of the calculation points (A_i) in the acoustical shadow zone

The pulse shape is determined by the values τ_1^* and τ_2^*; it was assumed that $\tau_1^* = 0.015$ [s] and $\tau_2^* = 0.06$ [s]. The maximum value of the field potential $f(\tau_1^*)$ at the point $Q(\varrho', \varphi')$ was assumed to vary between 1 and 10 m^2/s. The assumption of the different values of $f(\tau_1^*)$ close to the source, aims at the achievement, in the sonicated zone close to the edge, of such values of the acoustic pressure level which would correspond to a real explosion.

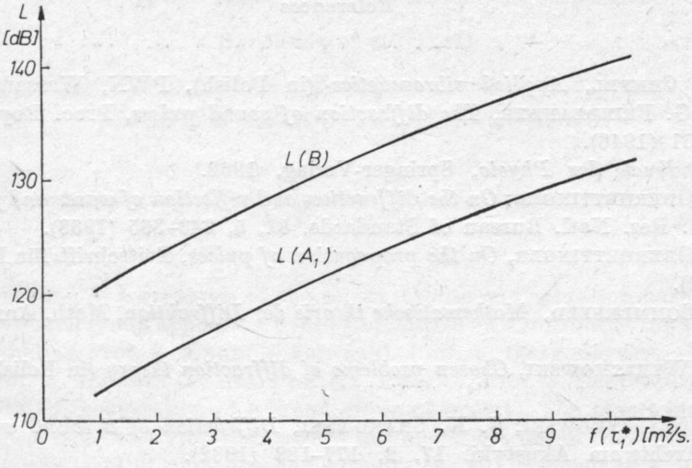

Fig. 4. The distribution of the acoustic pressure level before the edge of the corner in the sonicated zone (B) and behind it, in the silence zone (A_1), as a function of the peak value of the pulse

Fig. 4. shows the value of the acoustic pressure level $L(A_1)$ at the point A_1, and $L(B)$ at the point $B(L(A_1))$ is calculated from the formula $L(A_i) = 20 \log(p_i/p_0)$ [dB], where $p_0 = 2 \times 10^{-5}$ Pa. It follows from Fig. 4 that this drop is about 9 dB and is independent of the maximum value of the velocity potential $f(\tau_1^*)$ close to the source.

The drop in the pressure level along the wall of the wedge in the silence zone, was also calculated. With the view to the application of the results, the following calculation points were selected: $A_1 = 10$ m, $A_2 = 20$ m ... $A_{10} = 100$ m. The position of the point A_i less than 10 m from the edge of the corner has no practical justification, while at a distance of more than 100 m from the edge, it is tantamount to the design of a building that long. Buildings longer than 100 m are not often met and the assumption $A_{10} = 100$ m seems sufficient. In the calculations, the value of $f(\tau_1^*)$, varying between 1 to 10 m^2/s, was assumed.

It follows from the calculations that the drop in the pressure level $L(A_{10}) - L(A_1)$ along the wall of the wedge in the silence zone is independent, up to significant places, on $f(\tau_1^*)$ (over the investigated range of $f(\tau_1^*)$); it is about 10 dB and is approximately linear.

It follows from the whole of the calculations that the corner can be considered as an element protecting against noise. When the drop in the pressure level at the edge of the corner and that along its wall in the shadow zone are considered, its total is dozen-odd [dB], and this value is already of practical significance.

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NOISE AND VIBRATION HAZARD IN POLAND

(synthesis of a report)

ZBIGNIEW ENGEL, JERZY SADOWSKI

1. Introduction

This elaboration is a synthesis of the report "Noise and vibration hazard in Poland", prepared by a research group appointed by the Committee on Acoustics of the Polish Academy of Sciences, including Prof. Z. ENGEL (Chairman), Prof. L. GRZEGORCZYK, R. KUCHARSKI, M. Sc., Ass. Prof. A. LIPOWCZAN, Ass. Prof. Cz. PUZYNA, Prof. J. SADOWSKI, Ass. Prof. W. SUŁKOWSKI, with the cooperation of a broad group of experts. The report includes complex information on the noise and vibration hazard in Poland and on all the activities performed here to decrease the level of vibration and noise in the environment of man.

The purpose of the elaboration was to:

1. indicate to the state authorities, in particular the State Council for the Protection of the Environment and to the Board of the Protection of the Environment and Water Management, the state of the noise and vibration hazard;

2. analyse the present state and also the origin of the hazard;

3. evaluate the efficiency of activities in the scope of noise and vibration control;

4. analyse the needs occasioned by the state of the hazard;

5. evaluate the scientific, organizational and control structures engaged in the noise and vibration control:

6. propose conclusions and postulates, resulting from this report to the appropriate authorities.

2. Evaluation of the state of the hazard

2.1. Characteristic of the harmful effect of noise and vibration

Noise and vibration are forms of the pollution of the environment which are annoying, arduous and quite frequently harmful to man and other live organisms.

On the basis of the data given in the report, it can be stated that the noise and vibration hazard in Poland is so great that it is justified to define it as a general one, since it occurs throughout the country, in all the branches of the national economy, in the environment where man lives, works and rests, including also the natural habitat disturbed by the activities of man.

The noise and vibration hazard affects, to a varying degree, the population of Poland, up to about 40% of its inhabitants, both where they live, work and rest; in health service centres, sanatoria and resorts; in schools; in means of transportation; and also in urban and industrial areas.

Thus, noise and vibration are annoying factors with general social range, occurring in all the fields of the environment of man, affecting all citizens, having a harmful effect on their health, making it difficult for them to rest and regenerate, diminishing the effects of human work and increasing the probability of accidents at work.

2.2. Noise and vibration hazard to the population in urban areas and in housing and public objects

General and, at the same time, most annoying noise sources are the routes and objects of car, tramway, rail and aviation transportation, large industrial plants, small industries and communal objects. Transportation noise is the most annoying. In 1970–1982 the mean level of transportation noise in large Polish cities increased on average by 1 dB (A) per year. In urban areas transportation noise determines the quality of the acoustic climate of the environment. Up to 1983, about 250 acoustic maps of town had been made in Poland. It follows from them that the mean values (for the whole town) of the statistical noise levels L_{50} are as follows:

– in large cities – 61–72 dB(A) (67 dB(A) on average);

– in medium size towns – 57–68 dB(A) (63 dB(A) on average);

– in small towns – 52–69 dB(A) (61 dB(A) on average);

– in spas and holiday resorts – 48–66 dB(A) (58 dB(A) on average). Thus, apart from the spas and holiday resorts, for which L_{50} is 58 dB(A) on average, in the other three groups the level of 60 dB(A) is exceeded. This signifies that over much of urban area situated at transportation routes and streets, levels much higher than 60 dB(A) occur. This it true of 30–90% of the length of urban streets (depending on the characteristic and transportation system of the town).

Heavy vehicles contribute most to high noise levels. About 40% of these vehicles are characterized by noise exceeding 85 dB(A) and as much as 80% of them generate noise exceeding 80 dB(A). The annoying character of noise from road transportation means is also indicated by the number of motor vehicles used in Poland. The total number of about 4 mln vehicles includes about 650 000 lorries and 670 000 agricultural tractors, i.e. those vehicles whose level of external noise varies between 85–92 dB(A). The noise level of the other vehicles, mainly passenger cars, is 75–85 dB(A). These values are true of newly manufactured vehicles. With increasing age of the vehicle, the level of external noise generated by it increases by 2–4 dB(A). The external noise of vehicles does not exhaust the problem of the annoying character of the noise from means of transportation. There still remains the question of the internal noise in vehicles, whose negative effects are very harmful. Although it affects only the users of the vehicles, but taking into account the population using the means of transportation, only in urban transportation, every day the population of 17 mln, since so many persons use means of transportation every day, is exposed to bus internal noise.

In heavy vehicles, the internal noise reaches 90–92 dB(A). During normal drive in passenger cars, the mean noise level varies between 75 and 80 dB(A) and 80–85 88 dB(A) in heavy lorries and buses. These are levels to which the users of the vehicles are exposed continuously.

Noise inside the vehicle is accompanied by vibration, which, in particular in argicultural and ballast tractors, is of essential significance.

Noise from railways and airports was found to be very annoying, particularly when they are used close to housing estates (Warsaw, Poznań, Radom, Kracow, Kołobrzeg etc.).

The highly annoying character of transportation noise results from the fact that:

– there is a constant increase in the intensity of transportation;

– there is an increase in the number of vehicles and aircraft with high power and load capacity (lorries and buses). For over more than 20 years there has been no essential progress in decreasing the noisiness of cars, tramways and railways, without which it is impossible to decrease the annoying character of noise of this group to the level defined by standards.

Industrial plants, both large and small (situated as a rule among urban buildings), are highly annoying to the external environment, above all in view of the noisy technological processes, noisy machinery and bad localisation in the environment.

In buildings situated close to transportation routes, particulary those of rail vehicles, there also occurs, apart from noise, vibration, affecting not only people but also the construction of buildings, causing their damage, which requires more frequent repair, and can in some cases cause collapse. Vibration is particularly harmful to objects of historic interest.

Particularly annoying sources of noise and vibration in housing and public buildings are excessively noisy appliances and installations which are part of the equipment of the buildings (the installations of central heating, water supply, ventillation, lifts, in-built transformers). The noise levels generated by these sources, which penetrate into protected interiors, greatly exceed the permissible values. This is caused by the bad quality of these installations, lack of proper conservation and the low resistance of prefabricated ferro-concrete buildings (constituting about 70% of all the buildings erected recently in Poland) to noise and vibration transmission.

Among the most significant causes of noise hazard to the population in housing and public buildings, apart from the continuously deteriorating acoustic climate of the big-city environment, one should include; the insufficient use in practice of the possiblities of urbanistic and construction protection, the excessive noisiness of installations, the localisation of shops and services in housing buildings, the bad quality of construction, resulting from improper design and workmanship, but also from shortage of materials for noise-insulation of buildings.

It is estimated that about 30% of the population of large urban agglomerations is exposed to road noise. In smaller towns this percentage is about 20. Taking into account the additional exposure to transportation noise at housing estates localised close to inter-city trunk roads, it can be assumed that the total population exposed to traffic noise at levels of 40–55 dB(A) in the apartment is about 3.5 mln.

The installation noise hazard in housing buildings affects above all the inhabitants of multi-family apartment blocks built in the 1960's and later. This phenomenon has intensified recently and is related to the deteriorating quality of installations and the tendency of housing all the technical equipment inside the building, with no possibilities of proper insulation of these interiors, particularly in prefabricated buildings.

It should be pointed out, however, that despite the relatively low levels (30–45 dB(A) in average in the apartment), this type of noise us highly annoying, which is reflected in the very negative social evaluation of this phenomenon.

The exposure of inhabitants to installation noise increases in building with mechanical exhaust ventilation. In view of the very bad quality of equipment, lack of materials for duct insulation, improper conservation of already assembled installations; noise levels in apartments, particularly those on the upper two storeys, can reach 50 dB(A).

The exposure of apartments to neighbour noise has tended to increase, particularly over the last 5 years when in largepanel building the use of ceilings with floor finish as the only acoustic insulation has been favoured. This causes a large decrease in the acoustic insulation among apartments, particularly in prefabricated buildings, in which, as a result of bad workmanship, the joints are not tight enough. The percentage exposure to neighbour noise in prefabricated large-panel buildings erected in the 1960's and 1970's is much higher and, depending on the quality of execution and system, varies between a few and even 40%, in particular buildings; whereas in the recent period, after the elimination of floating floors, it has increased to 50–100%, with a simultaneous increase in noise penetrating from adjacent apartments.

The exposure of apartments to noise from services localised in housing buildings is infrequent, as a result of the tendency – correct from the acoustic point of view – to house these services in separate pavilions. In cases when they are situated inside housing blocks, the main sources of acoustic interference are appliances (e.g. compressors and refrigerators) causing noise at levels of 30–50 dB (A) to occur in apartments. Restaurants with recreational activity are also the source of large hazard to apartments.

The acoustic climate in health centres is distinctly bad. About 40% of objects in towns are localised in areas where the noise level exceeds 60 dB (A). Analogously to hounsig, the problems related to installation noise are also observed to increase, particularly in newly constructed hospitals. Another factor causing an additional deterioration of the internal acoustic climate is the increasingly often used medical equipment, mainly in the operation theatres and post-operational interiors. A gradual improvement in the situation can only be achieved by correct – from the acoustic point of view – localisation of new objects of health service and introduction of means of acoustic protection in typical construction designs.

Analysis of the acoustic conditions in institutions of education indicates the deciding role played by the internal noise in shaping the acoustic climate, related to life and the activities of the institutions themselves.

The children's and youth's activity and overcrowding, combined with the insufficient use of technical means of protection, lead to an excessive increase in the noise level, particularly in the corridors at breaks and lessons, during gym classes or in recreation rooms.

Above all creches and kindergartens are exposed to external noise. Although these institutions usually tend to be better localised, nevertheless in about 10–30% of the objects the external noise can interfere with children's rest and sleep.

The acoustic climate of most sanatoria, centres of preventive treatment and the convalescents' recreation grounds involves relatively favourable conditions for rest and cure. However, some objects are situated in areas hardly different in acoustic terms from city centres or big-city agglomerations.

2.3. Noise hazard in industry

Noise levels at a large number of work posts in industry exceed both the safe noise values (80 dB (A) and the values of 85 dB (A) and 90 dB (A)).

E.g. noise levels at work post in industry are: in heavy industry between 90 and 134 dB (A); in machinery industry between 92 and 125 dB (A), in light industry between 90 and 114 dB (A), in building and construction materials industry between 91 and 119 dB (A), in chemical industry between 90 and 120 dB (A).

There is the following state of hazard:

1) It is estimated that in the work environment about 3.5 mln employees are exposed to noise with levels exceeding 80 dB (A), including more than 600 000 employees working in noise of above 90 dB (A), 116 000 are exposed to noise exceeding 100 dB (A).

2) The number of employees exposed in Poland, to a different degree, to local vibration is estimated at 90 000 persons, and 822 000 persons are affected by general vibration.

3) Noise and vibration in the work environment, depending on the values of the level

and duration of the employees' exposure, are the causes of professional diseases — permanent hearing loss and vibration disease. The occupational deafness is the most frequent among the profesional diseases in Polish industry and occurs oftener than skin diseases and acute, permanent poisoning.

4) In 1975–1982 the percentage of occupational hearing loss per 100 000 employees increased from 12.3% in 1975 to 23% in 1982. The number of found cases of the occupational vibration disease increased from 424 in 1970 to 898 in 1981.

5) The highest number of found cases of occupational deafness in 1975–1982 occurred in the industries of: means of transportation (740), coal minimg (384), textile (357), machinery (305), iron metallurgy (176), metals metallurgy (169), construction (152), transportation and communications (117).

6) The most cases of the vibration diseases were in 1970–1982 found in the industries of: forestry (247), means of transportation (145), coal mining (113), machinery (96), construction (92) and metals industry (82).

Taking into account the recent results of world research on the harmful effect of noise and vibration, from which it follows that it is only at noise levels below 80 dB (A) that no cases of occupational deafness occur — it should be stated that even when the currently standing permissible value has been decreased from 90 dB (A) to 85 dB (A), still 10% of employees will be endangered by deafness.

3. Evaluation of the current situation in terms of prevention

3.1. General evaluation of the progress in research and utilization of its results

Over the last decade in Poland there has been a dynamic development of objects of industry transportation, housing and general construction. At the same time, the annoying character of towns has increased. These has occurred the necessity of limiting the annoying character of noise in construction and industry, causing also the need for scientific research on the protection of the environment of man from noise and vibration and for dissemination of the research in a large number of fields of the national management. Hence, the period 1970–1982 was characterized by the undertaking of large complex research programs with essential significance for the national management, aimed at considerable application of the research results in practice. It involved an intensive development of research and utilization cadres, whose scientific level greatly improved, and was related to the development of the alreadyexisting and the formation of new research centres, both at universities and in industrial departments. An important role in this development was played by the undertaking of large research programs also in the range of anti-noise and anti-vibration protection and expansion of collaboration with other countries.

The research up to 1983 in the range of the protection of the environment from noise and vibration covered in fact most problems related to this protection, while the development of research in this period was very dynamic, even when taking into account all kinds of difficulties in which this period abounded.

Due to progress in the research, necessary legal acts were formulated in the protection of the environment from noise and vibration, permitting the implementation of this protection in practice, although the activity in the field of standardization is not organized in a correct way.

Methods were developed for noise and vibration control in the work environment, in the home and in urbanized areas, including automation and computerisation of the measurements, which permitted the intensification of control activities, preliminary studies of the environment, and also the evaluation of the vibroacoustic quality means of transportation and communications, machinery, tools and installations, construction materials, products and elements in urban areas and interiors in buildings.

The progress in the research in 1970–1982 permitted:

– the decrease in the noisiness of some machinery and devices e.g. moulding machines, vibratory screens, energy media discharge stations, some construction machines, tools, devices and installations in buildings e.g. central heating centres, transformer stations, mechanical ventilation;

– the starting of the production of anti-noise units and devices sound-absorbing structures and absorbers, sound-absorbing and insulating barriers, soundproof cabines etc.;

– the improvement of the acoustic quality of blocks of flats built by industrial methods;

– the introduction, in newly designed housing estates, of a number of planner designs, to limit the penetration of traffic noise into the estates;

– the elaboration and introduction in practice of methods for the determination of anti-noise protection zones round the industrial plants;

– the consideration of acoustic planning solutions in designing some transportation routes.

Despite the undoubted progress made in 1970–1982, the progress in means of noise and vibration control, necessary for effective protection of the environment from noise and vibration, has not been made to a sufficient degree, which still prevents efficient noise and vibration control in the environment. There has been no progress in the research and utilization related to decreasing the noisiness of motor and rail vehicles. The decrease in the levels of transportation noise in buildings is achieved by planning and construction means, which is neither correct nor justified economically.

Because of the investment restrictions in 1976–1982, the research base in Poland dis not develop to a necessary degree. The lag between the research base of the Polish research centres leading in the field of acoustics and that of the Western countries has continuously widened to the disadvantage of Poland, both in view of lack of laboratory space, research posts, lack of modern equipment and the rapid outdating of the existing one, which is also caused by the lack of the possibility of buying spare parts. Unless this state changes over the next few years, it will not be possible at all to undertake some studies, requiring special research posts and modern equipment.

There has been no sufficient progress in the development of the industry of measurement devices for the research on noise and vibration, which prevents the possibilities of correctly organized monitoring of the environment from the point of view of noise and vibration.

There has been hardly any research on the degree of noise hazard in administration buildings and special communal objects.

Analysis of data acquired from the research carried out by institutions of scientific research and the control examinations performed by sanitary-epidemiological stations indicates that the population is exposed to noise in housing and public buildings.

The considerable progress in the research on the evaluation of transportation noise and the elaboration, for a large number of towns and cities, of acoustic maps provide the basis for estimating the degree of transportation noise hazard to the population in housing and public buildings. However, the complexity of the phenomena and the variety of planning situations bring about the necessity of further intensive studies, in order to grasp the causal relationships and specify the procedures.

There has been a distinctly insufficient progress in the research on the exposure of housing and public buildings to external noise, generated by industry and communal objects.

Research in the field of the anti-noise protection of housing and public buildings currently performed in Poland does not cover new future material and construction solutions, such as e.g. skeleton systems. A barrier preventing the undertaking of research of this type is above all the lack of an appropriate research base. In this field, the Polish lag is estimated at about 10–15 years with respect to the level in the West European countries.

The state of Polish studies on the acoustic climate in the interiors of public buildings is insufficient. This applies both to research on the degree of noise hazard to the interiors and to studies in the field of technical design of these objects. There is no full understanding whether the incorrect acoustic conditions in most public buildings (mainly hospitals and schools) are the results of bad design or the poor quality of the installations and faulty workmanship.

3.2. Detailed evaluation of the state in the field of standardization

From the division and juxtaposition of the current standards presented in the report, it may appear that they represent correctly and many-sidedly the vibroacustic problems. However, analysis indicates that this is only apparent. The Polish standards mentioned in the report were constructed in 1961–1983, of which more than half were formulated in 1973–1975. They are greatly outdated. Most of them are attest standards; they apply to the state of technical solutions and constructions which are the objects of the standards, based, however, on the technological level current when they were formulated. The maintaining of standards and regulations for a long time (6–8 years on average) prevents no doubt technological progress, since it does not enforce the need for modernisation and updating of given industrial goods. When consideration is given to the general world developments in technology, where the question of occupational hazards and working confort have become the element of economic competition, more often than not a deciding factor in large exports contracts, it becomes clear that a correct standardisation policy should be the main stimulus for technological progress rather than a barrier.

In the light of the previous experiences, it seems justified that a different form of standardisation should be proposed. Assuming at the first stage that preliminary projects will still be formulated in the departmental centres, it is proposed that a specific opinion-making group should be set up, consisting of experts named. The lists of experts authorized to evaluate draft standards in particular fields should periodically be estabilished by the Committee on Acoustics of the Polish Aacdemy of Sciences as the most competent and well-versed expert institution.

The final establishment of a given standard should take place among experts, who, apart from specific written remarks at the preliminary stage, establish by expert discussion the final form of the standard. In the further succession, it would be necessary to establish units, mainly research ones, authorized to formulate standards, which would undertake their elaboration.

The more active exports, as predicted within the economic reform, will require increasingly that most of exported industrial goods should undergo attest measurements. The necessity of collaboration among the national and foreign centres indicates the urgent need for regulating the contribution and activity of Poland also on the international standardisation forum.

3.3. The state in the field of standardisation on the antinoise protection in building and planning

The state of standardisation in the field of the protection of housing and public buildings from noise, although not totally satisfactory, achieves in many points at least the average world level. This is true particularly of the requirements in the range of permissible noise levels inside interiors, and also, to some extent, of the required acoustical parameters of partitions in public buildings. Requirements on the acoustic parameters of inter-apartment partitions are on a level occurring in all the socialist countries, but lower with respect to that demanded in West European countries. It is necessary to undertake research on the final coordination of all standards and regulations in the field of anti-noise protection of housing and public buildings, with particular consideration given to the following problems:

— the limitation of the acoustic power of equipment installed at housing and public buildings;

— the specification and uniformization of the permissible levels of installation noise;

— the increased requirements on partitions in housing construction by regarding the previous requirements as the standards, but introducing higher demands as objective;

— the introduction of the principles of acoustic classification of areas destined for housing and public construction, taking into account the basic sources of external noise and the possibility of acoustic — construction protection of the objects.

4. Evaluation of the existing organizational structures

4.1. Significance of organizational structures

The shaping of the correct acoustic climate of the environment of man and the implementation of the effective protection of man from noise and vibration requires the coordination of activities in all the fields of the national management. All the undertakings in planning, communications and transportation industry and construction, and also in other fields of life, should take into account, to an appropriate degree, the needs for the protection of the environment of man from noise and vibration. In particular, it is necessary that the following activities should be performed:

— the permanent research on the state of the acoustic environment and the evaluation of the sources of noise and vibration from the point of view of the shaping of the correct acoustic climate in the environment;

— the formulation of legal acts permitting the correct shaping of the acoustic climate in the environment;

— the development, creation and application of technology, means of transportation and communications, appliances, machinery, tools and installations, not generating excessive noise and vibration;

— the elaboration and utilization of technical solutions in communications, transportation, industry, planning and construction, permitting the correct protection of man from noise;

— the continuous control of the acoustic parameters of the sources of noise and vibration and the environment, and continuous activities towards the improvement of the acoustic state of the environment;

— the continuous didactic and educational activities.

The organizational structures are of very essential significance in implementing the above objectives. Correct organizational structure facilitate these activities; incorrect ones succesfully hamper them.

4.2. Central structures

Central structures are of deciding significance for the efficient protection of the environment.

At present, there are in Poland:

– the State Council for the Protection of the Environment (an advisory organ of the Prime Minister);

– the Board of the Protection of the Environment and Water Management;

– the Ministry of Health and Social Security;

– the Ministry of Work, Pay and Social Matters;

– the Polish Committee for Standardisation and Measures;

– the Ministry of Science and Higher Education;

– the Polish Academy of Sciences;

– the State Inspection of Work.

These are the most important central organs deciding on the protection of the environment (also from noise and vibration). From the point of view of the protection of the environment from noise and vibration, the number of the central structures is sufficient. However, their activity will be fully sufficient when, in the matters of the protection of the environment, the Board of the Protection of the Enviroment and Water Management has effective influence on the other departments, above all the industrial and economic ones and those of communication and construction. It is essential to create appropriate relations among the Board of the Protection of the Environment and the particular Ministries and Central Offices, permitting the correct functioning of the mechanisms of the protection of the environment from noise and vibration and the successful control of the implementation in this range.

4.3. Control activity

The control activity related to noise and vibration is carried out by:

– the department of the protection of the environment at the Board of the Protection of the Environment and Water Management (and partly in the Ministry of Administration and Town Planning).

– the sanitary department in the Ministry of Health and Social Security,

– the department of the protection of the environment in economic and industrial ministries, occupational security and hygiene services and the State Work Inspection. There is no unified coordination of the activities of control services belonging to three departments and no distinct division of competence. As a result of which, some of the control activities are sometimes carried by two institutions, others are not performed at all.

There is excessive partition of control sections, experts and equipment, to the disadvantage of the efficiency and quality of work. An example of this can be quantitative control without going deeper into the causes and effects, and the possibilities of decreasing excessive noise and vibration.

The services of the particular departments apply the different methods of evaluating noise and vibration, often reaching divergent conclusions.

All this suggests the necessity of unified coordination of the control activity, the introduction of unified control methods, the establishment of the range of activity and competence for the particular departments of control services. However, it would be best to organize these services in such a way so that they would be subordinated to one central organ.

4.4. Research, design and other centres

There is a sufficient number of research institute and centres for the performance of studies in the range of the protection of the environment from noise and vibration. However, the possibilities of performing research by the existing institutes are limited by the insufficient research base, whose projected extension in 1970–1980 was unfortunately effectively stopped. Therefore, the basic condition for the implementation of correct research is the establishment of opportunities of the development and updating of the research base and the complementation of the research equipment both in the leading ministerial and high-education institutes.

In design vehicles, ships, machinery, applicances, tools and installations, and also in designing industrial technologies, no account at all, or insufficient, is taken of the acoustic requirements related to the emission of noise and vibration by these pieces of equipment.

This results from the lack of appropriate standards, regulations, control and also from the lack of experts in the design offices. The solution of the problems of the protection from noise and vibration in designing transportation routes, industrial plants, housing estates and other areas and objects, which should be protected from noise and vibration, is similarly neglected.

This also results from the lack of appropriate regulations and control in the process of design and implementation, and the damage to the environment caused by this is often irreversible. Thus, the process of designing and constructing the objects mentioned above nedds improvement.

Acousticians' proposals related to the need for the formation of an industry of means of noise and vibration control have not been implemented so far. The sporadically produced anti-noise materials and systems are made on a scale far from necessary, with more than modest variety of the means produced. If noise control is to be really implemented, it will be necessary to develop in Poland a network of enterprises producing the means of protection from noise and vibration.

In Poland there is a sufficient number of scientific, technical and social organizations engaged in the protection of the environment from noise and vibration, both in the field of scientific research and in the range of technical, educational and popularizing activities. An essential problem is here the directing of the activities of the existing organizations and structures.

1) It is postulated that the State Council for the Protection of the Environment, by evaluating the state of exposure of the environment to noise and vibration, should, through the Council of Ministers, bring the central ministries to take decisions related to:

a) the coordination of scientific research on the protection of the environment of man from noise and vibration, carried out by services at a large number of national ministries, in order to direct them correctly;

b) the granting to the Board of the Protection of the Environment and Water Management of all the decision-making, coordination and control powers to permit effective complex control of the protection of the environment. This Board should bear full responsibility for all decisions related to the protection of the environment of man, including also that from noise and vibration;

c) the creation of appropriate relations among the Board of the Protection of the Environment and Water Management and other ministries;

d) the improvement, or organization in particular ministries, of services carrying out tasks in the field of noise and vibration control.

2) It is indispensible to begin the implementation of the act on the protection and shaping of the environment, and also to include the vibroacoustic problems in this act. It is also necessary to update the Regulation of the Council of Ministers from 30 September, 1980, on the protection from noise and vibration.

3) It is indispensible to elaborate new important standards and to revise and update the existing ones. It is necessary to elaborate the design norms taking into account the vibroacoustic problems, and also to elaborate and pass the appropriate regulations of technical nature, e.g. the regulation recognizing the parameter of "quiet run" as equally important as the other parameters applied in evaluating machinery and appliances.

4) It is indispensible to unify and coordinate the control activity, which is now carried out independently by several ministries and institutions.

5) The achievement of real progress in the range of the protection of the environment from noise and vibration is indispensibly conditioned by limiting the emission of noise and vibration by means of transportation, machinery, appliances, installations and tools. It is postulated that decisions should be made on the projected decrease in their noisiness over two time intervals, by the following values:

Sources	Postulated noise level decrease in dB (*A*)	
	up to 1995	up to 1990
lorries, buses, tractors road and construction vehicles,	10–15	7
passenger cars	10	5
rail vehicles, locomotives, trains, tramways	10–15	7
airplanes, helicopters	10–20	10
technology, machinery, appliances and tools in industry	10–33	10–15

The above values should also be observed in the import of these pieces of equipment.

6) It is postulated that the maximum permissible level should be established for the installations in housing, as follows:

- water pumps 55 dB (*A*),
- dry transformers 55 dB (*A*),
- lifts 63 dB (*A*),
- sanitary appliances 45 dB (*A*),
- ventilators 50 dB (*A*).

The above values should, at the same time, be observed in the possible import of these pieces of equipment.

7) It is postulated that appropriate means of the protection from noise should be introduced in town planning by:

– the use of appropriate methods for evaluating the acoustic climate in towns and housing estates;

– the observation of the principles of the protection from noise in the process of accepting for general use of building materials, elements and constructions;

– the control of the observation of acts and regulations;

– the appropriate design of transportation route;

– the creation of protective zones;

– the elimination of particularly annoying objects from the areas of towns and housing estates.

8) It is postulated that appropriate structural changes should be introduced and means of vibroacoustic protection should be created in means of transportation.

9) In view of the fact that the production of equipment for the study and control of vibroacoustic phenomena is insufficient, appropriate steps should be taken to ensure the elaboration and production of the basic equipment. A similar situation occurs in the range of sound-insulating and vibration-insulating materials and systems.

10) In view of the fact that the state of education of cadres engaged in the problems

of vibroacoustic protection is insufficient, aprropriate steps should be taken to ensure:

– the development of post-graduate studies,

– the organization of specialist courses,

– the further organization of scientific-technological seminars and conferences,

– the performance of educational and popularizing activities by scientific, technical and social organizations.

11) In the scientific research, it is necessary:

a) to coordinate all scientific research on the protection of the environment from noise and vibration,

b) to coordinate and intensify the activities in the framework of international cooperation, mainly within the Council for Mutual Economic Aid,

c) to take steps to modernize and develop the research base and provide the leading scientific centres with sophisticated research equipment,

d) to create conditions permitting an improvement of the present state of utilization of the research results.

INTERNATIONAL COMMISSION ON ACOUSTICS ICA/INFORMATION AND COORDINATION SERVICE

Plzenska 66, 151 24 Prague 5

Acoustical Events
1987–1989

1987

February 1987 in Rostock — German Democratic Republic

III. Conference on Hydro-and Geophysical Acoustics

Details from: Prof. Dr. Schommartz
Wilhelm Pieck Universität Rostock
Sektion Technische Elektronik
Albert-Einstein-Str. 2
DDR-2500 Rostock 1

May 11-15, 1987, Indianapolis, Indiana — USA

Meeting of the Acoustical Society of America

Details from: Mrs. Betty Goodfriend, Secretary
Acoustical Society of America
335 East 45 Street
New York, N. Y. 10017

May 19-21, 1987, Gdańsk University — Poland

International Conference on "How to teach acoustics"

—presentation, discussion and exchange of experience in teaching — programs, methods in various specializations and in different relations to educational disciplins of various schools —

Details from: Prof. Dr. A. Śliwiński
University of Gdańsk,
Institute of Experimental Physics
80-952 Gdańsk, Wita Stwosza 57

June 1-4, 1987, Portorož Slovenia — Yougoslavia

XXX Etan Conference
— all branches of acoustics —
Details from: Prof. P. Pravica
Electrotechnical Faculty
Bulevar revolucije 73
Yu-11000 Belgrade

June 23-25 1987, Lisabon — PORTUGAL/SPAIN

5th FASE Congress
— Advances in the domain of Physical Acoustics,
— Oceanographic Acoustics, Use of Acoustics in Bio-engineering, Harmonization of legislation on the protection of hearing —
The Congress will be preceded by a specialized scientific conference on "Acoustics and Ocean Bottom" on June 19, 1987, in Madrid
Secretariat: SPA — FASE 87
Lab. Nac. Engenharia Civil
Av. Brasil
1799 Lisboa Codex
of the conference:
SEA — FASE 87
Calle Serrano 144
Madrid 6

beginning of October 1987, High Tatra — Czechoslovakia

26th Acoustical Conference on "Noise and Environment"
Details from: House of Technology
Ing. Goralikova
Škultétyho ul. 1
832 27 Bratislava

middle of October, 1987, Varna — Bulgaria

"Acoustique' 87"
— l'acoustique architecturale et de la construction, l'électro-acoustique, le bruit et les vibrations, l'acoustique de la parole et physique —
Details from: Unions Scientifiques et
Techniques de Bulgarie
Ing. I. Ivantchv, Secrétaire
Ul. Rakovski 108, BP 431
1000 Sofia

November 16-20 1987, Miami, Florida — USA

Meeting of the Acoustical Society of America
Details from: Mrs. Betty Goodfriend
Acoustical Society of America
335 East 45 Street
New York, N. Y. 10017

1988

May 16-20, 1988, Seattle, Washington — USA

Meeting of the Acoustical Society of America
Details from: Mrs. Betty Goodfriend

Acoustical Society of America
335 East 45 Street
New York, N. Y. 10017

August 29 – September 1, 1988, Edinburgh U. K.
7th FASE SYMPOSIUM on "Speech"
Details from: Mrs. Cathy Mackenzie
Institute of Acoustics
25 Chambers Street
Edinburgh EH1 1HU

beginning of October 1988, High Tarta Czechoslovakia
27th Acoustical Conference on Electroacoustics
Details to be announced

November 14-18, 1988, Honolulu, Hawai USA
2nd Joint Meeting of the Acoustical Society of America and The Acoustical Society of Japan
Details to be announced

1989

May 22-26, 1989, Syracuse, New York USA
Meeting of the Acoustical Society of America
Details from: Mrs. Betty H. Goodfriend
Acoustical Society of America
335 East 45 Street
New York, N. Y. 10017

April 1989, Rostock German Democratic Rep.
VI Symposium on Maritime Electronics
Details to be announced

middle August 1989 preliminary date, Belgrade Yougoslavia
13th ICA-CONGRESS (Congress of the International Commission on Acoustics)
2 Symposia are foreseen in Zagreb and Dubrovnik
Details to be announced

October (beginning) 1989, High Tatra Czechoslovakia
28th Acoustical Conference on "Physiological Acoustics, Acoustics of Speech and Music"
Details to be annouced

November 6-10, 1989, St. Louis, Missouri USA
Meeting of the Acoustical Society of America
Details from: Mrs. Betty H. Goodfriend
Acoustical Society of America
335 East 45 Street
New York, N. Y. 10017