ARCHIVES OF ACOUSTICS
12, 3-4, 251-272 (1987)

THE PROBLEM OF CHANGES IN THE STRUCTURE OF A SOUND PROPAGATING IN A ROOM IN THE ASPECT OF MULTIDIMENSIONAL SPACE

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A change in the amplitude-frequency structure of sound in a room is a complex physical phenomenon depending on a number of acoustic properties of the interior. The essence of this change consists in the influence of the acoustic parameters of the room on the spectral-temporal course of the sound propagating in it.

The starting point of the undertaken studies was to represent the changes in the sound structure in the room based on the relations occurring between the elements of two sets, *P* and *S*. All the possible acoustic states of the room were subordinated to the elements of the set *P*, thus gaining the so-called space of states. On the other hand, all the possible changes in the sound structure were subordinated to the elements of the set *S*, thus achieving the so-called space of the signal structure. Analysis of the relation occurring between these two spaces showed that physical changes in the sound structure in a room could be mapped in a space of subjective sensations with coordinates being the corresponding psychoacoustic quantities. Such a mapping can be an important step towards the determination of the common plane of objective and subjective evaluations of the acoustic quality of a room, which is still looked for in the problems of room acoustics.

1. Introduction

The analysis of changes in the structure of a sound propagating in a room ([1]), which was the object of a detailed study in paper [1] made it possible to gain better knowledge of the "interaction mechanism" of exerted by its acoustic parameters on the spectral structure of the registered sounds. In a general case, this effect can be considered theoretically on the basis of relations occurring between the elements of two sets, *P* and *S*. The essence of these considerations is based on the following conception:

All the possible „acoustic states" of the room are assigned to the elements

([1]) The notion of changes in the sound structure in a room is understood to be a change of the value of the physical parameters of this sound caused by the acoustic properties of the interior.

$p_1, p_2, \ldots, p_r$ of the set P ([2]). The notion of the acoustic state of a given room is understood to mean a set of real numbers $x_1, x_2, \ldots, x_n$ (namely, the values of the parameters of the state) describing its acoustic properties.

All the possible changes in the sound structure related to particular acoustic states of the room can be assigned to the elements $s_1, s_2, \ldots, s_r$ of the set S. Let the character and the form of these changes be determined by the set of real numbers $y_1, y_2, \ldots, y_n$. On the other hand, the function F connecting each element of the set S with an element of the set P describes in quantitative terms changes in the signal structure which occur for a given acoustic state of the room. If it were possible to assume that these sets are equivalent, it would then be possible to predict, on the one hand, the character of changes in the sound structure for known values of the parameters of an acoustic state, or, also, on the other hand, to evaluate its acoustic properties on the basis of measurements of the quantity of changes in the sound structure registered in this room. However, in practice this problem is a very complex one, above all because of the difficulties in determining the set of all possible acoustic states of the room and the set of the occurring changes in the signal, and in determining the one-to-one and only one-to-one relation between these sets. So far it has not been considered in this approach in the literature.

Considering this problem, the present study consists of two principal parts. The first contains theoretical considerations, involving a certain conception of the representation of changes in the sound structure in a room in the aspect of a multidimensional space. An attempt was made to use this conception in the other part of this study, representing the results of initial experimental studies in a simplified three-dimensional space of changes in the spectral structure of the transient courses of chosen speech sounds propagating in the room.

2. The space of the acoustic states of the room

As was mentioned above, the acoustic state of a room can be defined by giving a set of the values of certain parameters $x_i (i = 1, 2, \ldots, n)$, describing its acoustic properties.

This set of parameters should meet the following assumptions.

An arbitrary parameter x_i can vary irrespective of the changes of parameter x_k $(i \neq k)$. This means that these parameters should be independent variables. The set of such parameters is a minimal system, since it does not contain redundant elements, which are insignificant in a general evaluation of the acoustic state of the room. Moreover, the set of the parameters of the acoustic state of the room should be complete.

([2]) In this study it is assumed that a given room can take different so-called "acoustic states", as a result, e.g., of applying appropriate acoustic adaptations, various ways of its being filled by the audience etc.

As the set of the three numbers x_1, x_2, x_3 can be considered as a vector given in a three-dimensional space, so, analogously, the set of n numbers $x_1, x_2, \ldots, x_n$, can be considered a vector in a n-dimensional space ([3]). This means that the acoustic state of the room can be regarded as a vector quantity pre-determined in a n-dimensional space of states, namely that a certain point in this space corresponds to each acoustic state of the room. Let us now consider what relations occur between the elements of this space. Let us consider the two acoustic states of the room, p_l and p_m, and determine the difference between them. Since two points in a n-dimensional space correspond to these states, the determination of the difference between these states is reduced to the estimation of the distance $d(p_l, p_m)$ between these points, which, in a n-dimensional space, is expressed by the following formula

$$d(p_l, p_m) = \sqrt{\sum_{i=1}^{n} (x_i^{(l)} - x_i^{(m)})^2}. \tag{1}$$

Thus, this gives a distance which is a function which subordinates to each pair of elements (states) p_l and p_m of the set P a certain positive number $d(p_l/p_m)$. This set is called the metric space, while the function $d(p_l, p_m)$ defines the metric of this space.

Formula (1) can also be written in a more general form, in the following form:

$$d_k(p_l, p_m) = \sqrt[k]{\sum_{i=1}^{n} |x_i^{(l)} - x_i^{(m)}|^k}, \tag{2}$$

where $k = 1, 2, 3, \ldots$

If $k = 2$, formula (2) is obtained for, on the other hand, , $k = 1$

$$d(p_l, p_m) = \sum_{i=1}^{n} |x_i^{(l)} - x_i^{(m)}|.$$

Assuming that the value of the coefficient $k \to \infty$, it can be seen that the estimation of the distance between the points (acoustic states of the room) is basically reduced to the determination of the difference between the coordinates of just one, with axis of the n-dimensional space, along which these points are farthest each other, namely

$$d_\infty(p_l, p_m) \to \max |x_i^{(l)} - x_i^{(m)}|, \tag{3}$$

where $i = 1, 2, \ldots, n$.

The difference between two acoustic states of a room can also be evaluated on the basis of the value of the angle between the state vectors $\mathbf{p}_l$ and $\mathbf{p}_m$.

Since the scalar product of two state vectors is equal to

$$\mathbf{p}_l \cdot \mathbf{p}_m = x_1^{(l)} \cdot x_1^{(m)} + x_2^{(l)} \cdot x_2^{(m)} + \ldots + x_n^{(l)} \cdot x_n^{(m)} = |\mathbf{p}_l||\mathbf{p}_m| \cos\varphi,$$

([3]) The notion of space is understood to be a set of arbitrary elements between which certain geometrical relations were established.

hence

$$\cos\varphi = \frac{x_1^{(l)}\cdot x_1^{(m)} + x_2^{(l)}\cdot x_2^{(m)} + \ldots + x_n^{(l)}\cdot x_n^{(m)}}{\sqrt{\sum_{i=1}^{n}(x_i^{(l)})^2}\sqrt{\sum_{i=1}^{n}(x_i^{(m)})^2}}. \quad (4)$$

According to formula (4), the greater the value of $\cos\varphi$, the smaller the difference between two acoustic states of the room. The extension of the set of points (the acoustic state of the room) in the considered the n-dimensional space can be expressed by means of the variance σ_d^2 in the following form

$$\sigma_d^2 = \sum_{i=1}^{n}\frac{1}{z}\sum_{i=1}^{z}(x_i^{(l)} - \bar{x}_i^{(l)})^2 = \sum_{i=1}^{n}\delta_i^2,$$

where δ_i — is the standard deviation.

It can be seen that for a pre-determined i, this variance is the sum of the squares of the distances of all points from their common "centre of gravity", determined by an average divided by the number of points, from the n-dimensional space.

The set of acoustic states of a room, expressed by points in a n-dimensional space, can be arranged in a certain way by introducing the notion of the state vector length and the angle between these vectors. As was mentioned previously, each vector of the state $\boldsymbol{p}$, with the coordinates $(x_1, x_2, \ldots, x_n)$, defines the position of the point P in a n-dimensional space with respect to the initial point P_0 with the coordinates $(0, 0, \ldots)$, to which, e.g., the standard acoustic state of the room can be assigned. Therefore, the length of the vector $\boldsymbol{p}$ is, e.g., the number $p \geqslant 0$ determining the distance between the points P_0 and P_m. According to formula (1), this distance can be expressed in the form:

$$d(p_0, p_m) = |\boldsymbol{p}_m| = \sqrt{\sum_{i=1}^{n}(x_i^{(m)})^2}. \quad (5)$$

Applying in turn formulae (2) and (3), one can obtain formula (6), from which it follows that the measure of the length of this vector is its projection with the highest value

$$d_k(p_0, p_m) = |\boldsymbol{p}_m| = \sqrt[k]{\sum_{i=1}^{n}(x_i^{(m)})^k} = \max|x_i^{(m)}|, \quad (6)$$

for $k \to \infty$

3. The space of the acoustic signal structure

In a general case, it can be assumed that the set of resultant changes in the acoustic signal structure is a mapping of the set of acoustic states of the room. It was already mentioned previously that a point in a n-dimensional space of the structure can be subordinated to each change in the signal structure, and it is possible to subordinate each point in a n-dimensional space of states to each acoustic state of the room. To determine exactly the „interaction mechanism" of acoustic parameters of the room and the form of the signal, the mapping of the space of the acoustic states of the room and the space of the structure of the signal must be on a one-to-one basis, i.e., only one point in the space of the signal structure should correspond to each point in the space of states. Assuming the similarity between the features of the space of states and that of the signal structure, in analyzing the features of the space of the signal structure, it is possible to apply the formulae given in chapter 1, changing only the physical sense of some of the notation. On the other hand, it should be borne in mind that then these formulae would describe changes in the sound structure only for the steady state, where it can be assumed that these changes are only static in nature. For this state

$$ds_l/dt = 0 \quad \text{where} \quad \mathbf{s}_l = [y_1^{(l)}(x_i^{(l)}), y_2^{(l)}(x_i^{(l)}), \ldots, y_n^{(l)}(x_i^{(l)})]$$

$$ds_l = \frac{\partial s_l}{\partial y_1^{(l)}} dy_1^{(l)} + \frac{\partial s_l}{\partial y_2^{(l)}} dy_2^{(l)} + \ldots + \frac{\partial s_l}{\partial y_n^{(l)}} dy_n^{(l)}; \quad l = 1, 2, \ldots, r, \tag{7}$$

where

$$dy_i^{(l)} = \frac{\partial y_i^{(l)}}{\partial x_1^{(l)}} dx_1^{(l)} + \frac{\partial y_i^{(l)}}{\partial x_2^{(l)}} dx_2^{(l)} + \ldots + \frac{\partial y_i^{(l)}}{\partial x_n^{(l)}} dx_n^{(l)}; \quad i = 1, 2, \ldots, n.$$

On the other hand, in transient states of sound, namely in their growths or decays, the representation of changes in the signal structure in a n-dimensional space becomes much more complex in view of the nonstationary character of this process. It is then that it is necessary to assume the dynamic character of these variations, related to the time-continuous change in the position of the vector $\mathbf{s}_l$ in a n-dimensional space. In a mathematical approach, this could be expressed in the following way,

$$\frac{ds_l}{dt} = \frac{\partial s_l}{\partial t} + \frac{\partial s_l}{\partial y_1^{(l)}} \frac{\partial y_1^{(l)}}{\partial t} + \frac{\partial s_l}{\partial y_2^{(1)}} \frac{\partial y_2^{(l)}}{\partial t} + \ldots + \frac{\partial s_l}{\partial y_n^{(l)}} \frac{\partial y_1^{(n)}}{\partial t}. \tag{8}$$

Therefore to determine the rate of change in signal structure in its transient state, it is necessary to known the already present change at the moment t and the change at the moment $t+dt$ expressed by the vector $\mathbf{s}+d\mathbf{s}$, with the coordinates $(y_1+dy_1, y_2+dy_2, \ldots, y_n+dy_n)$. For a finite time increment Δt, the change in the value of the parameters in the signal structure $y_i = y_i(t)$ can, from formula (2), be also expressed in the following way:

$$\Delta d_2(t) = \sqrt{\sum_{i=1}^{n} [y_i(t+\Delta t) - y_i(t)]^2}, \tag{9}$$

where

$$\Delta y_i = y_i(t+\Delta t) - y_i(t).$$

Similarly, the rate of changes in the signal structure in its transient state can be expressed by changes in the cosine of the angle between the respective vectors, becoming, from formula (4),

$$V_\varphi = \lim_{\Delta t \to 0} \frac{\Delta \cos\varphi}{\Delta t} = \frac{y_1(t)\,y_1(t+\Delta t) + y_2(t)\,y_2(t+\Delta t) + \ldots + y_n(t)\,y_n(t+\Delta t)}{\Delta t\,|s(t)|\,s(t+\Delta t)|}.$$

It is interesting to note in addition, that it follows from the research presented in study [1] that a change in the signal structure in a room depends essentially not only on the considered fragment of a time signal, but also on the position of the measurement point (see Figs. 4–6), which was not included in the theoretical part of the present study, making the considered problem even more complex.

To find certain qualitative relations between the space of acoustic states of the room and the space of the signal structure, it is essential to determine the dimensions of this space, corresponding to the establishing of the multi-dimensionality of the signal. On the assumption that it is periodic, the multi-dimensionality of the signal can be determined considering either its amplitude spectrum expressed by a set of Fourier series coefficients or a set of instantaneous values of time function. Having Fourier n-coefficients, each of which is a complex number containing two real numbers, it is possible to obtain altogether $n = 2k$ real numbers. From the theorem of the independence of the Fourier coefficients, and also the independence of their imaginary and real parts, it can be seen that from the amplitude spectrum of the periodic signal, one can obtain $2k$ independent parameters. These parameters can be considered as the coordinates of the multi-dimensional space of the signal structure. Just as from the signal with a duration T, with a spectrum limited by the highest frequency f_{max}, it is possible, as a result of sampling this signal at Δt intervals equal at least to $\Delta t \geqslant 1/(2f_{max})$, to obtain $N = T/dt \leqslant 2f_{max}$ independent time samples, which can also be treated as the coordinates of a multi-dimensional space of the signal structure. A different position of the vector in the space of the signal structure corresponds to each change in the signal structure caused by a change in the acoustic state of the room. The magnitude of this change can be determined from the distance between two points in the space of the signal structure, from formula (5), or on the basis of the value of the cosine of the angle between the two vectors $\boldsymbol{s}$ and $\boldsymbol{s}_0$, determining a change in the signal structure with respect to a signal compared according to formula (4).

At this point, it is interesting to mention that both the space of acoustic states of a room and the space of the signal structure in the present study do not concern the whole room, but a specific measurement point.

4. The relation between the space of acoustic states of a room and the space of the signal structure

On the basis of the considerations presented above, it can be stated in general that the space of acoustic states of the room shapes the space of the signal structure, or, in other words, the space of acoustic states of the room influences the space of the signal structure, causing as a result a change of its acoustic parameters. Hence, the room can be regarded as a "functional operator" of the vector of the state **p** with the coordinates $(x_1, x_2, \ldots, x_n)$ into a vector defining a change in the sound structure **s** with the coordinates $(y_1, \ldots, y_2, \ldots, y_n)$

$$s = F(p) \tag{10}$$

From the above relation, each change in the parameters of the received signal is related to a change in the parameters of the acoustic state of the room. By writing formula (10) in the form of a set of equations in which n variables of the parameters of the vector of the acoustic state of the room **p** corresponds to each parameter of the vector of the signal structure **s**, it is obtained that

$$\begin{aligned} y_1 &= F_1(x_1^{(1)}, x_2^{(1)}, \ldots, x_n^{(1)}) \\ y_2 &= F_2(x_1^{(2)}, x_2^{(2)}, \ldots, x_n^{(2)}) \\ &\ldots\ldots\ldots\ldots \\ y_n &= F_n(x_1^{(n)}; x_2^{(2)}, \ldots, x_n^{(n)}). \end{aligned} \tag{11}$$

It is possible to determine these dependences more exactly by another change in the parameters of the acoustic state of the room and measuring the parameters describing a change in the signal structure, namely

$$dy_1 = \frac{\partial y_i}{\partial x_1^{(i)}} dx_1^{(i)} + \frac{\partial y_i}{\partial x_2^{(i)}} dx_2^{(i)} + \ldots + \frac{\partial y_i}{\partial x_n^{(i)}} dx_n^{(i)}; \quad i = 1, 2, \ldots, n. \tag{12}$$

The value of the partial derivatives $\partial y_i / \partial x_i^{(i)}$ determines the "sensitivity" of changes in the signal structure to a change in the parameter of the acoustic state of the room.

For the set of equations (11) to be solvable, the functions F_i — should be continuous differentiable in terms of $x_n^{(i)}$. A necessary condition for the solution of the set of equations is the value of determinant (13) which is different from zero,

$$\begin{vmatrix} \frac{\partial F_1}{\partial x_1^{(1)}} & \frac{\partial F_1}{\partial x_2^{(1)}} & \cdots & \frac{\partial F_1}{\partial x_n^{(1)}} \\ \frac{\partial F_2}{\partial x_1^{(2)}} & \frac{\partial F_2}{\partial x_2^{(2)}} & \cdots & \frac{\partial F_2}{\partial x_n^{(2)}} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial F_n}{\partial x_1^{(n)}} & \frac{\partial F_n}{\partial x_2^{(n)}} & \cdots & \frac{\partial F_n}{\partial x_n^{(n)}} \end{vmatrix} \neq 0. \tag{13}$$

The basic task in looking for the relation between the space of acoustic states of the room and the space of the signal structure is to determine the form of the function F in formula (11) describing the relation in general. Assuming in the first approximation the function F to be linear, the set of equations (11) can be written in the form

$$\begin{aligned} y_1 &= a_1^{(1)}x_1^{(1)}+a_2^{(1)}x_2^{(1)}+\ \dots\ +a_n^{(1)}x_n^{(1)} \\ y_2 &= a_1^{(2)}x_1^{(2)}+a_2^{(2)}x_2^{(2)}+\ \dots\ +a_n^{(2)}x_n^{(2)} \\ &\dots\dots\dots\dots\dots\dots\dots\dots \\ y_n &= a_1^{(n)}x_1^{(n)}+a_2^{(n)}x_2^{(n)}+\ \dots\ +a_n^{(n)}x_n^{(n)} \end{aligned} \tag{14}$$

It is necessary to note that the set of equations (14), when written in form (15), can serve to determine the parameters of the acoustic state of the room on the basis of the measured parameters of changes in the signal structure

$$\begin{aligned} x_1 &= b_1^{(1)}y_1^{(1)}+b_2^{(1)}y_2^{(1)}+\ \dots\ +b_n^{(1)}y_n^{(1)} \\ x_2 &= b_1^{(2)}y_1^{(2)}+b_2^{(2)}y_2^{(2)}+\ \dots\ +b_n^{(2)}y_n^{(2)} \\ &\dots\dots\dots\dots\dots\dots\dots\dots \\ x_n &= b_1^{(n)}y_1^{(n)}+b_2^{(n)}y_2^{(n)}+\ \dots\ +b_n^{(n)}y_n^{(n)} \end{aligned} \tag{15}$$

Analyzing the set of equations (14), it can be seen that a change in successive parameters of the acoustic state of the room should involve a specific change in the parameters of the signal. The coefficients a_i^j which occur in these equations can be determined by a change in the parameters x_i – by the value Δx_i for the other parameters of the acoustic state of the rom being stationary.

The set of equations (14) can be solved if determinant (16) is different from zero

$$\begin{vmatrix} a_1^{(1)}a_2^{(1)} \dots a_n^{(1)} \\ a_1^{(2)}a_2^{(2)} \dots a_n^{(2)} \\ \dots\dots\dots \\ a_1^{(n)}a_2^{(n)} \dots a_n^{(n)} \end{vmatrix} \neq 0. \tag{16}$$

In the case the i-th row of the matrix of coefficients consists of zero terms, this means that the parameter of the signal y_i does not depend on any of the parameters of the acoustic state of the room. With the zero value of the i-th column the parameter of the state of the room x_i does not influence any of the parameters of the signal. On the other hand, if the terms of two rows or two columns differ with a constant coefficient, this means that there is a linear dependence between two parameters of the signal or two parameters of the acoustic state of the room.

5. The determination of the acoustic states of the room on the basis of a classification of changes in the signal structure

In a general case, all the possible acoustic states of the room can be divided into a number of classes. This classification can be carried out in various ways, nevertheless, considering its practical aspect, it would be convenient to perform it, e.g., from the point of view of chosen criteria of subjective evaluation of the acoustic quality of the room. The set of the possible acoustic states of the room could then be divided into two basic classes: the class of the states of the room which is satisfactory and their class which is unsatisfactory from the point of view of these criteria. Such a division could be made by marking a threshold value x_{0i} (or a few threshold values) on each coordinate axis of a multi-dimensional space of acoustic states of the room. A plane perpendicular to each axis, crossing the point x_{0i}, would then separate the space into two regions or a correspondingly greater number of them, determining the satisfactory or unsatisfactory acoustic states of the room. It is possible to subordinate an appropriate classification of changes in the signal structure to a classification of acoustic states of the room performed in this way, which is essential from the practical point of view. The threshold values of these changes plotted on the coordinate axes of the multi-dimensional space of the signal structure could be determined from psychoacoustic investigations.

In real conditions the precise description of the acoustic state of the room requires considering a very large number of the parameters of the state, which would be very troublesome and tedious in practice. On the other hand, this problem can be approached in a slightly different way. Namely, instead of describing the acoustic state of the room by the set of parameters $x_1, x_2, \dots, x_n$, all the acoustic states of the room could be divided into t class $c_l(1 = 1, 2, \dots, t)$ and a certain representative state $p_l = (x_1^{(l)} x_2^{(l)}, \dots, x_n^{(l)})$ could be chosen for them. Thus, the determination of the measured acoustic state of the room would consist in finding to which class c_l the studied state $\boldsymbol{p}$ belongs, requiring comparison of this state and the representative $\boldsymbol{p}_l$ of each class. On the basis of the relation between the space of acoustic states of the room and the space of the signal structure, one can note that the classification of acoustic states of the room is equivalent to the classification of changes in the signal structure. This means that, instead of the states $\boldsymbol{p}_l = (x_1^l, x_2^l, \dots, x_n^l)$ representative of each class, it is possible to assume the vectors of changes in the signal structure $s_l = (y_1^{(l)}, y_2^{(l)}, \dots, y_n^{(l)})$ corresponding to these states, involving the transformation of the problems of the classification of acoustic states of the room into the field of psychoacoustic investigations.

Let us assume that, on the basis of certain psychoacoustic criteria, certain classes of changes in the signal structure were established to which the corresponding vectors $s_l = (y_1^{(l)}, y_2^{(l)}, \dots, y_n^{(l)})$, where $l = 1, 2, \dots, t$, are subordinated. A certain change in the signal structure $\boldsymbol{s}_1 = (y_1^{(l)}, y_2^{(l)}, \dots, y_n^{(l)})$ measured for a given acoustic state of the room, can be classified into one of the established classes represented by the vectors s_l from the determined distance between points in the space of the signal structure, or the value of the cosine of the angle contained between the vectors of changes in the signal structure.

According to the formulae given in chapter 1, the distance between points in a n-dimensional space can be calculated by applying the formulae

$$d(s_1, s_l) = \sqrt{\sum_{i=1}^{n} (y_i^{(1)} - y_i^{(l)})^2}, \tag{17}$$

or

$$d_\infty(s_1, s_l) = \max |y_i^{(1)} - y_i^{(l)}|, \tag{18}$$

for

$$1 \leqslant i \leqslant n; \quad 1 \leqslant l \leqslant t.$$

It can be seen from (17) that the difference between the signals: the reference signal, representative of a given class, and the signal in question, is equal to the standard deviation of all the parameters of the two signals. In turn, according to (18), the difference between the reference signal and one in question is determined by the maximum value of the absolute difference between the parameters of these signals.

The vector of changes in the signal structure $s_1 = (y_1^{(1)}, y_2^{(1)}, \ldots, y_n^{(1)})$ can be classified into one of the classes represented by the vectors s_l, as was already mentioned, also by calculating the value of the cosine of the angle contained between the respective vectors (see(4)). The greatest value of the cosine of this angle makes it possible to include the vector s_1 representing a given class of changes in the signal structure.

In determining the acoustic state of the room on the basis of the classification of changes in the signal structure, it is necessary to note the presence of external interferences generating into the room. These interferences could be the cause of error in classification, as the vector of changes in the signal structure s, corresponding to a given acoustic state of the room p, would contain the additional component s_e related to the occurrence of the interferences e, which could be written in the following way:

$$s + s_e = F(p, e). \tag{19}$$

Moreover, in the above considerations it was assumed that the acoustic state of the room is fully described by n parameters $x_1, x_2, \ldots, x_n$, apart from which there are no other parameters characterizing the acoustic properties of the room. This assumption is not entirely valid, since theoretically many parameters can be attributed to each room. However, in practice only a few parameters, are assumed, being regarded as the most characteristic parameters describing the acoustic state of the room. Therefore, hence, two acoustic states of the room which are considered equal in terms of the set of the assumed parameters $x_1, x_2, \ldots, x_n$ need not to be the same, since they can differ in the values of the parameters $x_{n+1}, x_{n+2}, \ldots, x_{n+\alpha}$

which are not included in this set. As a result of this changes the in the signal structure, measured parameters for these two "identical" acoustic states of the room, are not exactly the same, namely

$$y_i + \Delta y_i = F_i(x_1^{(i)}, x_2^{(i)}, \ldots, x_n^{(i)}, x_{n+1}^{(i)}, x_{n+2}^{(i)}, \ldots, x_{n+\alpha}^{(i)}$$

moreover y_1 is the parameter of a signal corresponding to the state of the room $\boldsymbol{p}_l$ if $x_{n+1}^{(i)}, x_{n+2}^{(i)}, \ldots, x_{n+\alpha}^{(i)} = 0$, or more generally

$$s + s_e = F'(\boldsymbol{p}, \boldsymbol{p}', \boldsymbol{e}).$$

where $\boldsymbol{e}$ is the vector accounting for the value of the external interferences.

6. The results of preliminary experimental research

Apart from the theoretical considerations presented above, which constitute the essential part of the research, within the framework of the present study, preliminary experimental investigations were also undertaken. It is necessary to note that the results of these investigations are rather reconaissance in character, being an attempt to represent a change in the spectral envelope of a sound in the room in the so-called physical and subjective space of changes in the signal structure. The experimental research on changes in the amplitude-frequency structure of the acoustic signal propagating in rooms with different acoustic properties was discussed in detail in study [1].

The range of these studies included the following elements:
– the determination of changes in the spectral structure of a sound, successively in its growth process, the steady state and the decay process, for different acoustic parameters of the room; and
– the determination of changes in this structure depending on the spatial configuration of rooms shaped as acoustically coupled ones.

The studies were carried out in a special room permitting the shaping of four types of rooms with different acoustic properties. The applied measurement equipment made it possible to register and process in the analogue-digital way any time fragment, chosen from the analyzed course, having an essential significance for the study of its transient states (the growth, the decay).

The object of the study were the sounds of two natural vowels „a" and „e", a combination of these vowels in the word „rzeka" and a white noise signal, reproduced in a room with diversified acoustic properties. For each of these sounds, three characteristic time fragments were distinguished, representing successively the process of their growth the steady state and the decay process which were then subject to detailed spectral analysis by means of the Fast Fourier Transform (the FFT method), implemented on an Eliot 4130 computer. The ample experimental material presented in study [1] was carefully analyzed quantitatively and qualitatively over the range of which a number of quantitatives were determined, characterizing the amplitude-frequency changes in the harmonic and formant structures of the studied sounds in the range of their particular time fragments.

Figs. 1–3 present, as an example, for one of the analyzed sounds (the vowel „a"), computer records of chosen time fragments: of the growth process, the steady state and the decay process of this sound, and the corresponding spectra gained by the FFT method. These courses were obtained in three rooms different acoustically, namely in a room with properties close to those of anechoic chamber, denoted further as A, with the reverberation time $T_A = 50$ ms; in the so-called damped room, denoted as B, with the reverberation time $T_B = 250$ ms; and in an undamped room, denoted as C, with the reverberation time $T_C = 1 s$. A preliminary qualitative analysis of these spectra indicates that as a result of the influence of the acoustic parameters of the room different in terms of their value, on the form of the signal it is possible to note different changes in its spectral structure, expressed in a change in the amplitude relations between successive harmonics, a change in the half-width of the formants etc.

As can be seen, the quantity of these changes depends on the time section of the analyzed signal namely, the growth, steady state and the decay and on the acoustic properties of the room. A detailed quantitative analysis of changes in the spectral structure of this sound, and other signals too, which were mentioned above, depending on the acoustic properties of the considered rooms, the choice of the measurement point, were presented in study [1].

On the basis of the conception, given in the chapter 2, of representing changes in the sound structure in the aspect of the multi-dimensional space, in keeping with expression (5), the so-called vectors of changes in the signal structure were determined for the considered speech sounds, respectively in their growth process, the steady state and the decay process. The lengths of these vectors map the resultant difference between the sound spectra recorded in a room with properties close to those of an anechoic chamber, treated as reference spectra and the spectra of this sound recorded at a given measurement point P_x of a given room respectively for the growth process the steady state and the sound decay process

$$d(P_0, P_x)|\boldsymbol{p}_x| = \sqrt{\sum_{i=1}^{n} (L_i^{(P_0)} - L_i^{(P_x)})^2}, \tag{20}$$

where $L_i^{(P_0)}$ and $L_i^{(P_x)}$ are the acoustic pressure levels determined in the i-th frequency band, respectively for the reference spectrum and the spectrum measured at a chosen measurement point in a given room and n is the total number of frequency bands.

A similar conception of the quantitative evaluation of the spectral differences in the aspect of a multi-dimensional space was presented in study [3], concerned with the problems of changes in the sound timbre in depending on the position of the measurement point.

Assuming further that the essential information on the analyzed sound is contained in the bands of the first three formants, the n-dimensional space of the signal structure was limited to a three-dimensional space, subordinating, in keeping

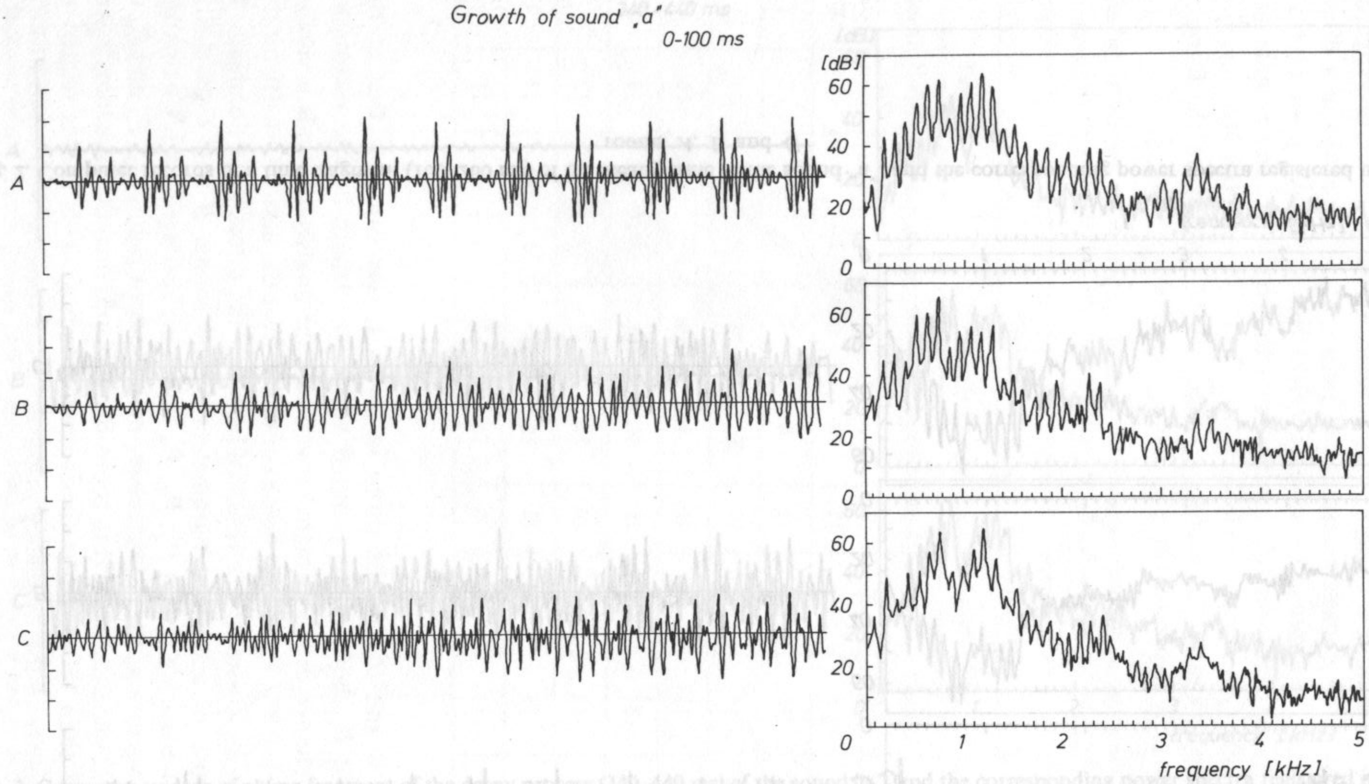

Fig. 1. Computer records of a time fragment of the growth (0–100 ms) of the sound "a", and the corresponding power spectra registered in three rooms *A*, *B* and *C*

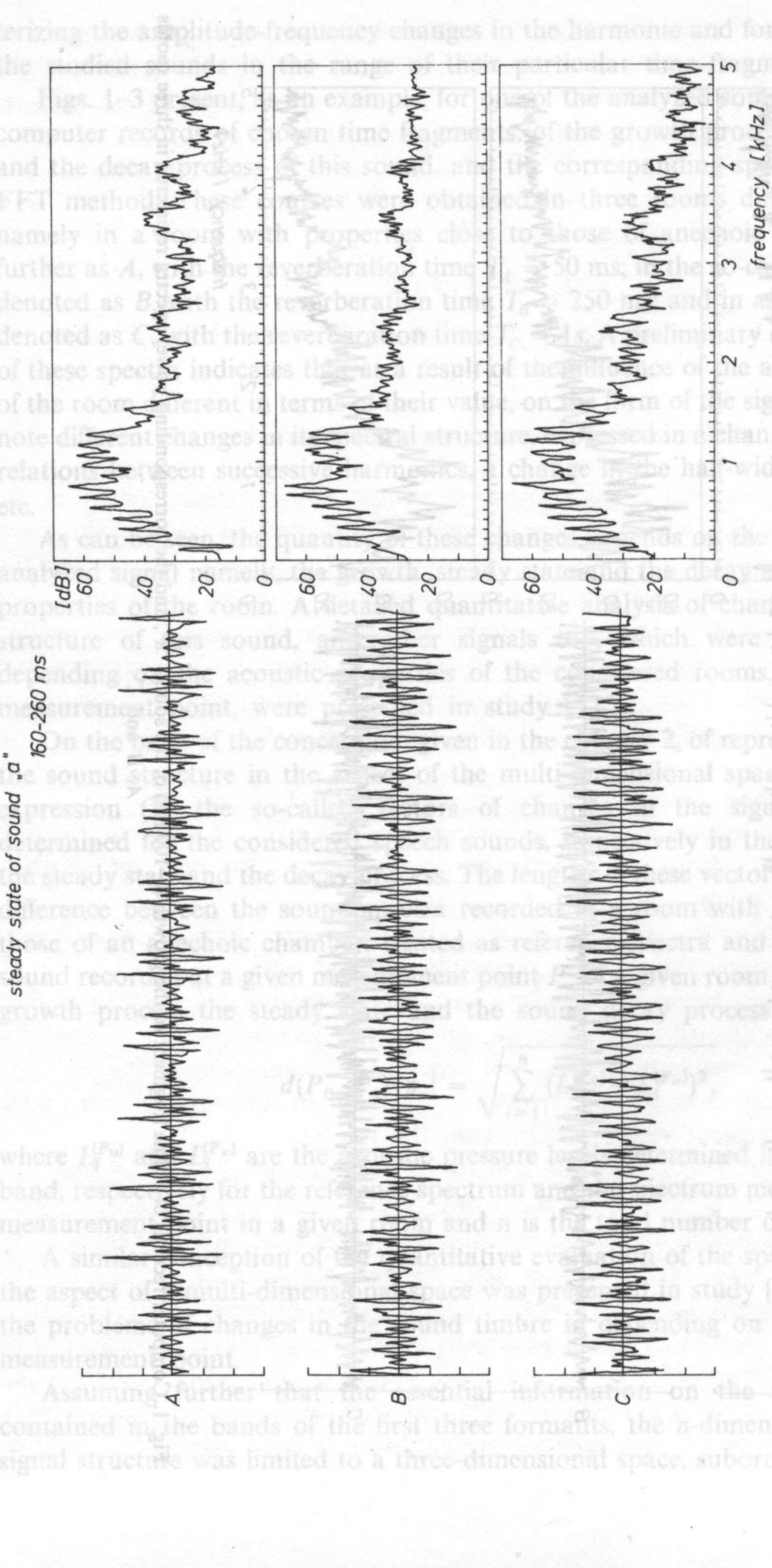

Fig. 2. Computer records of a time fragment (160–260 ms of the steady state of the sound "a" and the corresponding power spectra registered in three rooms A, B and C

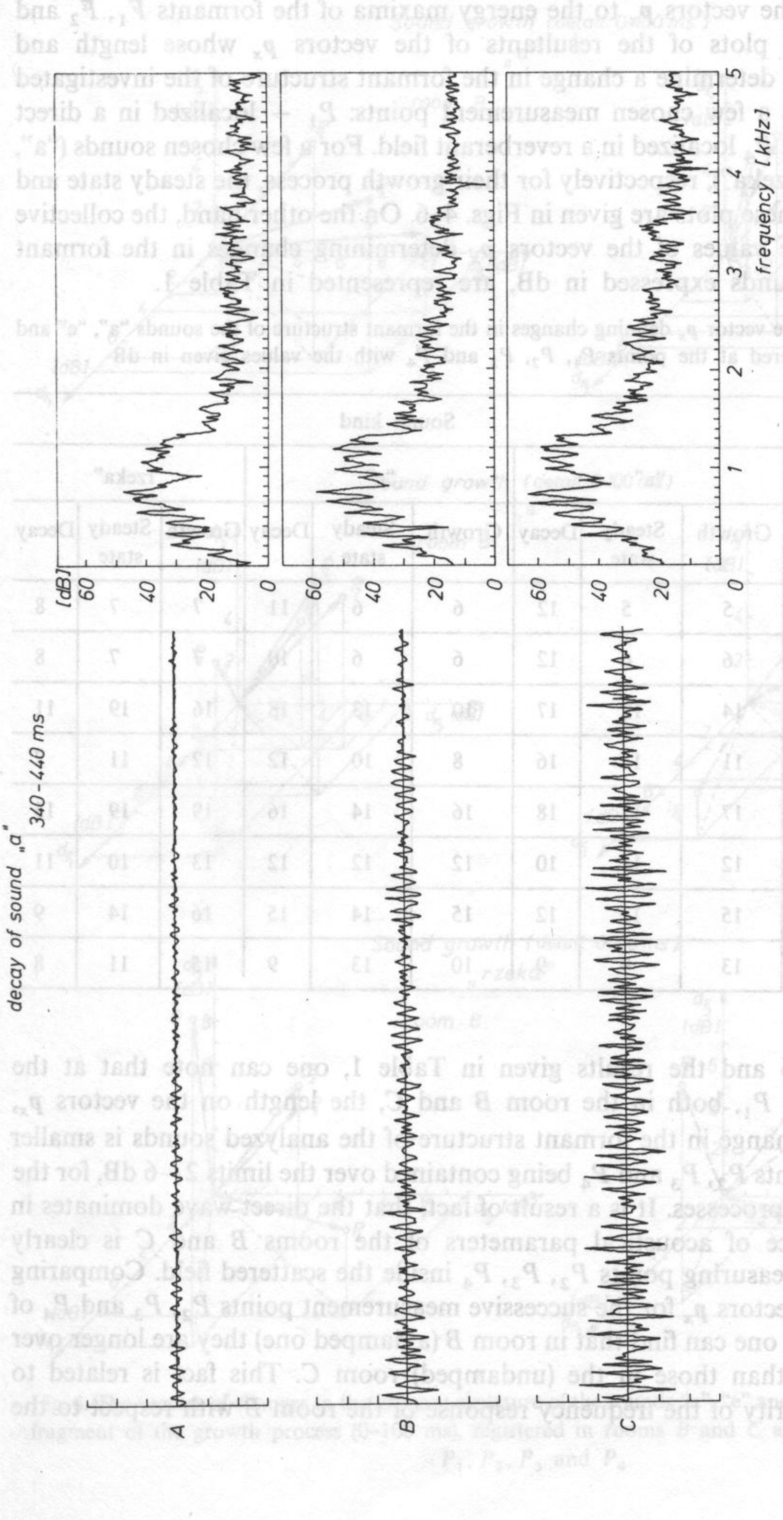

Fig. 3 Computer records of a time fragment of the decay process (340–440 ms) of the sound "a", and the corresponding power spectra registered in three rooms *A*, *B* and *C*

with formula (20), the vectors p_x to the energy maxima of the formants F_1, F_2 and F_3. This way gave plots of the resultants of the vectors p_x whose length and orientation in space determine a change in the formant structure of the investigated sound, registered at a few chosen measurement points: P_1 – localized in a direct field and P_2, P_3 and P_4 localized in a reverberant field. For a few chosen sounds ("a", "e" and the word "rzeka"), respectively for their growth process, the steady state and the decay process, these plots are given in Figs. 4–6. On the other hand, the collective juxtaposition of the values of the vectors p_x determining changes in the formant structure of the sounds expressed in dB, are represented in Table 1.

Table 1. The length of the vector p_x defining changes in the formant structure of the sounds "a", "e" and "rzeka" registered at the points P_1, P_2, P_3 and P_4 with the values given in dB

Vectors of formant structure changes	Room	Sound kind								
		"a"			"e"			"rzeka"		
		Growth	Steady state	Decay	Growth	Steady state	Decay	Growth	Steady state	Decay
p_1	B	5	5	12	6	6	11	7	7	8
	C	6	6	12	6	6	10	7	7	8
p_2	B	14	12	17	10	13	18	16	19	11
	C	11	12	16	8	10	12	12	11	7
p_3	B	17	12	18	16	14	16	19	19	13
	C	12	11	10	12	12	12	13	10	11
p_4	B	15	12	12	15	14	15	16	14	9
	C	13	9	9	10	13	9	15	11	8

From Figs. 4–6 and the results given in Table 1, one can note that at the measurement point P_1, both in the room B and C, the length on the vectors p_x, – determining a change in the formant structure of the analyzed sounds is smaller than that at the points P_2, P_3 and P_4 being contained over the limits 2–6 dB, for the growth and steady processes. It is a result of fact, that the direct wave dominates in this point. Influence of acoustical parameters of the rooms B and C is clearly noticeable in the measuring points P_2, P_3, P_4 inside the scattered field. Comparing the lengths of the vectors p_x for the successive measurement points P_2, P_3 and P_4 of the rooms B and C, one can find that in room B (a damped one) they are longer over the limits 2–8 dB than those in the (undamped) room C. This fact is related to the greater irregularity of the frequency response of the room B with respect to the

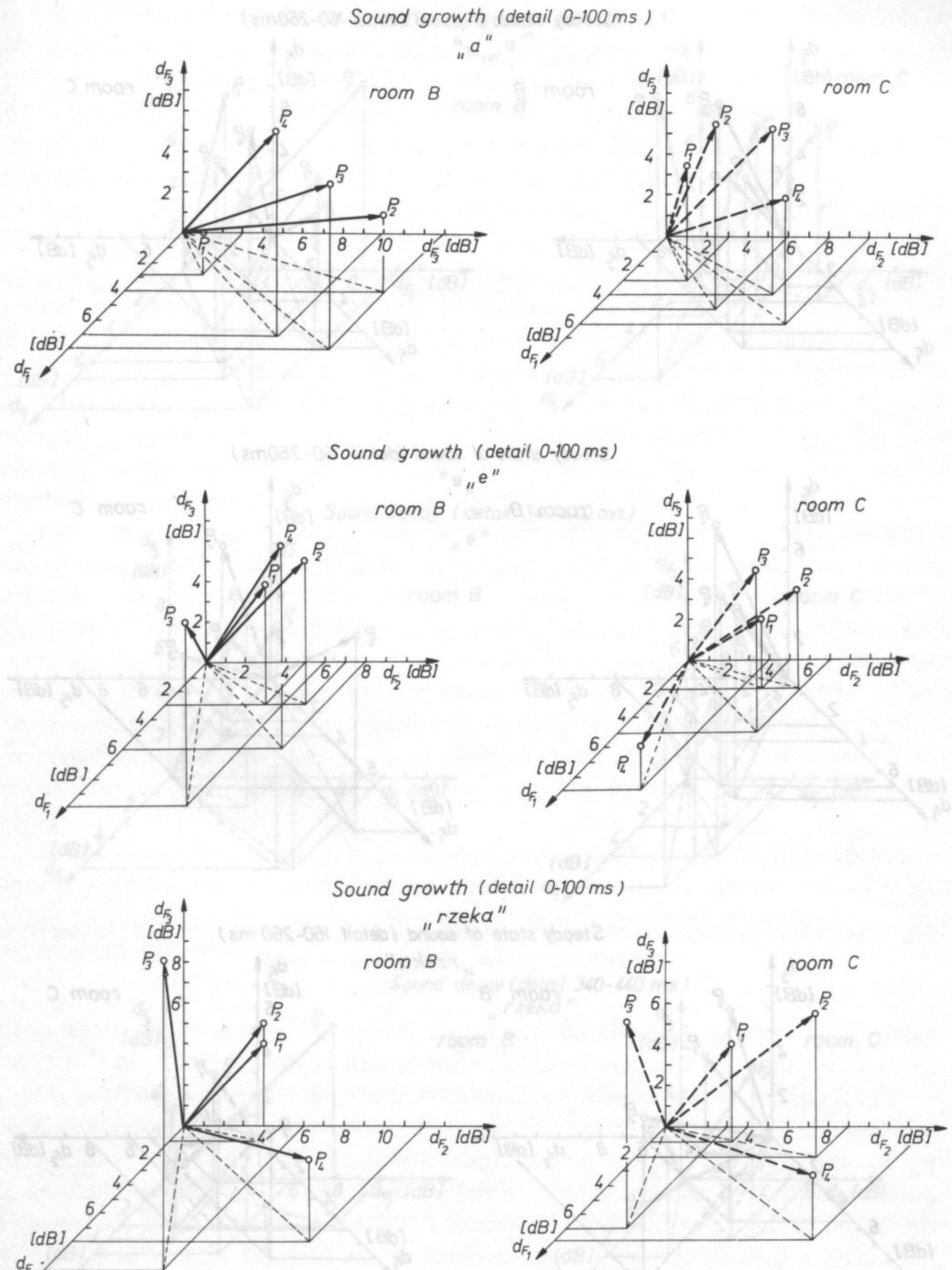

Fig. 4. The vectors of changes in the formant structure of the sounds "a", "e" and "rzeka" for a chosen time fragment of the growth process (0–100 ms), registered in rooms *B* and *C* at the measurement points P_1, P_2, P_3 and P_4

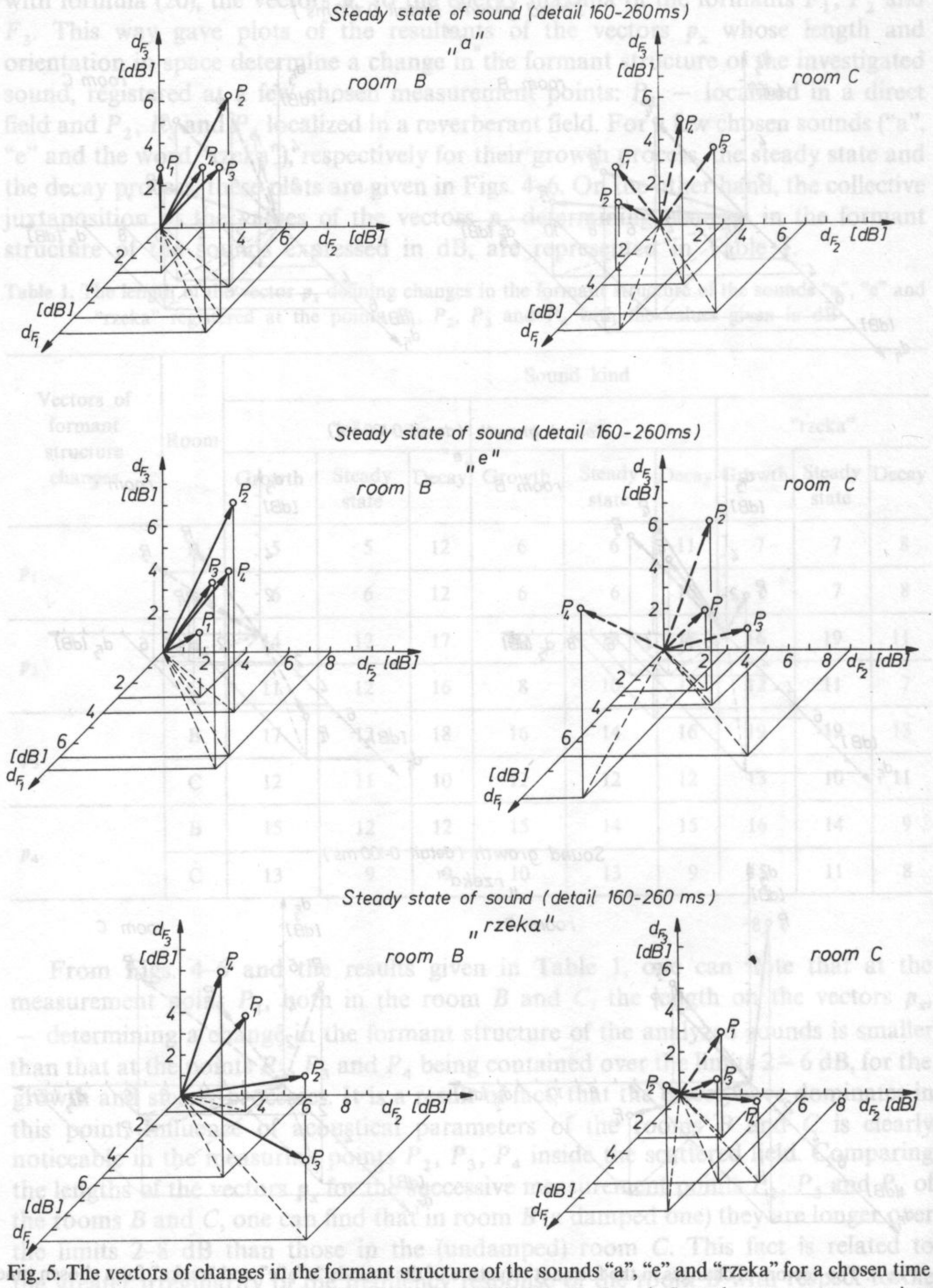

Fig. 5. The vectors of changes in the formant structure of the sounds "a", "e" and "rzeka" for a chosen time fragment of the steady state (160-260 ms), registered in rooms *B* and *C* at the measurement points P_1, P_2, P_3 and P_4

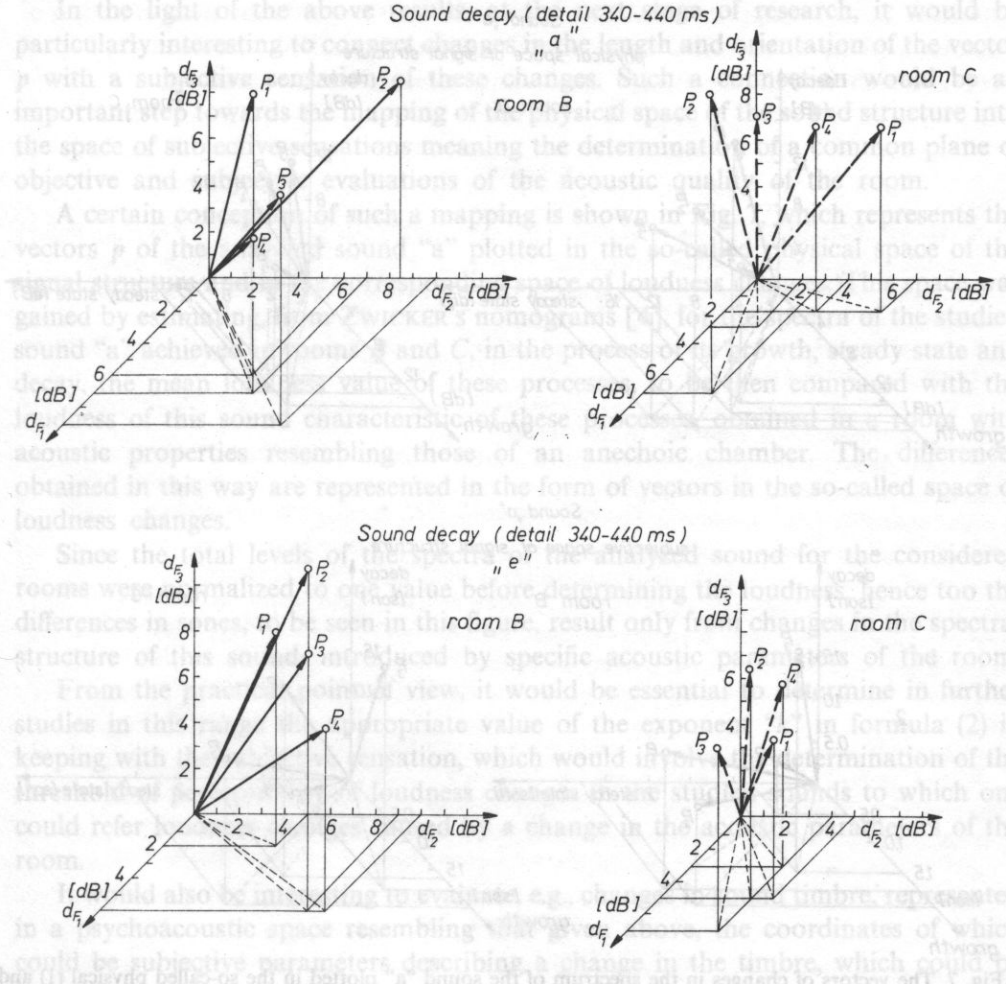

Fig. 6. The vectors of changes in the formant structure of the sounds "a", "e" and „rzeka" for a chosen time fragment of the decay process (340–440 ms), registered in rooms *B* and *C* at the measurement points P_1, P_2, P_3 and P_4

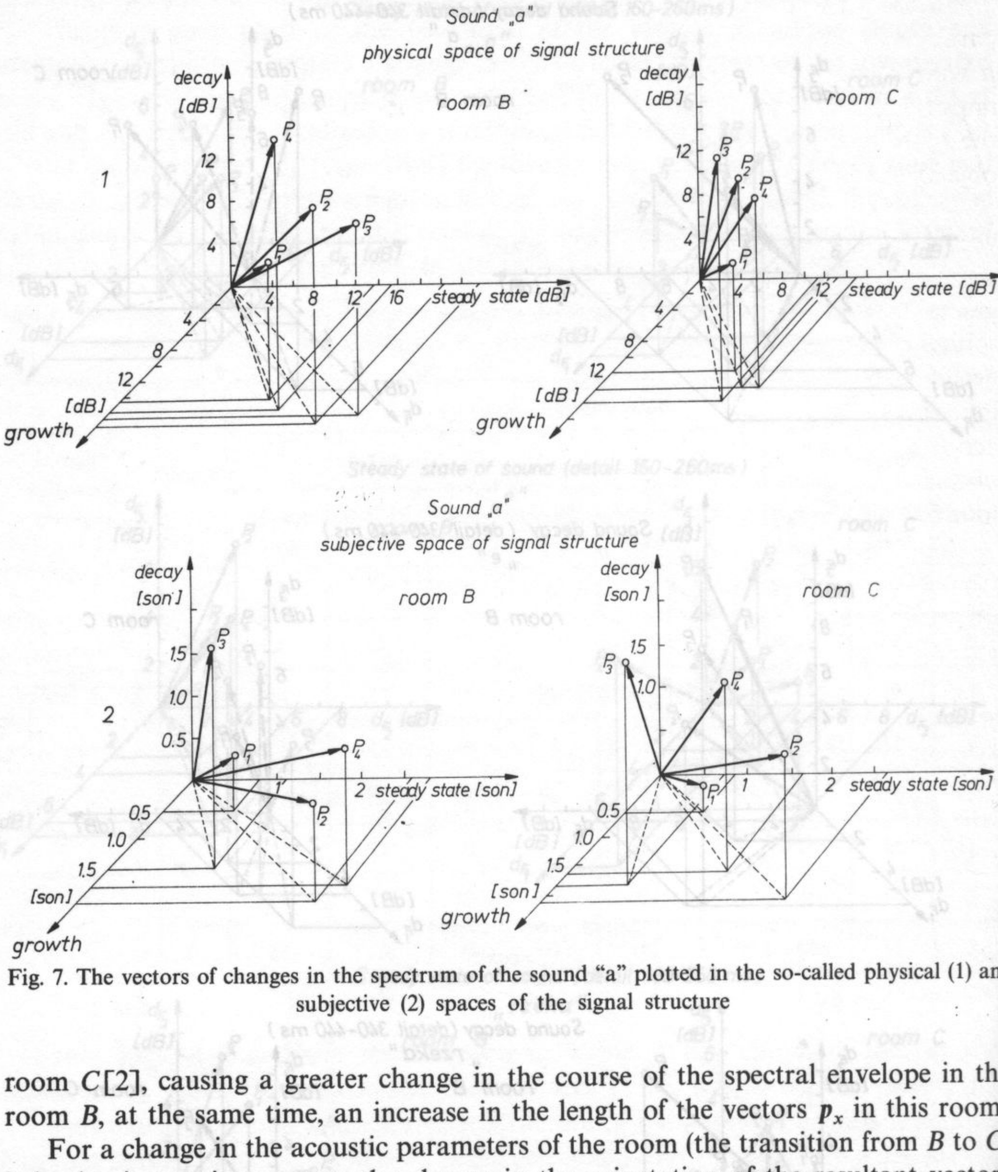

Fig. 7. The vectors of changes in the spectrum of the sound "a" plotted in the so-called physical (1) and subjective (2) spaces of the signal structure

room C[2], causing a greater change in the course of the spectral envelope in the room B, at the same time, an increase in the length of the vectors $\boldsymbol{p}_x$ in this room.

For a change in the acoustic parameters of the room (the transition from B to C) it is also interesting to note the change in the orientation of the resultant vectors $\boldsymbol{p}_2$, $\boldsymbol{p}_3$ and $\boldsymbol{p}_4$ in the space of the signal structure. The angles determining the position of these vectors are subject to change. Moreover, their mean orientation for the room C is closer to the coordinate F_3 [dB] compared with the room B, indicating a distinct change in the envelope of the formant F_3 in this room. The vector which is most sensitive to a change in the length and direction in space for a change in the acoustic parameters of the room, is the vector $\boldsymbol{p}_3$ characterizing the magnitude of changes in the formant structure of a sound registered at the measurement point P_3.

In the light of the above results, at the next stage of research, it would be particularly interesting to connect changes in the length and orientation of the vector $\boldsymbol{p}$ with a subjective sensation of these changes. Such a connection would be an important step towards the mapping of the physical space of the sound structure into the space of subjective sensations meaning the determination of a common plane of objective and subjective evaluations of the acoustic quality of the room.

A certain conception of such a mapping is shown in Fig. 7, which represents the vectors $\boldsymbol{p}$ of the analyzed sound "a" plotted in the so-called physical space of the signal structure and in the corresponding space of loudness changes. This space was gained by estimating, from ZWICKER's nomograms [4], for the spectra of the studied sound "a" achieved in rooms *B* and *C*, in the process of its growth, steady state and decay, the mean loudness value of these processes, to be then compared with the loudness of this sound characteristic of these processes, obtained in a room with acoustic properties resembling those of an anechoic chamber. The differences obtained in this way are represented in the form of vectors in the so-called space of loudness changes.

Since the total levels of the spectra of the analyzed sound for the considered rooms were normalized to one value before determining the loudness, hence too the differences in sones, to be seen in this figure, result only from changes in the spectral structure of this sound, introduced by specific acoustic parameters of the room.

From the practical point of view, it would be essential to determine in further studies in this range the appropriate value of the exponent "k" in formula (2) in keeping with the subjective sensation, which would involve the determination of the threshold of perceptibility of loudness changes in the studied sounds to which one could refer loudness changes caused by a change in the acoustic parameters of the room.

It would also be interesting to evaluate, e.g., changes in sound timbre, represented in a psychoacoustic space resembling that given above, the coordinates of which could be subjective parameters describing a change in the timbre, which could be represented quantitatively.

7. Conclusions

1. A change in the sound structure in a room which arises as a result of a change in its acoustic state, can be mapped in the form of the "interaction" of the space of states of the room on that of the signal structure.

2. The vectors of changes in the formant structure of the analyzed sounds are longer in a damped room than those in an undamped one for all the considered processes, moreover, a change in the orientation of these vectors in the space of the signal structure in the direction of the coordinate P_3 indicates a considerable deformation of the envelope of the third formant.

3. The physical space of the signal structure can be mapped into the space of subjective sensations with coordinates which are the respective psychoacoustic

quantities. Such a mapping can be an important step towards the determination of a common plane of objective and subjective evaluations of the acoustic quality of a room which is still sought for in the problems of room acoustics.

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Received August 8, 1987.