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Determination of Acoustic Impedance of Walls Based on Acoustic Field Parameter Values Measured in the Room

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Acoustic field in enclosed rooms in the low frequency range can be described by the wave model, based on solution of the wave equation. Solution to the wave equation for acoustic field in the room can be obtained using numerical procedures, e.g. the boundary elements method. Determination of acoustic impedance of the room walls surface material, based on the knowledge of the distribution of acoustic pressure amplitudes in the enclosed space, requires application of the inverse boundary elements method and gathering a proper set of input data. The paper presents the possibilities of analysis of acoustic properties for industrial-type rooms, by using inverse methods in the low frequency range.

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1. Introduction

The increasing capacity of parallel data acquisition and its effective processing combined with growing calculational efficiency of computers have increased the importance of inverse methods in many fields of science, including vibroacoustics. The idea of inverse method implementation in room acoustics consists in the fact that it is possible to recover parameters of the analyzed room area if one knows the transfer function or the propagation model connecting the acoustic field with parameters of the volume boundary [1]. The inverse formulation of the problem in acoustics means that the acoustic parameters of the model, e.g. a machinery set, or a given room are obtained from the measurement results. This requires a multitude of data concerning distribution of acoustic field parameters in the near vicinity of the examined objects or the interior of the analyzed room. It seems advantageous to carry out the measurements using multi-channel data acquisition systems for acoustic signals. The authors have combined experimental methods [2, 3] with numerical modelling of acoustic fields that allowed the determination of acoustic impedance for the surfaces enclosing the analyzed volume of acoustic field [4, 5]. The purpose of the study was to analyze the acoustic properties of industrial-type rooms using the inverse methods. Special attention was focused on small industrial rooms and phenomena taking place in the low frequency range.

2. The experimental stand – studies of the model room

In analysis of acoustic fields in enclosed rooms it is often assumed that the field exhibits a diffusive nature. For low sound frequencies, for which the wavelength is comparable with the dimensions of the room and the absorption coefficient of the wall material is rather low, the distribution of the acoustic field in the rooms exhibits considerable inhomogeneity and the above-mentioned diffusive behaviour assumption is not fulfilled. For such a case, solution of the problem is looked for using other acoustic field analysis methods like modal analysis or wave methods, with solutions obtained by means of numerical methods. The authors have proposed a new hybrid approach being a combination of experimental and numerical methods [6–8]. The acoustic pressure measurements in the room interior provide sets of input data, while inverse application of the boundary element methods allows the adjustment of the acoustic impedance of wall materials so that the simulated distributions of the acoustic pressure in the room converge in the optimization algorithms with the experimental results.

3. Experimental studies

In experimental and numerical studies dedicated software packages developed by the authors have been used for both data acquisition and later numerical analyses. For the experimental studies a dedicated measurement setup was built, offering simultaneous and synchronic 24-channel registration of acoustic signals and the signal registered from a laser vibrometer (the vibration velocity of the loudspeaker diaphragm). The system included also a generator producing a pure tone or white noise signal which after necessary amplification was fed to the loudspeaker exciting the room interior with harmonic signal or Gaussian noise. During a single measurement, the system registered 24 values of the acoustic pressure amplitude values, 24 phaseshift angles of the individual signals with respect to the sound source (loudspeaker), and the average vibration velocity value for the loudspeaker diaphragm. A general view of the measurement setup is shown on the block diagram (see Fig. 1). The anal-

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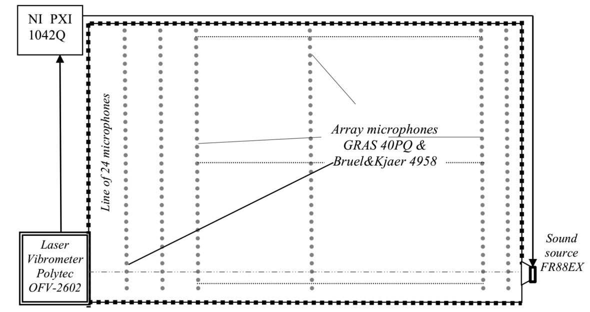

Fig. 1. The setup for acoustic measurements in the room.

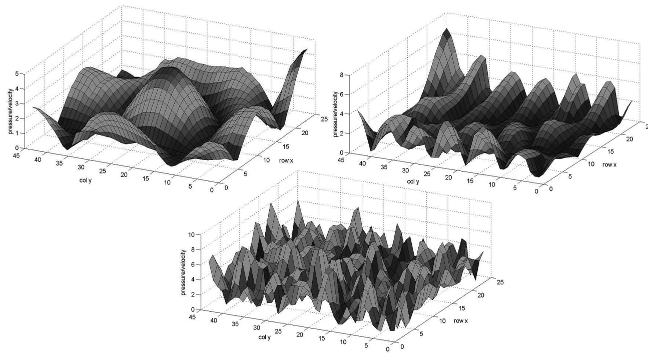

Fig. 2. Distribution of the acoustic pressure amplitudes in a steady state (f = 100 Hz). The ordinate contains pressure values expressed in Pascals (the distributions shown for 100, 200 and 400 Hz).

ysis of the registered signals allowed the calculation of the data matrix containing the acoustic pressure amplitudes registered in individual measurement points and the respective phase shift angles between the signal emitted by the source and the signals registered by the microphones, and additionally the velocity amplitudes for the source diaphragm vibration [7]. The measurements have been carried out in an empty room, without windows, $6.67 \times 3.9 \times 2.85$ m^3 in size. The walls of the room were covered with calcareous plaster and ceramic floor-tiles have been used on the floor. The measurement equipment was controlled from a neighboring room and no person was allowed to stay in the measurement room during the data acquisition. The preprocessed data files, containing the parameters of the acoustic field in the interior of the enclosed space provided input data for the numerical algorithms used for calculation of the acoustic impedance for the materials covering the space boundary. The figures (see Fig. 2) present example distributions of the acoustic pressure amplitudes on the surface located 1.5 m above the floor surface for selected frequencies. Inhomogeneity of the pressure distribution in the room increases with increasing frequency. The reason for this phenomenon is the increasing presence of higher-order eigenmodes in the room's response to the harmonic source excitation.

4. Numerical model of the room

In the low frequency range, the acoustic field in enclosed rooms is described using the wave model based on solution of the wave equation. The wave equation, with additional assumption that the solution is harmonic in time, is shown as Eq. (1) (Helmholtz equation):

$$\nabla^2 p + kp = 0, \tag{1}$$

where p is the acoustic pressure and k is the wave number. Boundary conditions, imposed on the space boundary for this equation can be written as follows:

- the Dirichlet condition: $p|_\Gamma = p_i$,
- the Neuman condition: $\left.\frac{\partial p}{\partial n}\right|_\Gamma = i\omega\rho_0 v_n$,
- the impedance condition (mixed boundary or Robin condition): $p|_\Gamma = Zv_n = Zi\omega\rho_0 \frac{\partial p}{\partial n}$.

Applying the Green's identity, one can write down the integral boundary equation in the volume enclosed by the surface S [4]:

$$c_p = \int\limits_S \left(g\frac{\partial p}{\partial n} - p\frac{\partial g}{\partial n} \right) \mathrm{d}S, \tag{2}$$

where $g = \frac{1}{4\pi r} e^{ikr}$ is the fundamental solution, while c_p is a coefficient depending the location of the observation point.

After digitizing the boundary and assuming appropriate shape functions for every separate sub-area, one obtains the following equation [4]:

$$c_p - \sum_j \int_{S_j} p\frac{\partial g}{\partial n} \mathrm{d}S = -\sum_j \int_{S_j} g\frac{\partial p}{\partial n} \mathrm{d}S. \tag{3}$$

By substituting $\frac{\partial p}{\partial n} = i\omega\rho_0 v$, where v is the acoustic velocity, one can transform the relation written above to its matrix form:

$$Hp = Kv, \tag{4}$$

where p and v are column vectors containing the node values for acoustic pressures and velocities respectively, while H and K are square matrices of coefficients called the influence matrices. The necessary condition for successful solution of the problem is the knowledge of values of acoustic pressure or velocity at each of the node points on the surface. Then, by applying Eq. (4), one can determine the unknown values of acoustic velocity or pressure on the surface. A numerical model was built being an exact counterpart of the actual measurement setup (see Fig. 3). On the border surface of the analysed area, the values of acoustic impedance Z_i were set, held as constant on the whole surface area S_i of each wall. The acoustic impedance Z_{Sx} at a certain point x located on the wall area S_i was defined as:

$$Z_S = \frac{p_{Sx}}{v_{Sx}}, \tag{5}$$

where p_{Sx} is the acoustic pressure at point x, and v_{Sx} is the particle's acoustic velocity at point x.

Then, effective values of the acoustic pressures were determined in 1056 observation points, being the exact equivalents of the measuring points in the actual experimental setup. It allowed determination of the objective function described by formula (6):

$$F(Z_1, Z_2, \ldots, Z_n) = \sum_{i=1}^{m} (\hat{p}_i - p_i)^2, \tag{6}$$

where $\hat{p}_i$ is the value of acoustic pressure calculated by the numeric algorithm, and p_i is the acoustic pressure measured at the i-th measurement point.

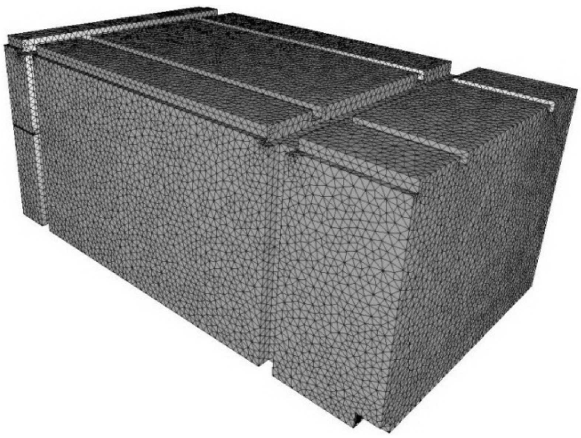

Fig. 3. Numerical model of the room.

The direct task for the numerical model is the determination of the acoustic pressure values at the observation points for given boundary conditions (acoustic impedances) on the surfaces enclosing the analysed space. In the inverse problem, one can determine the acoustic impedance values on the space boundary area from the measured values of the acoustic pressure. The presented problem of determination of the acoustic impedance on the surface enclosing the volume of a given room was solved using the boundary element method. A simulation of acoustic wave propagation described by Helmholtz equation was carried out using the Elmer software package ver.6.2 (open source software for simulation of physical problems developed by CSC — IT Center for Science Ltd), using the boundary element method. The mesh created on the walls, ceiling, and floor surfaces comprised a total of 37936 elements and 58347 nodes (see Fig. 3).

Optimization of the solution was carried out using the Nalder-Mead optimization procedure, a non-gradient method called also a crawling simplex method, implemented in the Matlab software package. It is a numerical method used for function minimization in multidimensional space. It consists of creation in R^n space an n-dimensional simplex with $n+1$ vertices with a special property that all the vertices are located on the hypersurface representing the examined objective function. A one-dimensional simplex is a segment with two vertices, two-dimensional simplex is a triangle, and in general an n-dimensional simplex with $n+1$ vertices is a polyhedron spanned by $n+1$ basis vectors. The calculations have been carried out for frequencies between 100 Hz and 400 Hz. The stimulation, represented by the acoustic velocity on the boundary, has been applied to the surface area equivalent to the loudspeaker diaphragm area. For the remaining surface area of the model, constant values of the acoustic impedance were assumed, appropriate for a given type of wall coverage (calcareous plaster, ceramic floor-tiles) and these values were subject to optimization. As a result of the calculation, complex values of acoustic impedance for the surface of bounding walls were obtained for the case with sinusoidal stimulation, presented in Table. The determined values of acoustic impedance are results that are specific for the individual examined room.

TABLE

Acoustic impedance of calcareous plaster and ceramic floor-tiles determined during the measurements executed in an industrial-type room

	Frequency, Hz							
	80	100	125	160	200	250	315	400
Acoustic impedance - calcareous plaster, Rayl								
ReZ	1252	141	796	1063	133	274	115	125
ImZ	-2209	61	-4843	-1570	-1372	-1481	-1440	-1125
Acoustic impedance - ceramic floor-tiles, Rayl								
ReZ	289	897	416	363	1081	635	648	398
ImZ	-740	-244	497	-832	-639	-1363	-1377	-1436

5. Concluding remarks

The specification of variability range for the values of sound absorption coefficients returned by the appropriate data bases allows the reproduction of correct sound distributions in the room in the middle and high frequency range. For the low frequency case, when the acoustic field is modelled using numerical methods, e.g. the boundary element method, the problem of boundary area properties is specified by the acoustic impedance value of the wall material. The study shows that there is a possibility to determine the values of acoustic impedance for surfaces of the walls enclosing the space by means of the analysed acoustic field. The model used for numerical calculations assumed completely rigid walls enclosing the analysed space volume, while in the real room the walls were not perfectly rigid. However, the effect of wall rigidity on the determined values of acoustic impedance of the bounding surface was not studied. Homogeneous distribution of the acoustic impedance values was assumed for the whole surface material. It opens a prospect for further studies on the effects of varying acoustic impedance values on the examined wall surface area. One of the main advantages of the acoustic parameters estimation based on the boundary elements method is the fact that it can be easily applied for various geometries of the room.

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