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SUBJECTIVE EVALUATION OF SOUND EMITTED BY A LOUDSPEAKER SYSTEM IN CORRELATION WITH ITS STEADY-STATE AND TRANSIENT RESPONSES

M. NIEWIAROWICZ, A. FURMANN, E. HOJAN, P. PERZ

Institute of Acoustics,
Adam Mickiewicz University
(60-769 Poznań, Matejki 48/49)

Objective parameters of a loudspeaker system, which describe its transmission properties in a transient- and steady-state, have been determined. These parameters have been related to the attributes of the sound perception space (fullness, clearness, sharpness, spaciousness, loudness, lack of distortions) with respect to the overall subjective evaluation and the parametric one. A good correlation between sharpness, fullness, spaciousness and selected objective parameters have been obtained. An influence of the test signal on the results of the subjective evaluation was also discovered.

1. Introduction

The multi-dimensional character of the sensation space connected with the perception of acoustic signals creates a number of significant difficulties when attempts to correlate the subjective evaluations of such signals with their physical parameters are performed [10, 13, 16, 17]. Investigations of those problems indicated, among other things, the applicability of the multi-dimensional scaling technique to the analysis of the results of the subjective evaluation [1, 6] and to the modelling of physical parameters of signals on the basis of psychoacoustic data in the case of objective evaluations [4, 7]. The physical parameters of the signals can be directly connected to the physical parameters of their sources and, in this context, subjective evaluations of the sound can be related to the parameters of their sources [5]. This kind of investigations performed for electroacoustic transducers showed that it was necessary to include physical parameters, which characterise their work in both the steady and transient states [14]. Results presented in many papers showed that the subjective evaluation of the acoustic signals emitted by transducers depends on many factors, connected with the investigations procedure [3]. The procedure of investigations of the subjective evaluations must optimise all these factors whenever possible so that the final evaluation be recurrent, provided precisely defined conditions have been met.

The subjective evaluation of sounds reproduced by the loudspeaker systems depends on the parameters of the sound perceived by the subject. These parameters depend on the parameters of the test signal, on the physical parameters of the loudspeaker system and the acoustic properties of the room. When the acoustic parameters of the room are known, the same test signal reproduced by different loudspeaker systems result in different values of objective parameters and different subjective evaluations of the reproduced sounds. The present investigations aimed at the determination of the influence of changed amplitude and phase response of the loudspeaker systems on the subjective evaluation of sounds reproduced by these systems [9].

2. Procedure of the subjective investigations

2.1. Scenery

The investigations were performed using a pair of three way loudspeaker systems (with a passive radiator), available in the random production series (Factory of Loudspeakers TONSIL S.A. in Września, Poland). The geometry of the system and the structure of the crossover network is presented in Fig. 1.

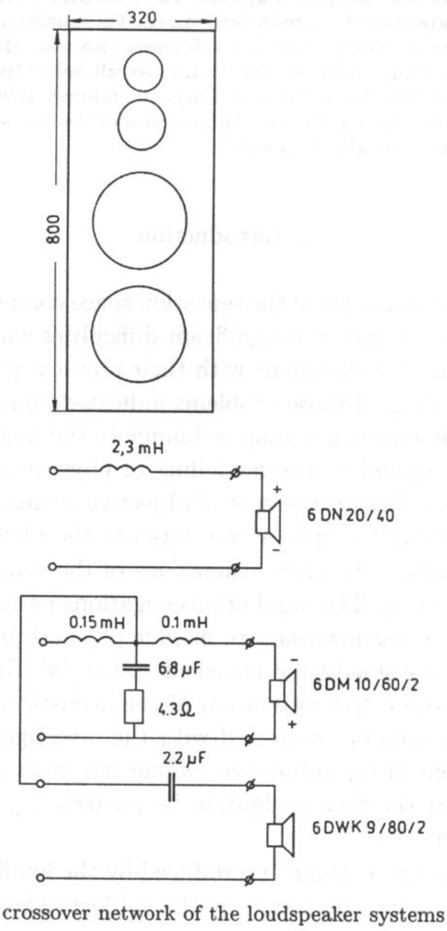

Fig. 1. Geometry and crossover network of the loudspeaker systems under investigation.

On the basis of those loudspeaker systems, measurement systems with different amplitude and phase characteristics have been artificially set up. For this purpose, special filters with a set of response curves, corresponding to the frequency responses of the loudspeaker systems, have been used. The filter characteristics are shown in Fig. 2.

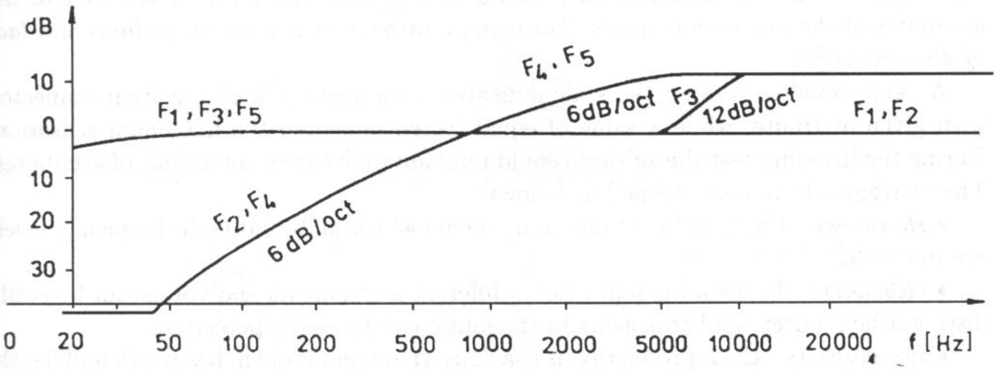

Fig. 2. Filter frequency characteristics.

In this way, the set-up imitating the five loudspeaker systems with different amplitude and phase characteristics was created.

Four one-minute test signals have been used in the investigations:

P1 – pink noise,

P2 – speech sound,

P3 – wide band music,

P4 – white noise.

The selection of the test signals was motivated by the desire to check whether the influence of the amplitude and phase characteristics of the loudspeaker system on the subjective evaluation of the reproduced sound depends on the test signal. Listening tests were presented on the stereophonic way and the level of the sound acoustic pressure was 80 dB (pink noise was the calibration signal). The measuring signals were tape-recorded and then reproduced using the same tape recorder. The white noise and pink noise signals were tape-recorded directly from the signal generator. The wide band music and speech signals were tape-recorded under natural conditions – during the musical performance in a concert hall and during the lecture in an auditorium, respectively.

Eight hi-fi experts were the subjects during the tests. The listening tests were carried out in a listening room, compatible with IEC standards.

2.2. *Methodology*

The subjective investigations were aimed at the determination of attributes of the perception space [8] which would help to explain the differences between the evaluation of sounds emitted by the loudspeaker systems. The subjective evaluation of sounds emitted by the loudspeaker systems consisted of two parts: an overall evaluation and a parametric evaluation.

The overall evaluation was conducted by means of the method of triadic comparisons [12]. The subject's task was to determine a pair of most similar sounds and another one of least similar sounds.

The parametric evaluation was carried out by means of the method of rating scale. The subject's task was to assess each sound on a 0 – 10 scale. Those scales refer to the attributes of the perception space: *sharpness, clearness, spaciousness, fullness* and *lack of distortions* [6].

A value equal to zero on the scale indicated a complete lack of sensation connected with given attribute, while a value of equal to ten indicated the maximum sensation. During the listening test the subjects could refer anytime to the definitions of attributes. The attributes have been defined as follows:

• *sharpness* – the sound contains components which mid- and high- frequency levels are too high,

• *clearness* – the sound is pure, clear; different instruments and voices can be easily distinguished, onsets and transients in the music can be easily perceived,

• *spaciousness* – the reproduction is spacious, the sound is open, has width and depth, fills the room, gives the impression of the subject's presence in the space surrounded by the sound,

• *fullness* – the sound contains the entire spectrum without any limitations, at least in the bass range

• *lack of distortions* – indicates a pure sound, without distortions, one which is not harsh, hiss or rumbling.

2.3. Results of the subjective evaluation

The results of the evaluation of dissimilarities between sounds have been analysed by the technique of multidimensional scaling, the method of individual differences (INDSCAL [1]) which showed that a two-dimensional space determines dissimilarities between the tested sounds. The calculations revealed that two dimensions are the optimal number of dimensions of the metric space, and enables to describe the configuration of the experimental data. The value of "stress", designating the difference between both the experimental and fitted data, was 5%. The investigations performed by KRUSKAL [11] showed that a value of stress less than 10% is an indicator of good fitness of configuration points to the experimental data. The dimensions of that space have been interpreted by the multiple regression analysis; the results of the evaluation of sound attributes have been used. It was found that one of the dimensions of the dissimilarity space is determined by the *sharpness* and the other one by the *fullness* and *spaciousness* (see Fig. 3).

On the basis of the analysis of the amplitude and phase characteristics (see Subsec. 3.1, Fig. 4) and the results of the subjective evaluation of sounds emitted by the loudspeaker systems under investigations, it has been found that:

1) the amplitude characteristic affects the *sharpness, fullness* and *spaciousness* of the sound,

2) the phase characteristic affects the *fullness* and *spaciousness* of sounds (these statements result from the qualitative analysis of the shape of the amplitude and phase characteristics),

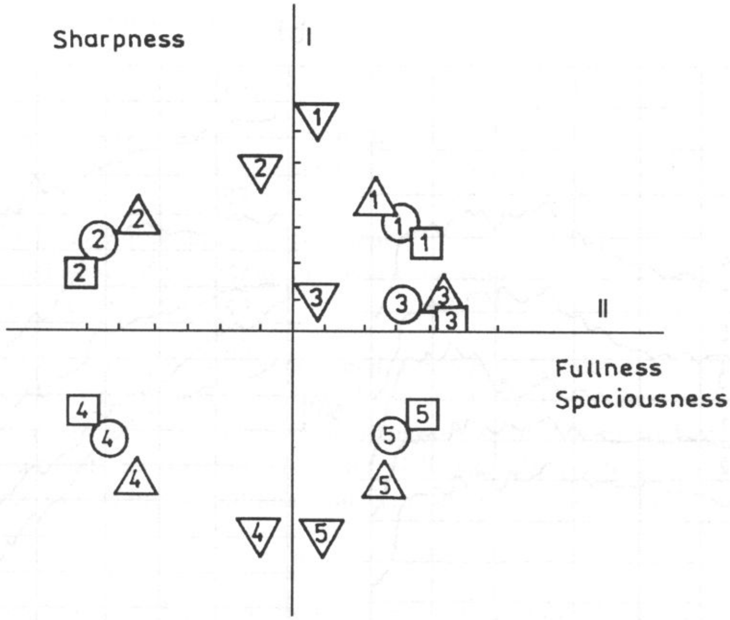

Fig. 3. Results of the subjective evaluation (symbols: △ – pink noise, ▽ – white noise, □ – speech, ○ – music; numbers inside symbols denote the number of filter).

3) the influence of the amplitude and phase characteristic depends on the test signal (in the case of white noise signal this influence is decisively different than for other test signals).

3. Procedure of the objective investigations

3.1. Steady state parameters

Amplitude and phase characteristics of loudspeaker systems have been determined in an anechoic chamber using the two-channel Bruel & Kjaer 20-32 analyser. White noise was the excitation signal and the measuring microphone was located at the distance of 1 m, on the reference axis of the loudspeaker system. Figure 4 shows the amplitude and phase characteristics of the loudspeaker systems under investigations (particular amplitude and phase characteristics were shifted one to the other of 10 dB and 50°, respectively).

Basing on the definition of the parameter, characterising the frequency response in a quantitative way [2], a new, similar parameter was introduced. Having defined limit frequencies, the value of its mean level was determined. Consequently, one can determine the mean value of ±2 dB deviations in the spectral extent by which the signal exceeded the mean level of the amplitude characteristic, which can be adopted as a measure defining the non-uniformity of this response.

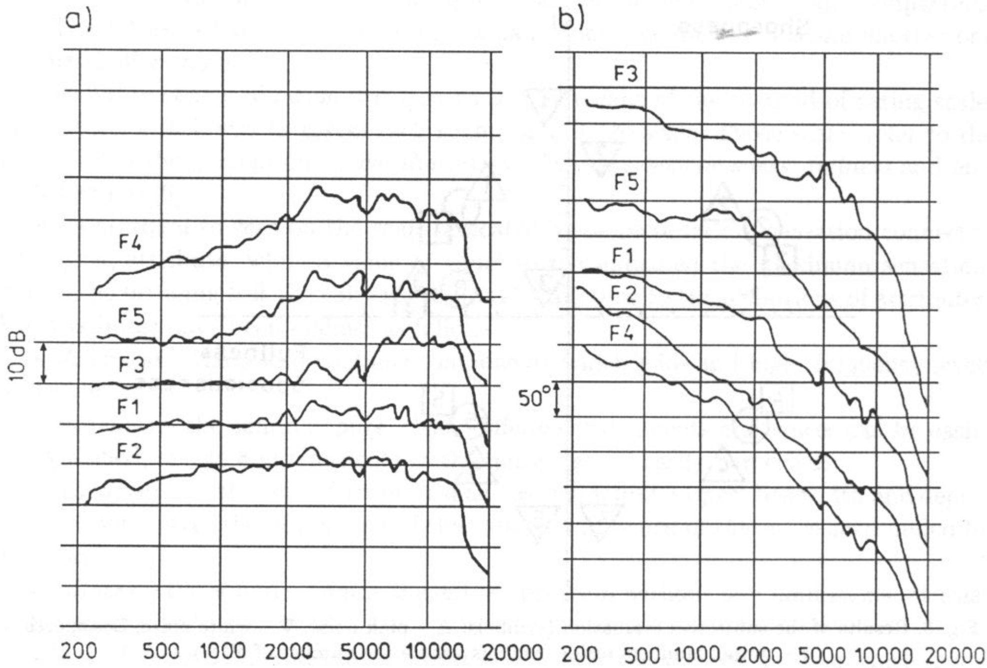

Fig. 4. Frequency (a) and phase (b) characteristics of loudspeaker systems.

Inversely, treating the amplitude characteristic as a spectrum of the acoustic signal emitted by the electroacoustic transducer, one can define the loudness in sones and the loudness level in phones, on the basis of Zwicker diagrams [15].

3.2. Transient parameters

The existence of a correlation between the subjective and objective evaluations, which we were looking for, can occur primarily when the objective evaluation is based on parameters which characterise the transient properties of a transducer [5]. The occurrence of transients in the transducers, resulting from the excitation of vibrations of mechanical elements that self-vibration frequencies, damping and reciprocal couplings are different, is related to the dynamic properties of the transducer and can make a basis for its quality evaluation. When selecting these parameters, we used the results of investigations of the perception of changes in the envelope of the transients, investigations of the transducers by impulse methods and of the perception of the deformation of impulses in the acoustic field of the loudspeaker systems; the modelling of objective parameters under the aspect of psychoacoustic phenomena has also been applied [7]. In order to obtain specific parameters, it was necessary to use both an appropriate kind of the forcing signal and a specific measurement set-up [14]. In the investigations under discussion the *tone burst* signal was used.

Its analytical form can be written as:

$$x(t) = A \sin \omega t \cdot g(t) \tag{1}$$

where $g(t)$ represents the rectangular gate function.

The objective evaluation of the loudspeaker systems was performed on the basis of the following transient parameters:

- duration of the initial and final transients,
- power coefficients of the initial and final transients,
- transient characteristic.

3.2.1. The duration of the initial and final transients. The duration of transient processes connected with the signal rise and decay is one of the fundamental measures of transient distortions introduced by the loudspeaker when it is excited by an impulse. Taking into account the response character of loudspeaker system excited with tone pulses, the duration of initial and final transients are defined as an intervals of time:

$$t_r = t_{01}, \qquad t_d = t_{23}. \tag{2}$$

Figure 5 shows the most characteristic forms of the transition between the steady state and transients. Hence, the determination of the mean value $\overline{x}$ of the signal at the steady state interval t_{12} helps specify, in accordance with the adopted definition, the duration of the transient from the moment when the envelope reaches 0.1 of the mean value in the steady state ($0.1\overline{x}$) until it reaches values lower than 0.9 or higher than 1.1 of the mean value in the steady state ($0.9\overline{x}$ or $1.1\overline{x}$).

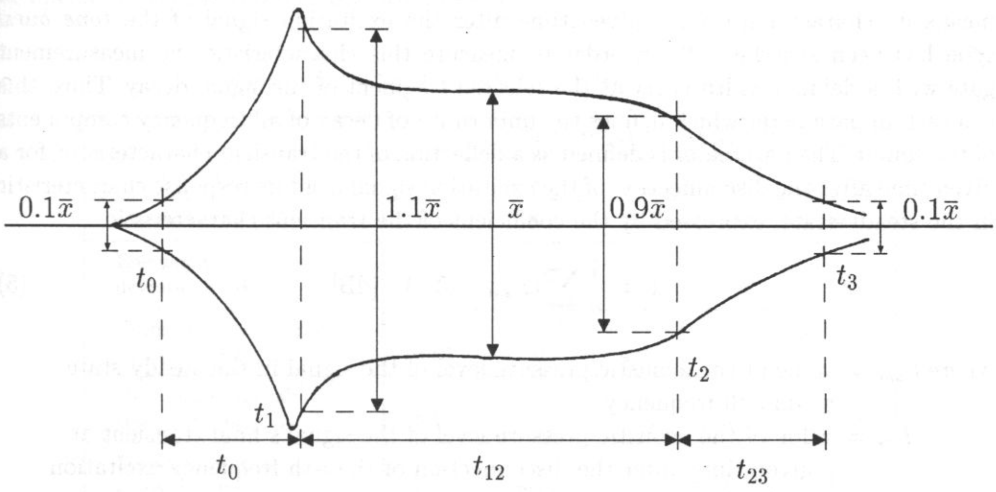

Fig. 5. Exemplary shape of the envelope of the signal transmitted by a transducer.

3.2.2. Power coefficients. The ratio of power per interval t_{01} and t_{23} related to the power per steady state at the time interval t_{12} has been adopted as a measure of the transient power at the signal rise and decay. They discrete forms which are the approximations of the integral formulas were defined as follows:

• for the initial transient

$$M_1 = \frac{\dfrac{\sum\limits_n |X_{01n}|^2}{n_{01}}}{\dfrac{\sum_k |X_{12k}|^2}{k_{12}}}, \tag{3}$$

where $X_{01n} \mathrel{\hat{=}} n^{\text{th}}$ value of the initial transient amplitude,
$n_{01} \mathrel{\hat{=}}$ number of samples for the initial transient,
$X_{12k} \mathrel{\hat{=}} k^{\text{th}}$ value of the steady state amplitude,
$k_{12} \mathrel{\hat{=}}$ number of samples for the steady state;

• for the final transient

$$M_2 = \frac{\dfrac{\sum\limits_n |X_{23n}|^2}{n_{23}}}{\dfrac{\sum\limits_k |X_{12k}|^2}{k_{12}}}, \tag{4}$$

where $X_{01n} \mathrel{\hat{=}}$ value of the final transient amplitude,
$n_{23} \mathrel{\hat{=}}$ number of samples for the final transient.

In the investigations under discussion the sample frequency was 50 kHz.

3.2.3. Transient characteristic. The loudspeaker system's transient characteristic means its characteristic for a given time after the excitation signal of the *tone burst* type has been switched off. In order to measure this characteristic the measurement gate with a defined width is set at the selected fragment of the signal decay. Thus, this is a certain parameter which defines the uniformity of decay of all frequency components of the sound. The parameter is defined as a deflection of the transient characteristic, for a given time after the disconnection of the excitation signal from its response characteristic in the steady state, expressed by the coefficient of the transient characteristic

$$D = \frac{1}{n} \sum_i (L_{ssi} - L_{\tau i}) \quad [\text{dB}], \tag{5}$$

where $L_{ssi} \mathrel{\hat{=}}$ value of the acoustic pressure level of the signal in the steady state at its i-th frequency,
$L_{\tau i} \mathrel{\hat{=}}$ value of the acoustic pressure level of the signal's final transient at a given time, after the disconnection of the i-th frequency excitation signal,
$n \mathrel{\hat{=}}$ total number of the frequency components.

In these investigations $n = 250$.

Having taken into account certain facts known from the theory of hearing, related to the change in the width of human ear's critical bands in the frequency function [18], the manner of determining transient characteristics has been modified – a measurement gate with varying width has been used. It has been assumed that up to 500 Hz the gate width is 10 ms and above 500 Hz it is $1/0.17\,f$, where f denotes the frequency of the *tone burst* excitation signal. Since $f = 1/T$, the gate width can also be expressed as equal to about 6 T. If the transient characteristics are determined in the above manner, they are subject to a particular "weighting" and, consequently, while retaining the features of objective parameters, they comprise a certain aspect of subjective nature [7].

All objective parameters under investigation were determined in an anechoic chamber. In order to approximate diffraction conditions around the measurement microphone to real conditions around the subject's head, the measurement microphone (condenser microphone B & K 1/4" 4135) was mounted in an artificial head.

3.3. Results of the objective investigations

The results of the objective investigations are presented in Table 1. Upon analysis of these results the following can be stated:

1) the power coefficient of the initial transient M_1 and the coefficient D of the transient characteristic of the loudspeaker systems 2 and 4 differ from the values of the other,

2) the duration of the final transient of the loudspeaker systems 1, 2 and 4 differ from the values obtained for the loudspeaker systems 3 and 5,

3) the value of the transient characteristic deviation of the loudspeaker system 5 significantly exceeds those of the other systems.

Table 1. Objective parameters of loudspeaker systems.

PARAMETER	LOUDSPEAKER SYSTEM				
	1	2	3	4	5
Coefficient D (dB)	15.5	18.1	13.6	17.6	14.0
Frequency characteristic deviation (dB)	2.78	2.66	3.24	2.10	1.87
Transient characteristic deviation (dB)	4.82	3.03	4.91	3.94	7.23
Duration of initial transient (ms)	2.77	1.74	2.21	4.08	3.03
Duration of final transient (ms)	6.54	6.26	3.29	6.40	4.76
Power coefficient of initial transient	0.96	0.91	0.95	0.92	0.96
Power coefficient of final transient	0.11	0.09	0.08	0.12	0.10

4. Conclusion

The attempt to find significant causes (within the physical parameters of the loudspeaker systems) contributing to the occurrence of differences in the subjective evaluation of the sound emitted by a loudspeaker system seems to be successful. It has been found that the amplitude characteristic affects the *sharpness, fullness* and *spaciousness* of the sound and the phase characteristic affects the *fullness* and *spaciousness* of the sound. A simple correlation between the objective evaluation and the subjective parametric evaluation as well as between the objective evaluation and the subjective overall evaluation has been found to determine the relation between objective and subjective evaluations. The value of the coefficient D of transient characteristic and the power coefficient of the initial transient M_1 are the objective parameters which differentiate investigated loudspeaker systems (2, 4 and 1, 3, 5); as a result of the correlation analysis it can be proved that the *fullness* and *spaciousness* are the attributes responsible for the differentiation of the investigated loudspeaker systems. On the other side, a slight correlation between the duration of the initial transient and *sharpness* exists. It has been also shown that the influence of the frequency and phase characteristic depends on the test signal, especially for the white noise signal.

A detailed analysis of the results of the subjective evaluation of transducers showed that the subjective evaluation of sounds obtained was decisively influenced by the work of the transducers in transient states.

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