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A BÉKÉSY AUDIOMETER WITH ELECTRONIC SIGNAL LEVEL CONTROL AND ITS APPLICATION TO PSYCHOACOUSTICAL MEASUREMENTS

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Improvements introduced in the new version of a Békésy automatic audiometer with electronic control of signal level are described, with some details of the separate circuits used.

Examples of the uses of the new audiometer in threshold audiometry and some other applications are discussed.

1. Introduction

Some years ago the concept of the realization of the Békésy audiometer with electronic control of the signal level was published [15]; the possibility of the realization of this concept using conventional generally available laboratory equipment being pointed out. The new audiometer thus developed was patented in Poland [16]. The simpler version of this concept was later given by Mohl [14]. The common feature of Békésy type audiometers is the possibility of the continuous tracking and recording of the threshold level, as a function of time (at a constant frequency) or as a function of frequency, which automatically changes with time at a predetermined constant rate. The subject's task is to keep the signal level near the threshold by operating a switch which, depending on the position, causes the continuous growth or decrease of the signal level.

With regard to typical commercially available automatic Békésy audiometers, and some unique laboratory-developed systems of that kind [4, 13], one of the basic advantages of the new audiometer is the elimination of electromechanical step attenuators. The signal level is controlled continuously, using electronic volume control circuits, rather than step by step as in previous constructions in which potentiometers or attenuators and servomotors were commonly used.

The new Békésy audiometer with electronic level control, which has been used and progressively improved for over 6 years in our laboratory is basically constructed with typical Brüel and Kjaer laboratory equipment.

The latest version of the audiometer is characterized by the following specification:

1. Frequency range (without threshold equalizer) 20 Hz-20 kHz.
2. Frequency range with threshold equalizer 40 Hz-12 kHz.
3. Time of frequency scanning over the range 20 Hz-20 kHz, 10 s — over 100 hrs.
4. Dynamic range of the record 10, 25, 50, 75 dB (depending on the recording potentiometer used).
5. Paper speed 0.003-100 mm/s.
6. Writing speed 2-1000 mm/s.
7. Signal level control rate 3, 10, 30, ..., 100 dB/s.

In the present report some representative results of measurements carried out using the improved version of the audiometer are given to illustrate its possible applications in the fields of psychoacoustics and clinical audiometry. The new units which have been constructed and introduced since the first version of the new audiometer was publis hed [15] aredescribed in some detail.

2. Threshold equalizer

As a rule isophonic threshold equalization is introduced in clinical audiometers now in use. In such audiometers, or specifically on the audiograms, the normal hearing in the 18 to 25 years age group is represented as a straight horizontal line. Deviation of the record below this line corresponds to hearing loss and, vice versa, deviation of the record above the normal hearing line corresponds to hearing better than the average.

In order to make the operation of the new audiometer as close to the requirements developed and well accepted over the years of clinical practice as possible, threshold equalization was introduced in the present version. This results in a simplified interpretation of the records obtained compared to those from the former version, as well as in some improvement in accuracy.

The frequency response of the threshold equalizer was assumed to be equivalent to the ZWICKER and FELDTKELLER data [17] with an accuracy of approximation ± 1 dB. Active elements were used in the network to simplify the computation and to avoid attenuation which is usually significant in passive networks. Active elements are also more easily available and much smaller, particularly in the low frequency range where inductances for the passive LCR networks reach from 5 to 10 H.

The preliminary modelling of the equalizer networks was performed using a digital computer*. The final adjustments of the frequency response were

* Computer programme in ALGOL-Archives, Lab. of Musical Acoustics.

done on the completed network using an analogue tracer and a step by step error elimination technique.

The assumed frequency response of the equalizer was obtained using three almost independent networks. Their outputs are added in the output amplifier supplying power to a 600 ohm load (6 V at 40 Hz). This load is the input im-

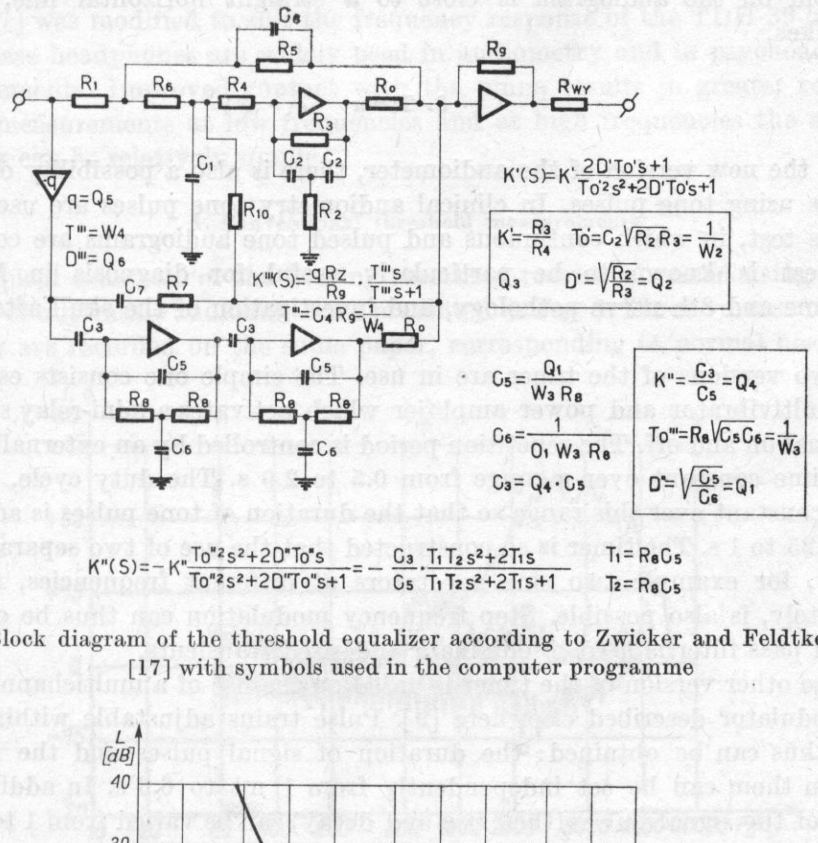

Fig. 1. Block diagram of the threshold equalizer according to Zwicker and Feldtkeller data [17] with symbols used in the computer programme

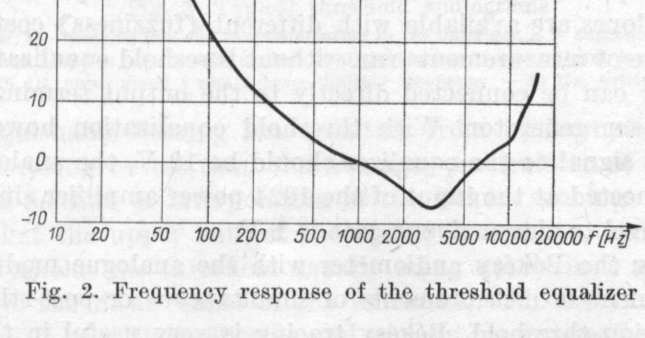

Fig. 2. Frequency response of the threshold equalizer

pedance of the modified version of the Beyer-DT-48 headphones equalizer described by ZWICKER and FELDTKELLER [17].

The low and high frequency networks consist essentially of operational amplifiers with «shunted T» filters in the feedback loops. The mid-frequency network, apart from passive elements contains an RC differential network and inverter to shape up the «drop» between the frequencies 2 and 5 kHz, Fig. 2.

With the two equalizers involved, the record of a normal hearing threshold on the audiogram is close to a straight horizontal line, halving the spikes.

3. Timer

In the new version of the audiometer, there is also a possibility of measurements using tone pulses. In clinical audiometry tone pulses are used in the Jerger's test, in which continuous and pulsed tone audiograms are compared. This test is known to be particularly useful for diagnosis in Menière's syndrome and 8th nerve pathology, and investigation of the skull after injury cases.

Two versions of the timer are in use. The simple one consists essentially of a multivibrator and power amplifier which activates a mini-relay switching the signal on and off. The repetition period is controlled by an externally adjustable time constant over a range from 0.5 to 2.0 s. The duty cycle, equal to 0.5, is constant over this range so that the duration of tone pulses is adjustable from 0.25 to 1 s. The timer is so constructed that the use of two separate signal sources, for example two sine generators at different frequencies, switched alternately, is also possible. Step frequency modulation can thus be obtained. A band pass filter is used to eliminate undesired transients.

The other version of the timer is based on the use of a multichannel analogue modulator described elsewhere [9]. Pulse trains adjustable within a wide range thus can be obtained: the duration of signal pulses and the intervals between them can be set independently from 1 ms to 6.6 s. In addition, the flanks of the signal pulses (their rise and decay) can be varied from 1 to 500 ms using linear slope analogue modules, or Gaussian envelope analogue modules. Gaussian envelopes are available with different «fuzziness» coefficients.

In the case of measurements run without threshold equalization, the analogue modulator can be connected directly to the output terminals of the 1024 Brüel and Kjaer generator. With threshold equalization however, in which case the input signal to the equalizer should be 12 V, the analogue modulator should be connected at the input of the 1024 power amplifier since the nominal input signal level to the analogue gate is 1 V.

Combining the Békésy audiometer with the analogue modulator is particularly convenient in measurements of simultaneous or post-stimulatory masking or pulsation threshold. Békésy tracing is very useful in these cases and results in a simplification of procedure and a significant decrease in the duration of the experiments [7].

4. Headphone equalizer

For some purely technical reasons the Telephonics TDH-39 headphones with MX 41 AR cushions were used in the present version of the audiometer, replacing the headphones used formerly, Beyer DT-48. Thus the previous headphone equalizer constructed according to ZWICKER and FELDTKELLER data [17] was modified to suit the frequency response of the TDH-39 headphones. These headphones are widely used in audiometry and in psychoacoustical measurements. Improved contact with the pinna results in greater reliability of the measurements at low frequencies and at high frequencies the equalizer network can be relatively simple.

5. Conventional threshold measurements

Typical examples of the hearing threshold records obtained using the new version of automatic audiometer are presented in Fig. 3. Three various threshold tracings are recorded on the same paper, corresponding to normal hearing (a),

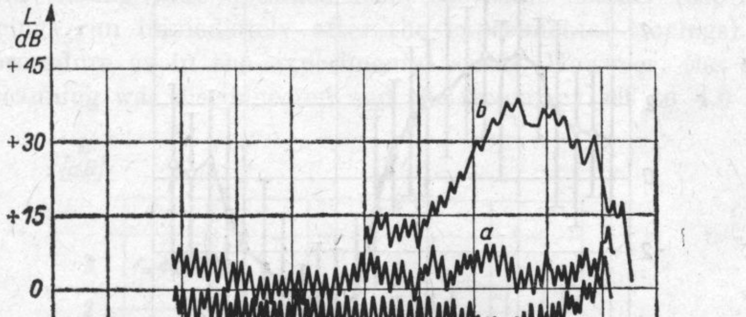

Fig. 3. Typical threshold audiograms

a – normal hearing, *b* – hearing loss due to inflammation in the inner ear, *c* – supranormal hearing between 2 and 3 kHz; tracings *a* and *c*: rate of level control 10 dB/s, tracing *b*: rate of level control 3 dB/s; recording potentiometer – 75 dB, paper speed 1 mm/s, lower limiting frequency – 50 Hz, writing speed – 100 mm/s

clearly distinguishable hearing loss resulting from inflammation in the inner ear (b), and hearing better than the average, particularly at mid-frequencies (c). The usual method of interpolation of the Békésy tracings is based on the assumption that the upper half of the spikes lies above, and the lower half below the threshold, the threshold usually being determined as a line halving the spikes (i.e. the mean value of the extremes). This assumption, however, does not seem to be fully acceptable and such an interpretation of Békésy tracings should be regarded as only approximate, particularly at higher rates of the signal level control.

It has to be pointed out that in the audiometer described, hearing loss or supranormal hearing are represented in the record or tracing by a deviation of the recording in a direction opposite to that in typical, clinical commercially available audiometers. To reverse the direction of the recording would require substantial redesigning of the 2305 level recorder, which in the average laboratory is hardly possible and, in view of the other applications of the equipment, of questionable value.

6. Special threshold measurements

One of the valuable features of the Békésy audiometer with electronic signal level control set up using Brüel and Kjaer equipment (or comparable) is the case of conversion of the dynamic scale of the recording. For the system described here, this conversion can be achieved by changing of the recording

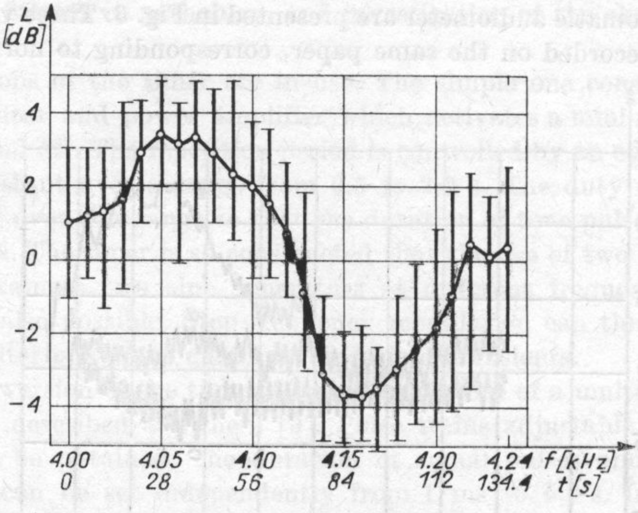

Fig. 4. Threshold audiogram determined from 25 experimental tracings for the same subject (Investigation of diplacusis binauralis [3])

Median values and interquartiles for 25 threshold tracings taken at equal frequency increments, rate of level control – 3 dB/s, recording potentiometer – 10 dB, paper speed – 1 mm/s, lower limiting frequency – 200 Hz, writing speed – 100 mm/s

potentiometer in the 2305 level recorder. The full dynamic scale of the record may thus be chosen to equal 10, 25, 50 or 75 dB.

In normal practice a 75-dB scale is commonly used which allows the tracing both of quite considerable hearing loss and of normal hearing, with sufficient accuracy.

Recording scales narrower than 75 dB, particularly 10 dB and 25 dB, have proved to be very useful for more accurate investigation of the threshold curves over a limited frequency range and/or at constant frequency. Limitation of the frequency range to the range of particular interest, results from the obvious fact that for accurate tracing of the threshold curve, the rate of automatic frequency scanning must be sufficiently low. At such low rates of frequency scanning the tracing of the whole auditory range would be greatly prolonged and could result in tracing errors due to fatigue.

Tracing of the threshold curves with increased accuracy can be applied to the investigation of, for example, diplacusis binauralis (an anomalous threshold affecting the perception of pitch). An illustrative example of the usefulness of such tracings is the audiogram presented in Fig. 4, obtained with 10 dB recording potentiometer in the 4.0 to 4.25 kHz frequency range. This audiogram resulted from 25 separate audiometric tracings obtained from one listener (right ear). Circles in the diagram represent median value and vertical lines the interquartiles. Median values were taken at equal time and frequency increments.

To determine the significance of the threshold level variations observed in the experiment, particularly in view of the considerable dispersion of the results, control measurements were also performed. In the control series, the threshold tracing were obtained from the same listener (the same ear, control tracings run immediately after the experimental tracings) following the same procedure as in the experimental series. However, the automatic frequency scanning was disconnected and the frequency set to 4.0 kHz. The

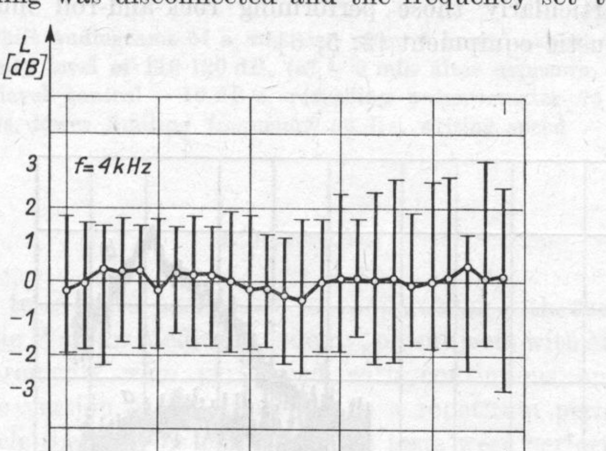

Fig. 5. Threshold audiogram determined from 25 control tracings as in Fig. 4. (Investigation of diplacusis binauralis [3]). Setting of audiometer controls as in Fig. 4

duration of each of the 25 control tracings was the same as in the exper mental tracings and amounted to 140 s. The results obtained from the control runs are presented in Fig. 5.

The results presented in Figs. 4 and 5 demonstrate well the degree of accuracy which can be achieved by using the system described and by averaging the results. The curve in Fig. 4, representing a fraction of the hearing threshold, shows distinct hearing loss near 4.05 kHz and some supranormal hearing in the region of 4.15 kHz. The measurements of the other (left) ear in the same listener resulted in a flat threshold curve to within ±1 dB.

In the threshold curves presented in Figs. 4 and 5 a small discrepancy between the threshold levels at 4 kHz is observed. It seems probable that this discrepancy may have resulted from the procedure applied in the experiment, namely from running the whole of the experimental measurements and then the whole of the control measurements rather than alternating them. Some small change of the threshold criterion in the subject could have introduced the observed constant error of about 1 dB.

7. Temporary threshold shift measurements

In industrial audiometric tests, concerning the hazards of hearing loss in employees exposed to high intensity sounds, it often appears necessary to determine the amount of temporary threshold shift (TTS) as quickly as possible. Such data are used for the determination of the risks of hearing loss and eventually for the determination of permissible daily exposures, or a reduction of dangerous exposures [11, 12]. Similar hazards of hearing loss are observed also in musicians, particularly those performing rock-and-roll music using high power electroacoustic equipment [2, 5, 6].

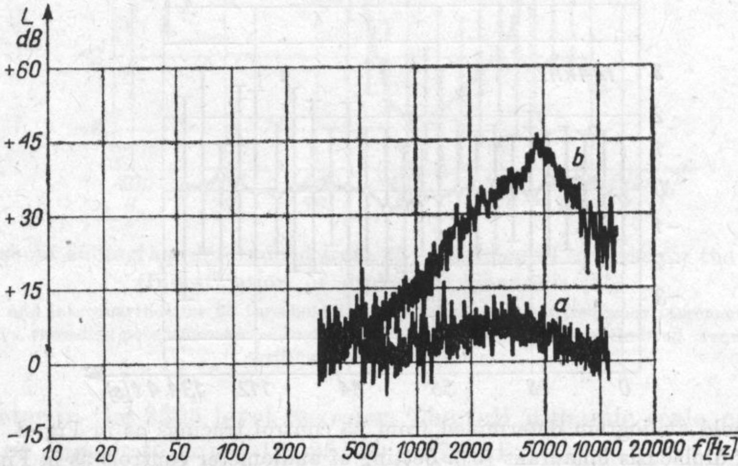

Fig. 6. Threshold audiograms before (a), and 9 min after exposure (b) to shock sound at 130 dB SPL; rate of level control – 10 dB/s, recording potentiometer – 75 dB, paper speed –0.3 mm/s, lower limiting frequency – 200 Hz, writing speed – 250 mm/s

Examples of the TTS tracings obtained in various conditions are presented in Figs. 6 and 7. In Fig. 6 the threshold audiograms before and after exposure to shock sound at about 130 dB SPL and characterized by almost uniform spectrum density over the auditory range is given. The threshold audiograms in Fig. 7 were obtained from the musician after 4 hours' performance in the «Hybrydy» students' club dance hall, where the high power electroacoustic system gave a peak intensity of 110 to 120 dB.

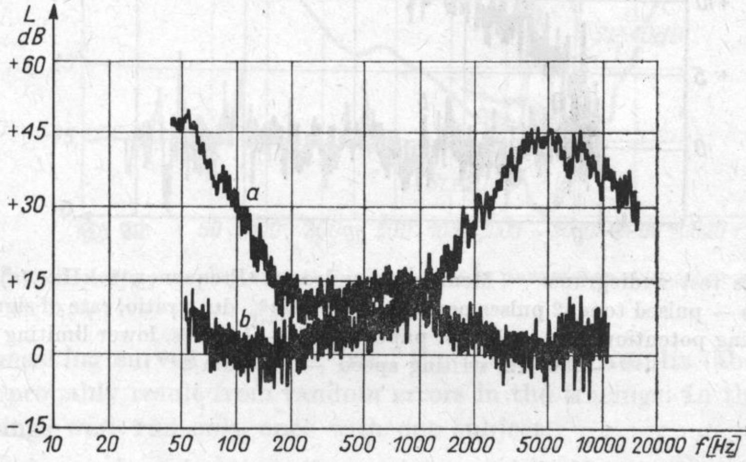

Fig. 7. Threshold shift audiograms of a musician after 4 hours' exposure to rock-and-roll music at an intensity level of 110-120 dB, (a) — 9 min after exposure, (b) — 96 hrs after exposure; rate of level control — 10 dB/s, recording potentiometer 75 dB, paper speed — 0.3 mm/s, lower limiting frequency 50 Hz, writing speed — 250 mm/s

8. Jerger's test

The Jerger tests were performed in cooperation with the Dept. of Otolaryngology of the Warsaw Medical Academy, on subjects with Menière's syndrome. The measurements were performed with continuous and pulsed tones using the simple version of the timer set to a repetition period of 0.5 s and a 50% duty cycle (i.e. 250 ms pulses). These tests were performed to compare the results obtained with the data published by JERGER [10].

In fact the results showed some diagnostic significance for this method. The threshold audiogram from one of the subjects with Menière's, obtained at a constant frequency, is presented in Fig. 8 as an example.

It seems worth pointing out that this type of Békésy tracing was observed in subjects with Menière's syndrome only in the high frequency region of the auditory range, and only in subjects with a hearing loss of at least 20 to 30 dB in that frequency region, mostly at frequencies corresponding to the maximum hearing loss. In the other cases investigated the differences observed between the continuous and pulsed tone tracings were less pronounced or undetected.

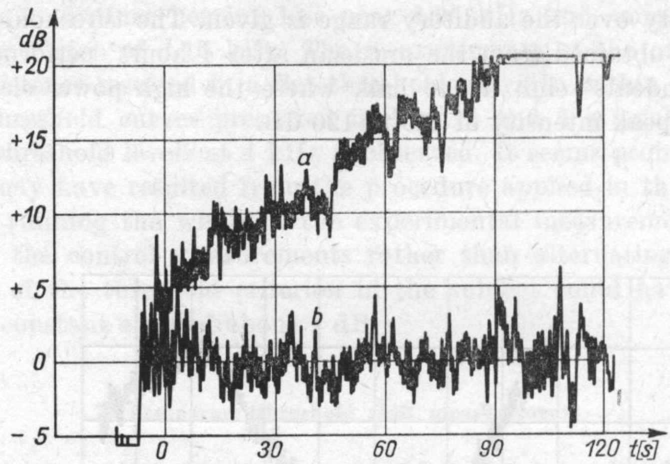

Fig. 8. Jerger's test audiograms — Menière's syndrome. Frequency 8 kHz: (a) — continuous tone, (b) — pulsed tone, 2 pulses per second at a 50% duty ratio, rate of signal control 3 dB/s, recording potentiometer — 25 dB, paper speed — 1 mm/s, lower limiting frequency — 50 Hz, writing speed — 100 mm/s

It would seem that further research on a large number of cases is necessary to evaluate the significance of this method for diagnostic purposes.

9. Masking measurements

Masking methods in psychoacoustics and in audiometry can be divided into two classes i.e. simultaneous masking, and per and post stimulatory masking.

In simultaneous masking various methods based on the use of continuous (as a function of time) stimuli, pulse stimuli or their combinations are known. In per and post stimulatory masking pulse stimuli are used as a rule.

The simplification of experimental procedure which results from the possibility of automatic signal level control, automatic frequency scanning and automatic tracing and recording of the signal level is unquestionable. This seems to be evident in masking experiments from the large number of papers published over the last decade in which Békésy tracings in classic or modified form were used [8].

To illustrate the usefulness of automatic audiometry in the investigation of simultaneous masking, typical masking curves for a 3 kHz sinusoidal signal at various sensation levels, obtained using the system described (without threshold equalizer) are presented in Fig. 9. Each circle on the diagram corresponds to the average level recorded at the appropriate frequencies. The tracings had at least 100 threshold crossings (spikes) and lasted about 120 s each. The rate of level control was 3 dB/s. Some small discrepancies observed at the

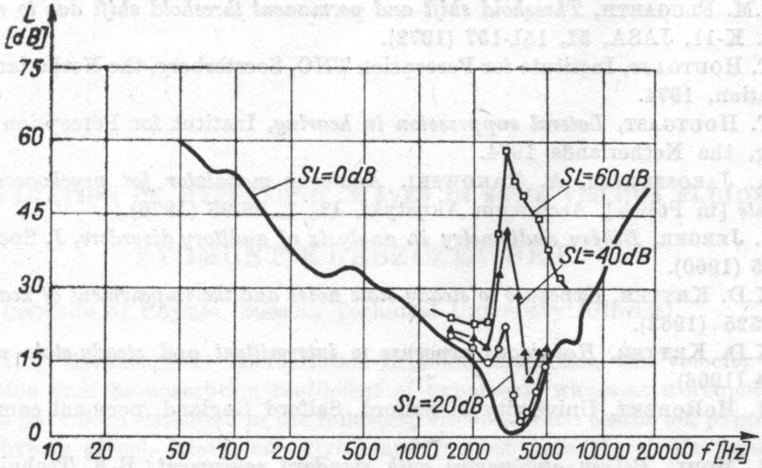

Fig. 9. Simultaneous masking curves for 3 kHz tone; parameter — masker sensation level

tops of masking curves in Fig. 9, from the theoretical results (about 2 dB difference) probably result from random errors in the tracings. In the case shown the tracings were run only once with one subject.

10. Conclusion

A Békésy audiometer constructed from conventional Brüel and Kjaer laboratory equipment and some specially designed additional units has now been in use for over 6 years. It can be used in a number of applications in hearing threshold measurements and in the other psychoacoustical measurements.

The possibility of conversion of the recording scale, the possibility of using pulse signals of varying character from the external units (described elsewhere), and the automatic averaging of the tracings by suitable adjustment of the 2305 controls, have been shown to be particularly useful.

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