

OBJECTIVE CHARACTERISTIC PARAMETERS OF LOUDSPEAKERS IN THE ASPECT OF PSYCHOACOUSTIC DATA

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The paper presents the proposal of an objective evaluation of loudspeakers. Certain subjective properties of the hearing organ should be taken into consideration. The aim of these loudspeaker investigations is to correlate results of objective investigations with a subjective evaluation of the sound emitted by loudspeakers.

1. Introduction

The correlation of objective and subjective evaluations of a sound propagating in a given room or open space is one of the basic problems faced by audio-acousticians [3, 10, 14, 15].

When an electric transducer, e.g., a loudspeaker, acts as a sound source, the physical parameters of the loudspeaker can affect the subjective evaluation of the sound. The question arises about the relation between the parameters and the evaluation. Transfer response and harmonic distortions are the most frequently determined physical parameters of a loudspeaker.

The method of subjective evaluation of a sound transmitted by a loudspeaker used to date lead to their one-dimensional arrangement with respect to, for example, the degree of fidelity of sound reproduction understood as, for example, global evaluation or with respect to selected attributes of sound sensation [14].

A critical analysis of methods of subjective evaluation of loudspeakers indicates that such factors as:

- the reference sound source, the number of loudspeakers tested, the test material, the acoustic properties of the listening room, the selection and number of subjects, the tasks assigned to the subjects,
 - the aim of the investigations, e.g., the arrangement of loudspeakers with respect to the selected attribute of the sensation perceived, the selection of a loudspeaker which reproduces the sound signal with the highest fidelity,
- significantly affect the results of the investigations.

In reality, a subject is guided by more than one criterion of evaluation — also in the case of a global subjective evaluation of a sound emitted by loudspeakers.

The multidimensional character of the sound perception space was the basis of an attempt to apply the multidimensional scaling technique (MDS) to investigate this space [3].

In the subjective evaluation of sounds by the multidimensional scaling technique, the number of the dimensions of the perception space indicates how many independent criteria are used by the subject during this evaluation.

The measurements of objective parameters of loudspeakers provide data which help arrange loudspeakers with respect to a given parameter and then compare this arrangement with arrangements which are the result of the subjective evaluation along another dimension of perception [6, 7, 8, 9].

The results obtained indicate, however, that the correlation between these arrangements is still not satisfactory.

2. Aim

The aim of the investigations was to determine the relation between the subjective evaluation of a sound and modified objective parameters of loudspeakers. We employed the technique of multidimensional scaling for the subjective evaluation, whereas in the objective evaluation excitation with a stationary signal as well as the impulse technique were used.

It would seem that this domain has been fully investigated and only a further development of technology can increase the precision and rate at which objective parameters of a loudspeaker are determined [6, 11].

Our working hypothesis was that if the results of psychoacoustic investigations are used to evaluate objectively the parameters of a loudspeaker, the results of subjective evaluations can further approach objective investigations.

Therefore, through the weighing of results of evaluations of objective parameters, given that the function of the weight is the result of psychoacoustic investigations, it is possible to determine the parameters of a loudspeaker which incorporate some kind of effects, namely subjective evaluations.

3. Objective parameters of the loudspeaker

When selecting loudspeaker parameters, the author's experience was helpful in investigating the perception of changes in transient sounds [4], in checking loudspeakers by means of impulse methods and in studying the perception of the deformation of impulses in the acoustic field of the loudspeaker [5].

It follows from this experience that the parameters connected with the loudspeaker response to the excitation by the Tone Burst sound are a necessary

complementation of parameters which directly describe the transmission properties of the loudspeaker in the steady state. This is so as it is necessary to treat the loudspeaker as a nonminimal-phase system, especially in the high frequency range.

The justification of the selection and detailed definitions of objective parameters of the loudspeaker have been quoted elsewhere [1, 4, 6]; those which have been used in the present investigations are discussed below.

3.1. Transfer response

This response was determined by excitation using a sinusoidal signal with retunable frequency. Next, the width of the transfer band Δf was determined. Maximal values of deviations from the value of the mean level indicate the irregularity of ΔL response in the response band.

3.2. Transient response

The loudspeaker transient response, i.e., its transfer response for a given time moment, after the disconnection of the excitation Tone Burst signal, was recorded by the measurement system described in detail elsewhere [6]. The transient response index D was adopted as the measure of the deviation of the loudspeaker transient response from its transfer response in the steady state (for a given time τ after the disconnection of the excitation signal) where

$$D = \frac{1}{n} \sum_{i=1}^n (L_{ssi} - L_{\tau i}) \quad [\text{dB}]$$

L_{ssi} — the value of the acoustic pressure level of a steady state signal at its i -th frequency. $L_{\tau i}$ — the value of the acoustic pressure level of the signal final transient at a given time after the disconnection of the excitation signal with the i -th frequency, n — the overall number of frequency components.

Additionally, the quantities D_τ , which define the difference between the maxima and minimal values of the index D for successive times τ were determined.

3.3. Duration of the initial and final transients

The duration of transients connected with the signal growth " t_n " — the initial transient, and with the signal reverberation " t_z " — the final transient, is one of the basic measures of transient distortions introduced by the loudspeaker when it is excited by an impulse.

Taking into account the character of transients of loudspeakers excited by tone

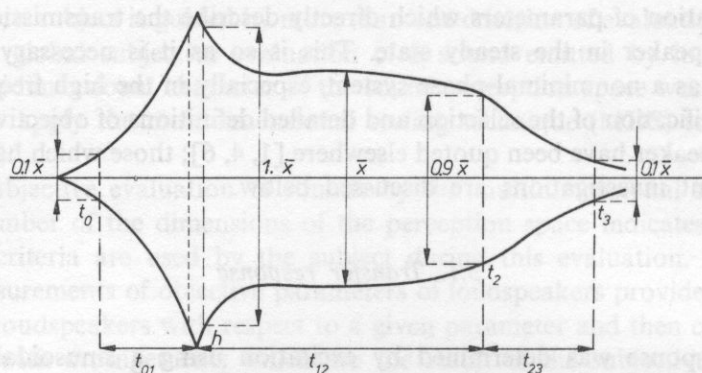


FIG. 1. Time response of the loudspeaker to impulse excitation

\bar{x} — mean value curve at the steady time segment

t_{01} — duration of the initial transient

t_{12} — duration of the steady state

t_{23} — duration of the final transient

impulse, we have defined the durations of the initial and final transients as time segments $t_n = t_{01}$ and $t_z = t_{23}$ (Fig. 1).

The duration of the transients can be expressed directly in time units (ms). It is also possible to take into account a specific value of the frequency of the signal excited by means of the number of vibration periods (T). Hence, for $f = 2000$ Hz ($T = 0.5$ ms) the duration of the 2 ms transient is equal to 4 in absolute units.

3.4. Energy, coefficient

The energy ratio at time t_{01} , t_{23} referred to the steady state energy at time segment t_{12} was adopted as the measure of energy of transient during the signal growth H_n and its decay H_z .

4. Selected results of psychoacoustic investigations

As was mentioned above, the loudspeaker parameter discussed in Section 3 were selected from a greater number of parameters. The selection criterion followed from the degree of their correlation with the subjective evaluation of the sound, defined through the arrangement of loudspeakers using the method of multidimensional scaling.

The results obtained were not satisfactory for the author ($\rho < 0.80$). It was decided to modify the objective parameters through their appropriate weighing resulting from the data obtained from psychoacoustic investigations.

When defining the weight of particular parameters, it was decided to take into account the following facts known from the theory of hearing [1, 2, 12]:

- the width of the critical band up to the band mid frequency $f_m = 500$ Hz is equal 100 Hz and for higher frequencies it is equal to 17% of the value of the mid frequency,
- the resolution capability of the hearing organ in the frequency domain changes in accordance with the curve shown in Fig. 2,

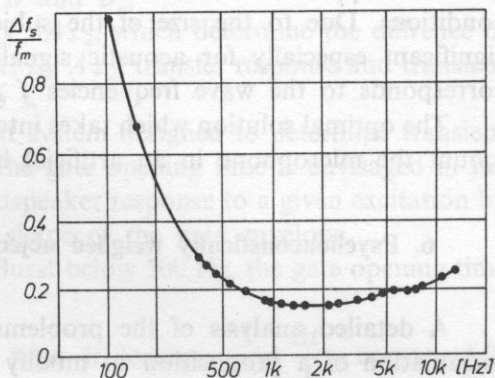


FIG. 2. The curve of changes in the resolution capability of the hearing organ in the frequency function [12]

- the masking effects affect the overall loudness of the sound, tonal balancing and hence the sound timbre. Sound loudness can be determined for example on the basis of, what are known as Zwicker nomograms. When determining sound loudness, its spectral composition and the effects of the mutual masking of components are taken into consideration,
- the hearing organ values are an acoustic signal in the frequency function in the band of up to 500 Hz according to the linear scale and above according to the logarithmic scale,
- the hearing organ is capable of recording changes in the values of the signal acoustic pressure; this capability is greater in the case of pressure increase than decrease.

5. Conditions of the investigations of loudspeaker objective parameters

When discussing problems connected with the determination of loudspeaker objective parameters, other problems which can affect the final result should also be taken into consideration. The latter include the determination of the conditions of objective measurements.

The first problem is where, in what room, the objective measurements of loudspeaker should take place. As has been indicated by the investigations conducted by the present author, among others, a correlation of the objective

evaluations with parameters of a loudspeaker for the steady state occurs only when these parameters have been determined in the same room in which subjective evaluation takes place.

When loudspeaker parameters were related to its work in the transient state, they correlated with the subjective evaluation also in the case when the parameters were determined in an anechoic chamber.

The second methodological problem connected with objective investigations is that of the approximation of diffraction around the measurement microphone to real conditions. Due to the size of the subject's head ($\varnothing \approx 17$ cm), these effects are significant especially for acoustic signals whose wave length $\lambda \leq 17$ cm, which corresponds to the wave frequencies $f \geq 2000$ Hz.

The optimal solution which takes into account the diffraction effects seems to be mount the microphone in an artificial head.

6. Psychoacoustically weighed objective parameters of the loudspeaker

A detailed analysis of the problems discussed above was the basis for the formulation of a proposition to modify the definitions and the methodology of measurement of selected parameters of the loudspeaker.

The propositions were presented with reference to each parameter.

6.1. Steady state

6.1.1. Transfer response. The measurement of this response was made in a listening room by exciting the loudspeaker with a sinusoidal signal. The microphone was mounted in an artificial head, and its output signal was recorded by the A/C transducer.

The following are adopted as parameters of the transfer response:

- transfer band Δf [Hz],
- irregularities of the response ΔL [dB] determined in the entire transmission band ($f_d \div f_g$) and in bands ($f_d \div 500$) Hz, ($500 \div f_g$) Hz,

where:

- f_d, f_g — the bottom and top frequency of the loudspeaker transfer band ($\Delta f = f_g - f_d$),
- loudness N in sones and the level of audible intensity L_n in phones, determined on the basis of Zwicker nomograms (transfer response is treated as a spectrum of the acoustic signal registered at the loudspeaker output),
- area A_{+2} [dB], exceeding the mean level of the transfer response by values greater than +2 dB in the entire transfer band and in ranges ($f_d \div 500$) Hz, ($500 \div f_g$) Hz. The parameter $\Delta f, \Delta L, N, L_n, A_{+2}$ are determined at linear (frequency up to 500 Hz) and logarithmic (frequency above 500 Hz) scales of frequency changes.

6.2. Transients

6.2.1. Transient response. The measurement of the transient response is done under the same conditions as was the case with the transfer response. The following are adopted as parameters of the transient response:

- the parameters Δf , ΔL , N , L_n , A_{+2} determined under the same assumptions as was the case with the transfer response,
- the parameters of transient response D and D_r ,
- the parameters $\Delta(\Delta f)$, $\Delta(\Delta L)$, ΔN , ΔL_n , ΔA_{+2} , which determine the difference of the absolute value of parameters Δf , ΔL , N , L_n , A_{+2} , transfer response and transient response for successive moments of time τ .

At the same time in the measurement system designed to determine transient responses, a possibility of the change of the gate opening time is envisaged in the microphone system which records the loudspeaker response to a given excitation by the Tone Burst signal, at a determined shape of the gate envelope.

Within the frequency range of Tone Burst below 500 Hz, the gate opening time is constant and equals 10 ms.

For frequencies higher than 500 Hz, time Δt decreases and $\frac{\Delta t}{T} = \text{const.} = 5.9$.

Hence,

for $f = 1$ kHz

$$\Delta t = 5.9 \text{ ms,}$$

for $f = 5$ kHz

$$\Delta t = 1.2 \text{ ms}$$

for $f = 10$ kHz

$$\Delta t = 0.6 \text{ ms,}$$

for $f = 16$ kHz

$$\Delta t = 0.4 \text{ ms}$$

6.2.2. Durations of the initial transient t_n and final transient t_z . Energy coefficients H_n , H_z

The measurements of these quantities are made under the same conditions as the measurement of the transient response in the measurement system with the gate width retunable in time.

7. Results

The investigations comprised three groups of loudspeakers: low, mid, and high tone ones, six loudspeakers in each case. The low tone loudspeakers are the same type of loudspeakers with changes in the design of the membrane mass and coil circuit. Individual mid- and high-tone loudspeakers differed with respect to their type.

7.1. Results of subjective evaluations

A sketch of the listening room in which subjective evaluations and part of objective evaluations were conducted is shown in Fig. 3.

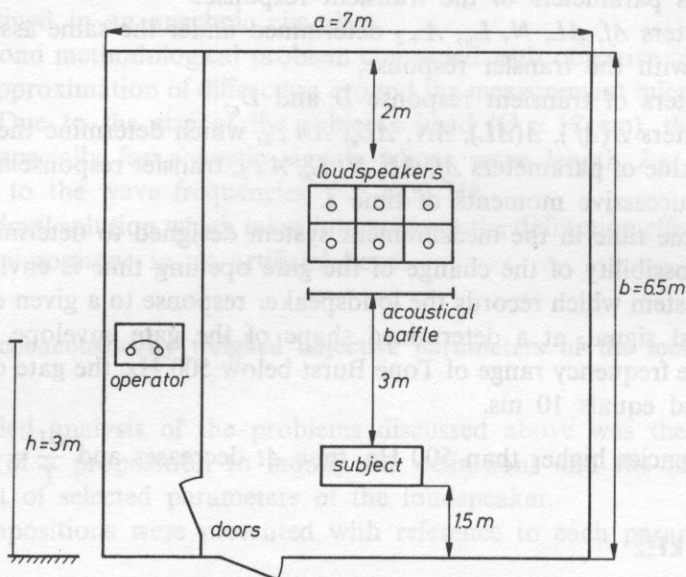


FIG. 3. A sketch of the listening room

The basic investigations were preceded by preliminary investigations which included a test of the subjects' selection and a selection of the listening material. They also helped define the influence of the source directivity on the results of the evaluations.

Following the preliminary investigations, in which the correlation of the ranks of each of the subjects was determined with respect to the subject for whom the value of the statistics tested was the highest, six subjects out of ten were selected to participate in the basic investigations. The results of this selection were verified using the MDS method. The compatibility of the evaluations of subjects was verified on the basis of Kendall and Babington-Smith's concordance index [3].

Once it was determined that the subjects evaluate the loudspeakers under investigation in a similar way, the differences in the arrangement of the loudspeakers with respect to different musical pieces were interpreted as a uniformity test of the sample material.

Table 1 includes a description of 6 musical pieces (duration ~ 10 s) together with stress values for particular dissimilarity matrices, respectively in three-, two- and one- dimensional perception space.

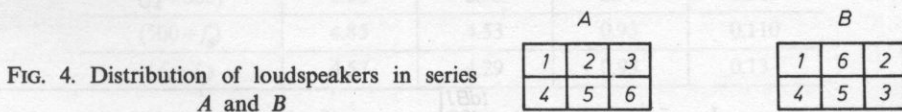
The criterion of 5% stress value was adopted as the measure of the adjustment

Table 1. Description of musical pieces

No	Type of music	Performer	Title	Stress [%]		
				I	II	III
1	big beat	Jimmy Hendrix	Stepping stone	43.4	0.244	x
2	popular	Bert Kaempfer orchestra	Caravan	39.2	0.001	x
3	popular	Uriah Heep group	Sunrise	—	22.6	0
4	popular	Zygmunt Malik orchestra	Sweet Beat	34.6	0.126	x
5	big beat	Jimmy Hendrix	Midnight	43.2	0	x
6	big beat	Dzamble group	I've got to have a girl friend	—	22.6	0

of the perception space to the data in the dissimilarity matrix. It follows from the analysis of the data in Table 1 that for four musical pieces (1, 2, 4, 5) the perception space of sensations is two-dimensional, and for two musical pieces (3, 6) it is three-dimensional. Considering the percentage of the total variance connected with a given dimension, a hypothesis was advanced about the significance of two dimensions of the perception space which differentiate the loudspeakers under investigation.

In an attempt to explain any influence of the source directivity on the results of the subjective evaluations by the subjects, the results of the evaluations from two series of the investigations *A* and *B* were compared. The series differed only as regards the location of the loudspeakers with respect to each other (Fig. 4).



The investigations conducted using the MDS technique have shown that the impression of the directivity does not have any influence on the arrangement of the loudspeakers in series *A* and *B* along the 1st dimension of perception and can be almost neglected (the transposition of loudspeakers 2 and 3) during their arrangement along the 2nd dimension of perception.

Six subjects took part in the basic investigations. They evaluated three groups of

loudspeakers (each time six loudspeakers) on the basis of the selected sample material. The method of stimuli comparison by triade was used. The same musical piece reproduced by one of the 3 loudspeakers switched on randomly by the experimenter was evaluated in the triad. The subject had at his disposal three buttons and made decision about the order in which he switched on one of the three loudspeakers. The subject's task was to point to the pair of loudspeakers most similar and most dissimilar with respect to each other. The results of the evaluation of the similarity between the sounds was processed by the method of multidimensional scaling of individual differences INDSCAL.

On the basis of the dissimilarity matrices defined for all subjects and for all pieces of music, a two-dimensional perception space and an appropriate arrangement of the loudspeakers along both dimensions were obtained for each group of loudspeakers.

7.2. Results of objective evaluations

A block diagram of the measurements system was shown in Fig. 5.

The use of the microcomputer helped fully automate the entire process of measurement and data processing. All loudspeakers from the three groups were

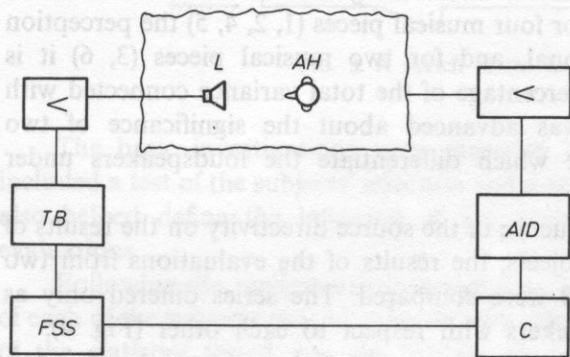
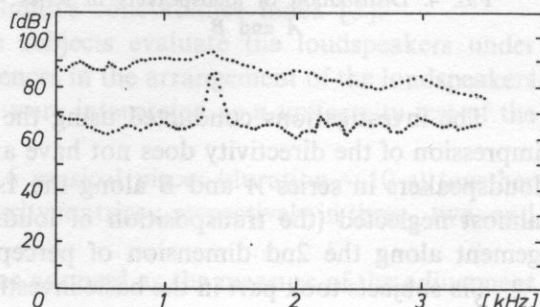


FIG. 5. Block diagram of the measurement system *L* – loudspeaker, *AH* – artificial head, *A/D* – analog-to-digital converter, *C* – computer, *FSS* – frequency sweep system, *TB* – tone burst generator

FIG. 6. Transfer response (top curve) and transient response (bottom curve) of a low tone loudspeaker



investigated. The same methodology as described in Section 5 was used and the same parameters as described in Section 6 were determined. Two cases were identified for transient responses: with constant and varying width of the time gate.

For example, Figure 6 and Table 2 show the results for one low tone loudspeaker with respect to the transfer response and transient response ($\tau = 1$ ms, varying width of the time gate).

Table 2. Values of low tone loudspeaker parameters determined from transfer response and transient response

	$f_d f_g$ [Hz]	ΔL [dB]	A_{+2} [dB]	Δf [Hz]	N [son]	L_n [fon]	D [dB]
Transfer response	$(f_d \div 500)$	2.45	0.56	—	—	—	—
	$(500 \div f_g)$	3.28	1.46	—	—	—	—
	$(f_d \div f_g)$	3.21	1.38	3306	891.1	138.1	—
Transient response	$(f_d \div 500)$	5.71	3.01	—	—	—	9.5
	$(500 \div f_g)$	4.12	2.41	—	—	—	12.3
	$(f_d \div f_g)$	4.26	2.47	3240	508.2	129.9	12.1
Difference in the value of the parameters of both responses	$(f_d \div 500)$	3.26	2.45	—	—	—	—
	$(500 \div f_g)$	0.84	0.95	—	—	—	—
	$(f_d \div f_g)$	0.95	1.09	66	382.9	8.2	—

Table 3 shows the results of the measurements of the duration of transients t_n , t_z and energy coefficients H_n , H_z .

Table 3. Values of low tone loudspeaker parameters determined from transients

$f_d f_g$ [Hz]	t_n [T] [ms]	t_z [T]	H_n	H_z
$(f_d \div 500)$	2.28	2.33	0.91	0.30
$(500 \div f_g)$	4.85	4.53	0.93	0.110
$(f_d \div f_g)$	4.57	4.29	0.93	0.13

Numerical data of particular parameters of loudspeakers shown in Tables 2 and 3 helped arrange the loudspeakers in three successive groups, according to the growing numerical values of the parameters.

7.3. Correlation of subjective and objective evaluations

SPEARMAN'S [3] rank correlation index ρ_s was used to investigate the correlation force between two arrangement scales. Adopting the significance level $\alpha = 0.05$, for

the number of elements tested $n = 6$, we get the critical value of the rank correlation index $\rho_k(\alpha, n) = 0.83$. Hence the value $\rho_s > \rho_k = 0.83$ decides on the existence of a dependence between the arrangements.

Matching the arrangements of loudspeakers obtained as a result of subjective and objective evaluations, each time in a given group of loudspeakers, the values of the rank coefficient ρ_s were determined. In practice, this means a comparison of arrangements in the dimension of the perception space which are the result of the subjective evaluation with arrangements which result from the growing numerical values of the parameters of the loudspeakers.

Assuming the value $\rho_s > 0.83$ as the necessary condition for the existence of a correlation between the evaluations, the following parameters of the loudspeakers were distinguished:

1. First group of parameters:

Parameter f , $\rho_s = 1.00$, first dimension of perception,

Parameter D , $\rho_s = 1.00$, second dimension of perception (parameter D — defined for the transient response determined at the constant width of the time gate).

2. Second group of parameters:

Parameter t_n (max), $\rho_s = 0.94$, first dimension of perception

Parameter $t_z(f_d \div f_g)$, $\rho_s = 0.83$, second dimension of perception.

3. Third group of parameters:

Parameter N , $\rho_s = 1.00$, first dimension of perception,

Parameter L_n , $\rho_s = 1.00$, first dimension of perception,

Parameter A_{+2} , $\rho_s = 0.89$, second dimension of perception

Parameter ΔL , $\rho_s = 0.89$, second dimension of perception.

A detailed analysis of the results helps formulate the following conclusions:

1. When evaluating different types of loudspeakers with assumed large differences in the transmission band range, a full correlation with the subjective evaluation is obtained by the band width of Δf (as defined in Section 3.1) — in the first dimension of the perception space and the transient response index D (as defined in Section 3.2) in the second dimension of the perception space.

2. When evaluating one type of loudspeakers (very small differences in the parameters of the design assumed), the best correlation with the subjective evaluation is obtained between the parameters of the loudspeaker connected with the transients, precisely with the duration of the initial transient t_n (as defined in Section 3.3; its maximal value in the entire transfer band) — in the first dimension of the perception space and the duration of the final transient t_z (as defined in Section 3.3: its mean value for the entire band of the space) — in the second dimension of this space.

3. The evaluation of different types of the same group loudspeakers leads to the statement that in this case the best correlation is found between the parameters of the loudspeaker connected with loudness N or the loudness level L_n (as defined in Section 6.1) — in the first dimension of the perception space and the area A_{+2} (as defined in Section 6.1) — in the second dimension of this space.

In the second dimension of the perception space the equivalent value of the correlation index is also provided by the non-uniformity of the transfer response ΔL (as defined in Section 6.1).

8. Conclusion

An attempt to correlate subjective evaluations of a sound emitted by loudspeakers with objective parameters of loudspeakers, on the basis of the technique of multidimensional scaling, subjective evaluations and the methods of the steady state and the impulse technique (objective evaluations) has shown that such a correlation exists at level $\rho \geq 0.83$. Specific requirements pertaining to the methodology of investigations and the selection of appropriate objective parameters of loudspeakers, depending on the object of the investigations, have to be observed.

The weighing of the loudspeaker parameters on the basis of the results of psychoacoustic investigations has produced a positive result through the increase of the degree of the power of the correlated evaluations.

Presently, it seems extremely interesting to look for two independent attributes which describe the quality of the sound perceived, ascribed to two determined dimensions of the perception space.

The results of these investigations will help bind specific parameters of loudspeaker parameters with attributes of the perception space.

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