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Research Papers

Sensitivity Analysis of Acoustic Field Parameters on a Change of Boundary Conditions in a Room

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The area of environmental protection concern minimises the impact that technical objects have on the environment. Usually the most effective way of protecting the environment is to influence the source of the problem. For this reason studies are conducted to modify the construction of machines, power machines in particular, so as to minimise their impact on the environment.

In the case of environmental protection from noise it is most convenient to carry out measurements in an anechoic chamber. Unfortunately, this is possible only in very limited circumstances. In all other cases measurements are performed using an engineering method or the survey method, both of which are described in the standards and by taking into account the so-called environmental corrections. The obtained results are burdened with greater error than those of measurements in an anechoic chamber. Therefore, it would seem advantageous to develop a method of obtaining similar and reliable results as those in an anechoic chamber, but in a reverberant field. The authors decided to use numerical modelling for this purpose.

The main objective of this work is a comprehensive analysis of the numerical model of a laboratory designed for acoustic tests of selected power machines. The geometry of a room comprising an area of analysis is easy to design. The main difficulty in modelling the phenomena occurring in the analysed area can be the lack of knowing the boundary conditions. Therefore, the authors made an attempt to analyse the sensitivity of various acoustic parameters in a room in order to change these boundary conditions depending on the sound absorption coefficient.

Keywords: sensitivity analysis, acoustics parameters, geometrical methods, sound absorption coefficient, noise of power machines.

1. Introduction

For new machine constructions or for modernised objects, studying the impact of these machines on the environment, i.e., in terms of the noise generated by them, can be most conveniently carried out in an anechoic chamber. There are widely known procedures being used in these studies (Standard ISO 3745, 2012). The *in-situ* acoustic measurements of machinery in factories are focused on determining the value of the *SPL* parameter. Measurements are carried out in accordance with (Standard ISO 11690-3, 2002) which contains recommendations for the choice of a method for calculating the sound pressure level at a work station in the industry interiors. It also recommends the use of statistical methods or geometrical methods. Measurement of power machines, for which it is not possible to perform measurements in a free field conditions, takes place in accordance with a standard (Standard ISO 3744, 2011). For determining of the values of equivalent A-weighted sound level, in accordance with (Regulation of the Minister of the Environment, 2007), the direct measurements method is used. The methodology is used when in the reference time the source emits the noise to the environment. Measurements are performed in series, then from the measured sample the L_{Aav} average value of sound level is calculated:

$$L_{A\mathrm{av}} = 10\log\left(\frac{1}{n}\sum_{k=1}^{n}10^{0.1L_{AK}}\right), \tag{1}$$

where n is the number of samples in the measurement series, L_{AK} is the measured sound level for the t_0 time.

Then the resulting average value of $L_{A\text{av}}$ is corrected by the average value of the background noise according to the relationship:

$$L_{Aeq} = 10\log\left(10^{0.1L_{A\text{av}}} - 10^{0.1L_{A\text{bn}}}\right), \tag{2}$$

where $L_{A\text{av}}$ is the average sound level for the t_p time interval, $L_{A\text{bn}}$ is the average level of background noise.

However, if it is necessary to determine the value of the noise level generated by the machine or the device under its normal operating conditions, these procedures do not work well. This is because apart from the direct sound generated by the machine, many reflected sounds occur in the object which very often have a significant impact on the resultant noise occurring in/around the object. Admittedly, the procedures for carrying out measurements under the normal operating conditions of machines and devices are specified by standards (Standard ISO 3744, 2011; Standard ISO 3746, 1995), although the applied environmental correction can only in an approximate way include the impact of the environment on the final result. In order to be able to do this precisely, it is necessary to know the properties of the analysed object in a comprehensive and in-depth way.

The basic properties of the room are the size, shape, and materials from which it is built. While the shape and dimensions are simple to determine, determining the materials that were used becomes more problematic. The geometrical methods are the most commonly used ones for an analysis of the acoustic field. These methods require determining the sound absorption coefficients of the materials used. The obtained results are usually close to the results obtained in the measurements of the sound field in real objects (Gołaś, Suder-Dębska, 2009) and are satisfactory for an analysis of the sound field in eligible objects, such as concert halls and theatres. However, when examining machinery noise it seems necessary to achieve even better results of analysis. This requires a more precise definition of the sound absorption coefficients because it seems that, depending on the values of these coefficients, the boundary conditions and values of the parameters characterising the acoustic field can be changed (Piechowicz, 2009; Piechowicz, Czajka, 2012). In this paper the issue of which parameters characterizing the sound field are the most sensitive to the changes in the values of the absorption coefficients and how these changes in the values of these coefficients influence the obtained acoustic parameters will be discussed. Therefore, it will be found out how to precisely determine the absorption coefficients of the materials used. The obtained information will also allow to try to identify the boundary conditions for a particular room in which measurements of power machinery noise can be made. This will improve the quality of numerical modelling of the noise sources occurring in the device measuring in a laboratory.

2. Characteristics of parameters describing the sound field

The sound field in a room can be described by means of a number of objective acoustic parameters. In this paper six acoustic parameters were selected for analysis. The list of parameters is much wider (e.g. Mechel, 2008), however, most of them are still determined on the basis of the impulse response. Therefore, at the initial stage of the study the following acoustics parameters characterizing the sound field: SPL, EDT, Definition, C_{50}, C_{80}, AL_{Cons}, were arbitrarily chosen. The selected parameters are defined as follows (Kulowski, 2007; Mechel, 2008; Kuttruff, 2009):

1. *SPL* Sound Pressure Level [dB];

$$SPL = 20\log\frac{p(t)}{p_0}, \tag{3}$$

where $p_0 = 2\cdot 10^{-5}$ [Pa] is the reference sound pressure, $p(t)$ is the measured sound pressure.

2. *EDT* Early Decay Time [s] is the parameter characterising the subjectively perceived reverberance of a room. It shall be evaluated from the slope of the integrated impulse response curves. The slope of the decay curve should be determined from the slope of the best-fit linear regression line of the initial -10 [dB] of the decay.

3. *D* Definition [%] is the parameter characterising speech intelligibility, defined as:

$$D = \frac{\int\limits_0^{50\ \text{ms}} |p(t)|^2\ \mathrm{d}t}{\int\limits_0^{\infty} |p(t)|^2\ \mathrm{d}t}. \tag{4}$$

4. C_{50} Clarity [dB] is the parameter characterizing speech intelligibility, defined as:

$$C_{50} = 10\log\frac{\int\limits_0^{50\ \text{ms}} |p(t)|^2\ \mathrm{d}t}{\int\limits_{50\ \text{ms}}^{\infty} |p(t)|^2\ \mathrm{d}t}. \tag{5}$$

5. C_{80} Clarity [dB] is the parameter characterizing music reproduction clarity, defined as:

$$C_{80} = 10\log\frac{\int\limits_0^{80\ \text{ms}} |p(t)|^2\ \mathrm{d}t}{\int\limits_{80\ \text{ms}}^{\infty} |p(t)|^2\ \mathrm{d}t}. \tag{6}$$

6. AL_{Cons} Articulation Loss of Consonats [%] is the parameter characterising speech intelligibility, referring to the loss of spoken consonant intelligibility, defined as:

$$AL_{\text{Cons}} = 0.652 \left(\frac{r_{LH}}{r_H} \right)^2 \cdot RT, \tag{7}$$

where r_{LH} [m] is the distance between the sound source and the listener, r_H [m] is the critical distance, RT [s] is the reverberation time.

3. The research object and the parameters of a numerical simulation

The object of the study was a laboratory (Fig. 1) for acoustic measures of selected power machines. The dimensions of this laboratory are respectively $7 \times 7 \times 4$ [m].

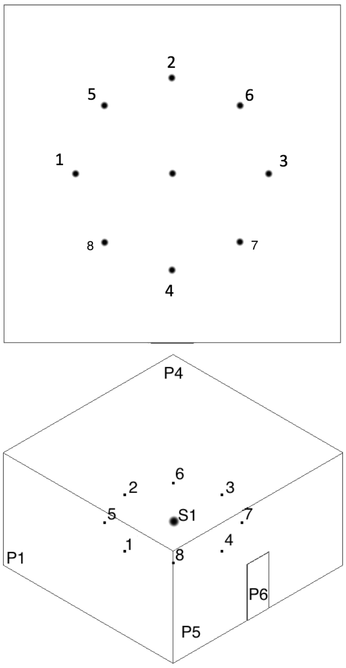

Fig. 1. Numerical model of a laboratory with the selected measurement points.

The simulations were performed using the geometric methods implemented in EASE software (AURA module). A total of 50 000 sound rays were sent from an omnidirectional sound source with a sound power level of 100 [dB] which was located in the geometric centre of the room. The acoustic parameters were calculated for 8 data points located on a circle with a radius of 2 [m], in the centre of which there was the sound source.

4. The course of numerical analysis

The aim of the analysis was to examine how a change in the values of influences on the absorption coefficient influences changes in the values of the parameters characterising the sound field and which one of these acoustic parameters is the most sensitive to these changes. This parameter can be later used to identify the boundary conditions.

Analyses were carried out with 4 options:

- on one of the walls there is a door-sized element whose sound absorption coefficient varies in the range from 0 to 1; the absorption coefficients of the other surfaces are equal to 0.15; the area of the element with a changing absorption coefficient is about 1% of the total laboratory area;
- 5 surfaces limiting the room have a constant sound absorption coefficient with the value of 0.15; the absorption coefficient of one of the walls changes its value from 0 to 1 progressively and this wall's area is about 15% of the total laboratory area;
- the floor and the ceiling have a constant value of the absorption coefficient which is equal to 0.15; whereas the walls have a gradually variable absorption coefficient of values from 0 to 1; the area of these walls with a varying absorption coefficient is slightly over 50% of the total laboratory area;
- one wall has a constant sound absorption coefficient with the value of 0.15; other surfaces have a gradually variable absorption coefficient with values from 0 to 1; the area of these walls with a changing absorption coefficient is around 85% of the total laboratory area.

Figures 2–3 show the changes in the Definition and SPL parameters in each measurement points as compared to the average value. Other parameters, i.e., C_{50}, C_{80}, EDT, AL_{Cons}, show a similar variation. For this reason, to evaluate the sensitivity the average value of 8 measurement points was used.

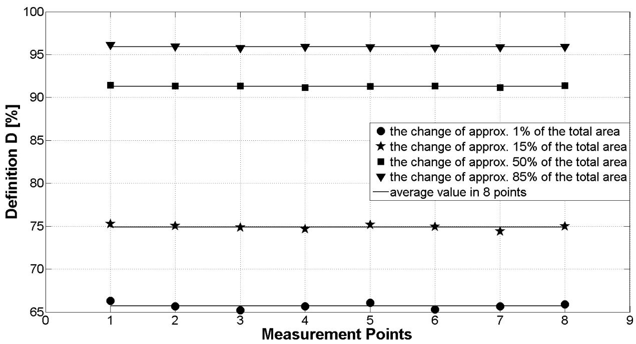

Fig. 2. Changes in the values of the Definition parameter in each of the measuring points.

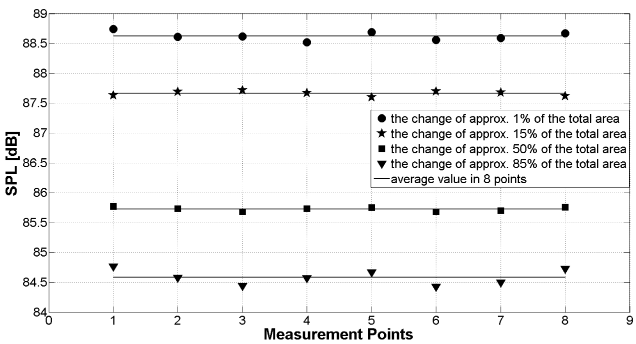

Fig. 3. Changes in the values of the SPL parameter in each of the measuring points.

Of course, along with the changes in the absorption coefficient also the values of the acoustic parameters change. As it can be intuitively assumed, the parameters demonstrate the greatest changes in their values in the case of changes of the absorption coefficient at 5 walls. Figures 4–9 present the dependencies of the discussed parameters' values on the values of the sound absorption coefficient in all of the options discussed above.

It can be seen that for all of the analysed acoustic parameters the slightest changes are indicated in the option with the surface equal to the size of the door.

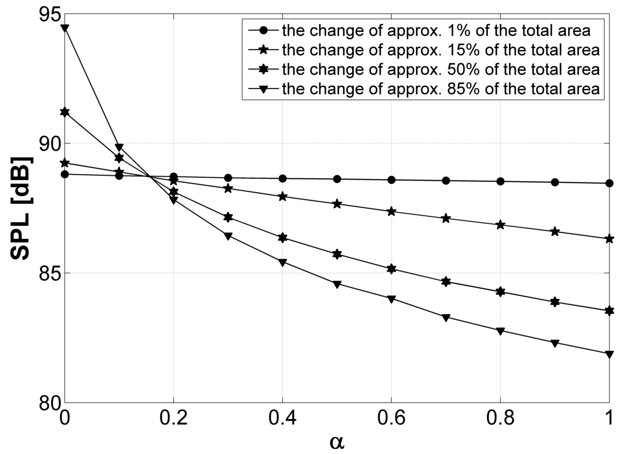

Fig. 4. Changes in the values of the *SPL* parameter depending on the values of sound absorption coefficient.

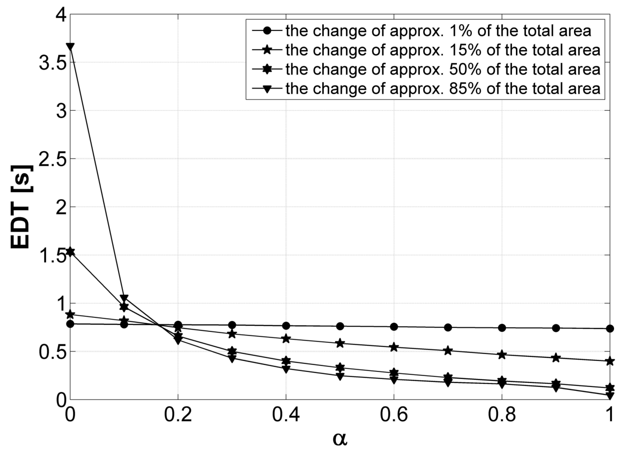

Fig. 5. Changes in the values of the *EDT* parameter depending on the values of sound absorption coefficient.

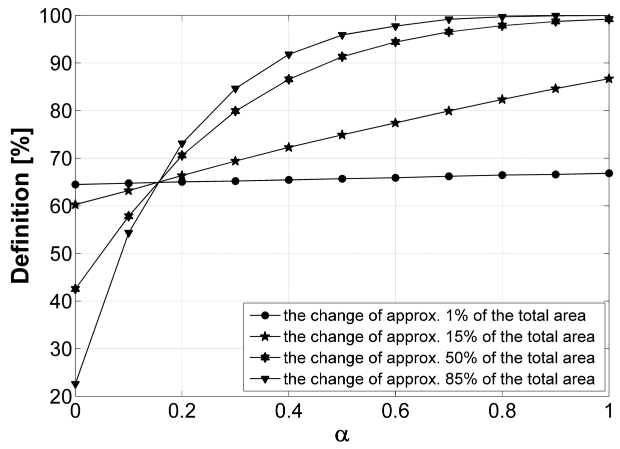

Fig. 6. Changes in the values of the D parameter depending on the values of sound absorption coefficient.

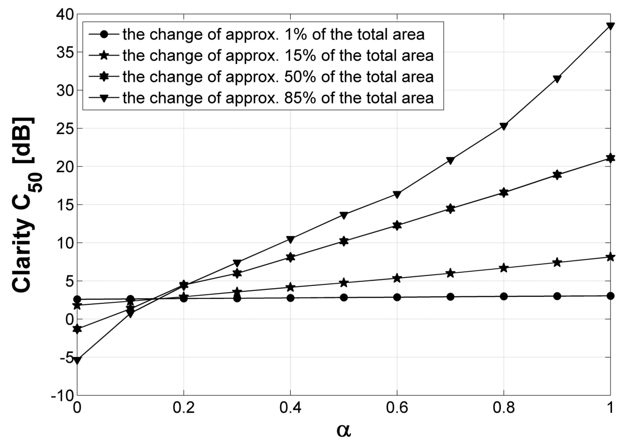

Fig. 7. Changes in the values of the C_{50} parameter depending on the values of sound absorption coefficient.

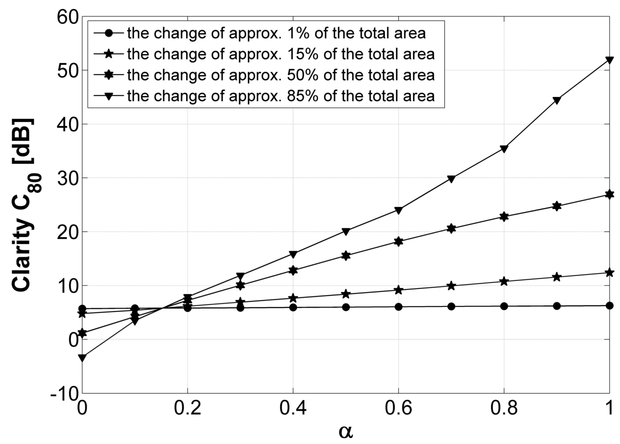

Fig. 8. Changes in the values of the C_{80} parameter depending on the values of sound absorption coefficient.

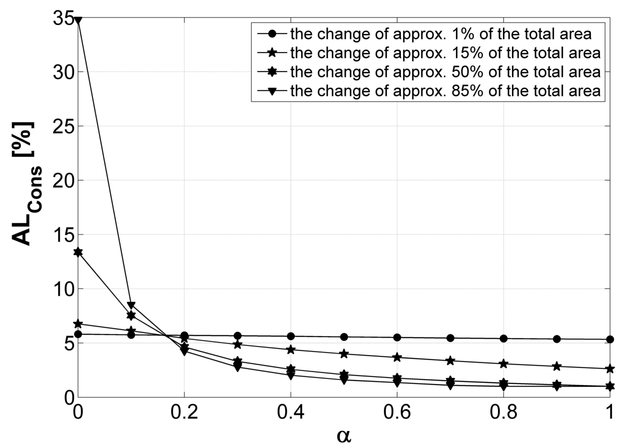

Fig. 9. Changes in the values of the AL_{Cons} parameter depending on the values of sound absorption coefficient.

The C_{50} and C_{80} parameters indicated a similar nature of the changes. These changes are in the full range of changes in the values of the absorption coefficient. With an increase in the value of the absorption coefficient and the size of the surface on which the absorption coefficient is changed, the values of these acoustic parameters are also increased.

The EDT parameter, like the AL_{Cons} parameter, indicates the biggest changes for the sound absorption coefficient in the range from 0 to 0.3, but above this value it indicates a stabilisation. Generally, it can be stated that there is a decrease in the obtained values with an increase in the values of the absorption coefficient, and that this decrease is greater the larger the surface area is for which the absorption coefficient is changed. At the same time, for the SPL parameter an evident decrease can be seen in the obtained values for the absorption coefficient which changes in the full range from 0.0 to 1.0. However, the similarity of the nature of its changes, as it is in the case of the EDT and AL_{Cons} parameters, should be emphasised.

With an increase in the values of the absorption coefficient, and at the same time with an increase in the surface area of the changing absorption coefficient, the biggest changes are indicated by the D parameter. Even for changes on the surface of approximately 15% of the total surface area limiting the room, significant changes can be seen in the obtained values, and the higher the absorption coefficient, the greater the value of the parameter.

5. Study of acoustics parameters sensitivity to changes in the values of the sound absorption coefficient

Sensitivity analysis is studying how uncertainty of the model output can be dependent on the various sources of uncertainty in the input data of the model. In other words, sensitivity is the ratio of relative changes of output functions to the relative changes in the input parameter (Saltelli *et al.*, 2004).

The essence of this study was to find the acoustic parameter that is the most sensitive to changes of the sound absorption coefficient. This parameter seems to be the most useful for identifying the room's boundary conditions. The research was reduced to a designation of the derivatives of acoustic parameter change functions in a discrete form. These derivatives were determined using the three-point numerical differentiation method with the use of Matlab software for the calculations.

Figures 10–13 present a list of the discussed parameters' sensitivities to changes of the values of the sound absorption coefficient for all four options of analysis.

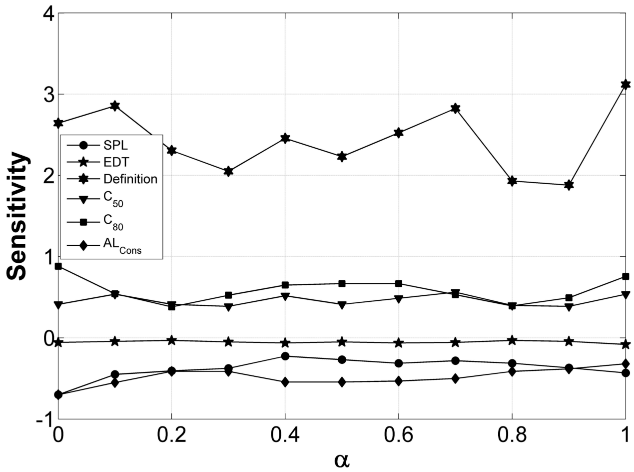

Fig. 10. Sensitivity of the selected acoustics parameters to changes in the values of sound absorption coefficient of an element of the door-sized.

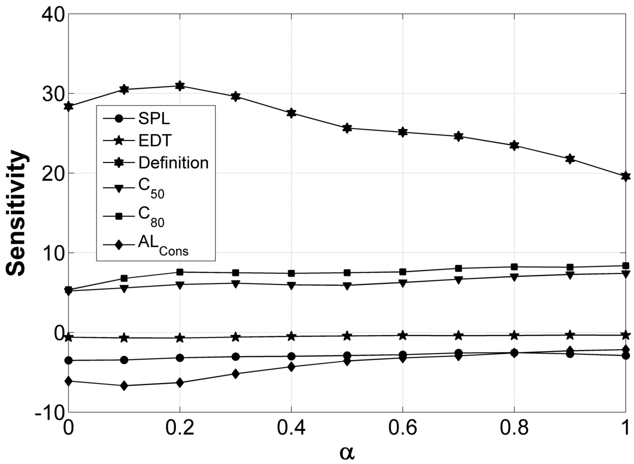

Fig. 11. Sensitivity of the selected acoustics parameters to changes in the values of sound absorption coefficient of an element of one wall size.

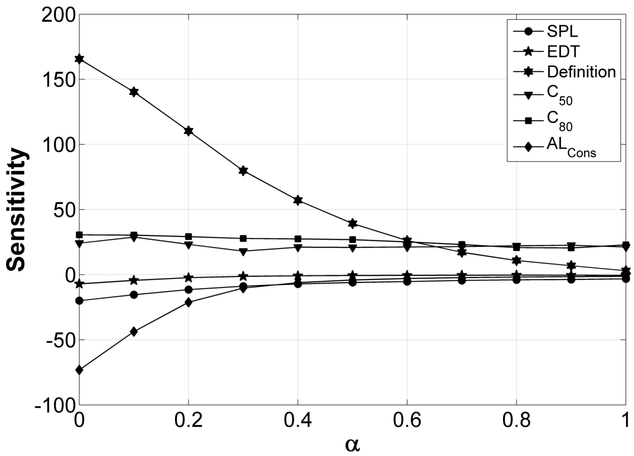

Fig. 12. Sensitivity of the selected acoustics parameters to changes in the values of sound absorption coefficient of an element of four walls size.

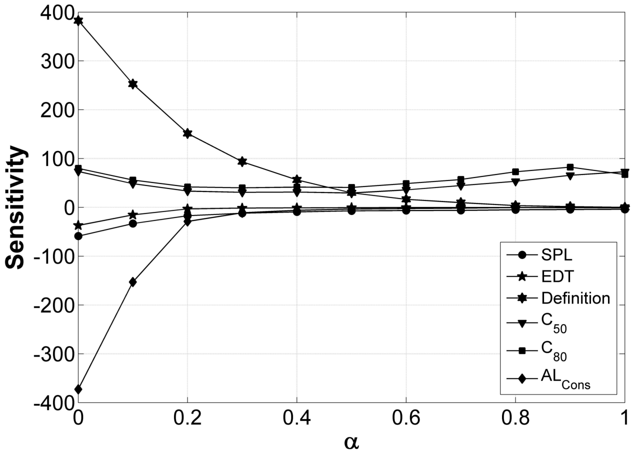

Fig. 13. Sensitivity of the selected acoustics parameters to changes in the values of sound absorption coefficient of an element of five walls size.

The C_{50} and C_{80} parameters indicated a similar sensitivity, irrespective of the size of the surface area which is characterised by a variable sound absorption coefficient.

On the other side for the D parameter the larger the area of the variable absorption coefficient, the sensitivity of this parameter increases. It should be noted, however, that this parameter is insensitive to changes of the sound absorption coefficient in the range of 0.8 to 1.0 for a surface area greater than 50% of the total surface area.

The analyses carried out showed that the smallest changes are indicated by the *EDT* parameter, which is the least sensitive to changes of the sound absorption coefficient regardless of the size of the areas for which the absorption coefficient is changed.

The AL_{Cons} and *SPL* parameters are sensitive to changes of the sound absorption coefficient, but only if those changes concern relatively large areas – then the sound absorption coefficient takes values in the range of 0.0 to 0.3. However, the AL_{Cons} parameter shows a greater sensitivity to these changes than the *SPL* parameter.

It should be noted that for all of the analysed acoustic parameters, their adopted values show the biggest changes for sound absorption coefficients of less than 0.3, and for those greater than 0.8. At the same time, for the sound absorption coefficients in the range from 0.3 to 0.8 the analysed acoustic parameters, except for the D parameter, do not exhibit significant changes in their values.

In order to determine the boundary surface area which is necessary to take into account during the numerical modelling of the sound field using geometrical methods, an analysis of the acoustics parameters sensitivity to changes in the size of the surface area of the varying sound absorption coefficient were carried out. The results of this analysis for all the discussed acoustics parameters are shown in Figs. 14–19.

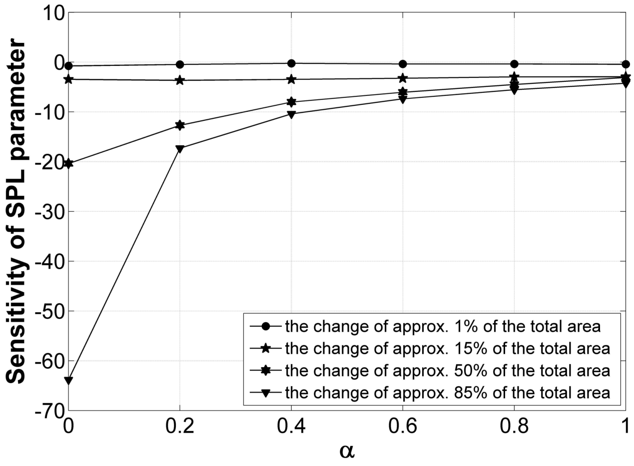

Fig. 14. Sensitivity of the *SPL* parameter to changes in the sound absorption coefficient depending on the surface area.

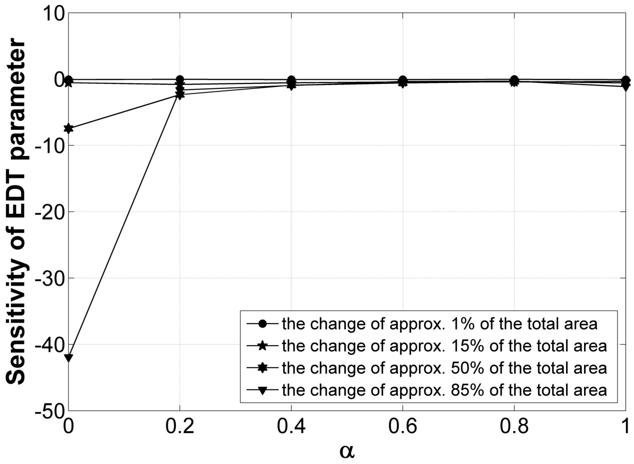

Fig. 15. Sensitivity of the *EDT* parameter to changes in the sound absorption coefficient depending on the surface area.

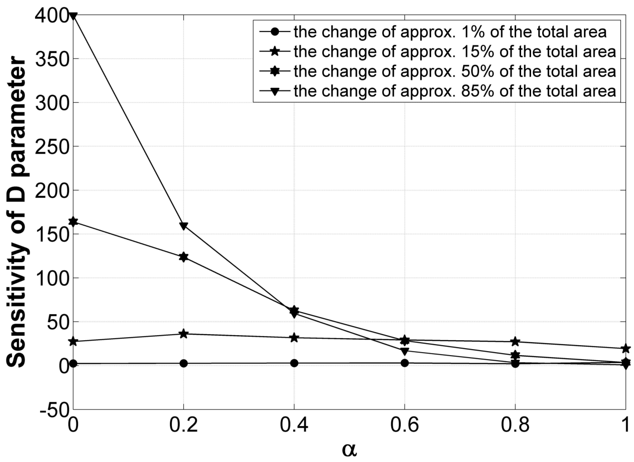

Fig. 16. Sensitivity of the D parameter to changes in the sound absorption coefficient depending on the surface area.

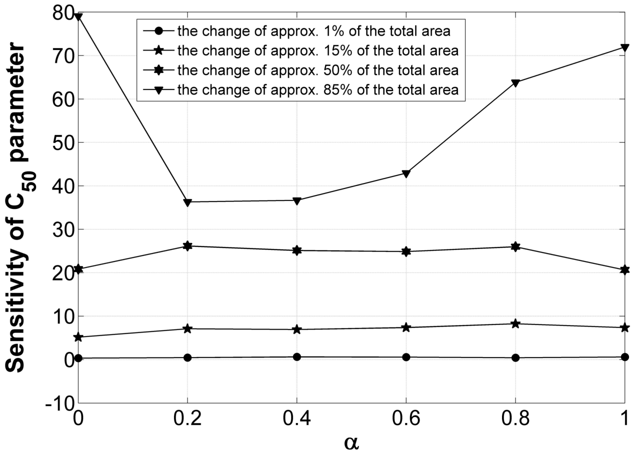

Fig. 17. Sensitivity of the C_{50} parameter to changes in the sound absorption coefficient depending on the surface area.

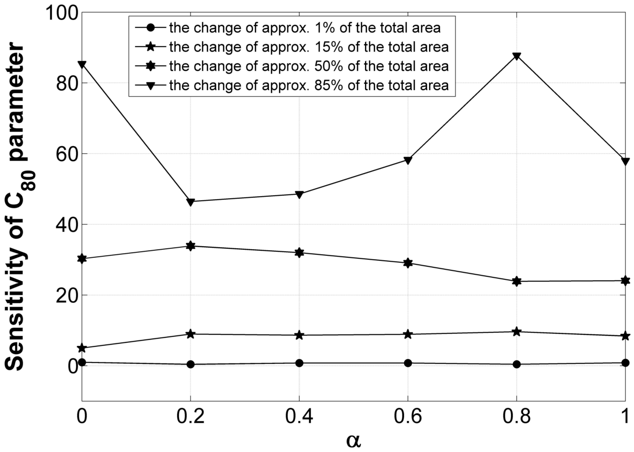

Fig. 18. Sensitivity of the C_{80} parameter to changes in the sound absorption coefficient depending on the surface area.

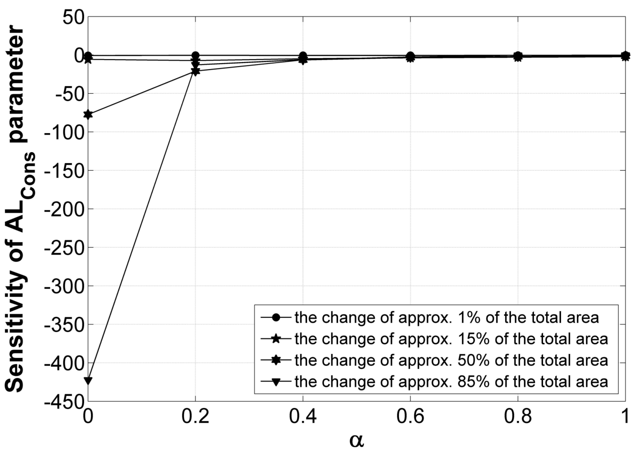

Fig. 19. Sensitivity of the AL_{Cons} parameter to changes in the sound absorption coefficient depending on the surface area.

6. Summary and conclusions

With a change of the values of the sound absorption coefficient the values of distinctive acoustics parameters also change. The magnitude of these changes depends on the size of the area for which the absorption coefficient has changed. For objects of the size of a few percent of the total area of the analysed room these changes are slight. Yet, for an object with an area of 10% and more of the total room area, it appears that these changes are important. Thus, in the simulations it is necessary to take into account such objects.

The acoustics parameter which is the most sensitive to changes in the values of the sound absorption coefficient is the D parameter, and it seems to be the most appropriate in identification of the boundary conditions.

The parameters of the Clarity group demonstrate high sensitivity, whereas the SPL and AL_{Cons} parameters demonstrate changes only when the values of the sound absorption coefficient for large areas are changed, and basically mostly for the sound absorption coefficients in the range of from 0 to 0.3.

The analysis shows that the EDT parameter is the least sensitive to changes in the values of the sound absorption coefficient of the whole group of the analysed acoustic parameters.

To conclude, it is necessary, while modelling, to take into account objects with areas constituting only several percent of the total area of the object and to do so properly, regardless of the value of their sound absorption coefficients, especially if these values are small, because in this area the changes are the most noticeable. The analysis shows the need of taking into account even small elements made of the same material, especially if in the object at least a few of these components occur, as globally their surface will influence the final result of the simulations being carried out.

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