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Identification of Sound Power Levels and Surface Absorption Coefficients in Multi-Source Industrial Buildings by Using a Simplified Diffusion Model

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This article deals with the identification of sound powers and absorption surface coefficients in multi-source industrial buildings from the knowledge of the sound pressure levels (SPLs) at several monitoring points. This inverse problem is formulated as one of optimisation in which the objective function is the difference between the measured and predicted SPLs. The methodology combines the use of a simplified acoustic diffusion model with the simulated annealing optimisation technique. The former is a recently developed model for estimating the SPLs in a fast and sufficiently accurate form. The low computational cost of the model constitutes the major advantage for the optimisation procedure due to the great number of simulations required. Numerical examples are given to show the efficiency of the proposed approach.

Keywords: industrial noise; noise source identification; sound absorption coefficient; two-dimensional acoustic diffusion model; simulated annealing algorithm.

1. Introduction

Noise control is an activity of great importance in almost any industrial building. For this purpose, it is essential to use an acoustic prediction model to estimate the sound field in order to assess the effect of different technical solutions (Ver, Beranek, 2006). This model will be realistic if the acoustic power levels of the sources and the surface absorption properties are properly known. In some cases, these magnitudes are not sufficiently well characterised (i.e., *a priori* information related to the acoustic characteristics of the sources can be obtained from machinery manufacturers, but the modification of equipment could change the real sound power spectra. Also, the absorption properties of surface materials could not be the original ones due to natural wear over time). Then, these properties should be identified *in situ*. In this sense, the best way to identify the sound powers is by stopping all noise sources, except the one to be analysed. This procedure should be repeated for every source with unknown power. However, this methodology is not generally applicable in factories because of the great economic cost associated with a shutdown of the production process. Accordingly, the development of procedures for estimating acoustic power levels of the sources and the surface absorption properties of multi-source industrial buildings in their normal operating conditions is very useful.

In the last two decades, an interesting approach for the identification of the mentioned magnitudes from measurements of sound pressure level (SPL) values at several monitoring points, in combination with a theoretical acoustic model, has been developed. In fact, a theoretical acoustic model allows to estimate the SPL field when the sound power levels (SWLs) and the absorption coefficients (α's) of the interior surfaces are known. The present identification problem is the inverse one. That is to say, the SPLs are known from measurements and the SWLs and α's constitute the unknowns of the problem. Obviously, the theoretical model may be used with different trials for the values of these unknowns. Then, the actual SWLs and α's will be obtained when the calculated SPLs coincide with the measured ones. However, considering the unavoidable uncertainties associated to both the measurements and theoretical model, it is difficult to obtain a perfect agreement between measured and calculated SPLs and, then, it is more convenient to require the minimisation of the differences between them. This difference may be evaluated by means of a least square function. From this point of view, the identification problem is formulated as one of optimisation. A detailed explanation of this problem for source power identification in enclosed spaces was presented by Luzzato and Lecointre (1986). Different versions of this approach have been implemented by several authors in order to obtain the SWLs in different industrial environments (Guasch *et al.*, 2002; Lan, Chiu, 2008; Mun, Geem, 2009; Piechowicz, 2009). This methodology was generalised to the identification of the acoustic impedance of interior surfaces for low frequency sound field (Nava *et al.*, 2009; Piechowicz, Czajka, 2012).

Considering the great number of trials necessary to find the searched unknowns, the solution of the present identification problem is based on two fundamental aspects: a) the theoretical acoustic model and b) the optimisation technique to direct the search of the actual values of the SWLs and absorption coefficients. The acoustic model should be sufficiently accurate but also of low computational cost. On the other hand, an appropriate optimisation technique should be used in order to minimise the number of trials to reach the solution. The existing studies related to the present identification problem differ in one or both of the indicated aspects.

Diverse acoustic models should be used for obtaining the SPL values. An obvious choice is the exact linear model based on the solution of the Helmholtz equation. This kind of methodology was employed to identify acoustic impedance for surfaces in enclosed spaces (Piechowicz, Czajka, 2012). However, for the range of mid and high frequencies and non-coherent signals, typical of industrial environments, this approach is difficult to apply. For these cases, an alternative is the use of models based on energy magnitudes (Hodgson, 2003; Keränen, Hongisto, 2010). The simplest and most widely used model is the one based on the classical Sabine's theory for sound fields. This approach provides an explicit, analytical formula to estimate the reverberant noise levels assuming uniformity of sound energy at every point in the enclosure (Kuttruff, 2000). A generalisation of this formula has been incorporated in a methodology for identifying sound power in an enclosure of simple geometry (Luzzato, Lecointre, 1986). Despite its great success in acoustic engineering, Sabine formula may lead to inaccurate results when the enclosure dimensions become disproportionate or the acoustic absorption becomes non-uniform. A more accurate approach is given by the geometrical methods because of their ability to consider complex geometries and different acoustic conditions in the range of mid and high frequencies (Keränen *et al.*, 2003; Piechowicz, 2007; Hornikx *et al.*, 2015). This technique has been used in connection with the sound source powers identification in a complex room (Luzzato, Lecointre, 1986). However, the calculation time increases as the complexity of the room shape becomes greater and/or several sources are considered.

In this paper, a new methodology for the identification of the sound power levels of each source, in the range of mid and high frequencies, and the absorption coefficients of the interior surfaces from the measurement of sound pressure levels at several monitoring points is developed. The methodology combines the use of the recently proposed simplified acoustic diffusion model (SADM), with the simulated annealing (SA) optimisation technique. The adopted prediction model constitutes an approximate two-dimensional simplification of the acoustic diffusion model (ADM), developed some years ago (Valeau *et al.*, 2006; Billon *et al.*, 2012; Kraszewski, 2012). SADM along with the finite element method allows to determine sound pressure levels in enclosures with an accuracy similar to those given by the ADM and the geometrical models although by employing much less computational time (Sequeira, Cortínez, 2012). Moreover, in order to reduce the number of required SADM simulations, a simple and robust optimisation technique known as simulated annealing is employed to direct the optimal search (Chiu, 2012; Sequeira, Cortínez, 2016). This stochastic and iterative method of global search avoids to get trapped in a local minimum. This property is important because this identification approach leads to a non-convex optimisation problem (it can present several local minima). The present methodology allows to identify the SWLs and α's variables for multi-source rooms with complex geometries with a reasonable accuracy and employing low computational burden in comparison with previously developed approaches. This study is complementary to a previous paper by the authors related to an optimal acoustic design methodology (Sequeira, Cortínez, 2016).

This paper is organized as follows. In Sec. 2, the identification problem is formulated. In Sec. 3, the theoretical basis of the simplified diffusion model is presented. In Sec. 4, the computational solution is explained. In Sec. 5, the accuracy of the diffusion model is checked by comparing simulated data with experimental results. Later, a numerical example for the identification problem is presented to show the efficiency of the proposed approach. Finally, the conclusions are given in Sec. 6.

2. Formulation of the identification problem

An industrial building with multiple sources emitting sound in stationary conditions is considered. Noise-related problems in this kind of enclosures are described by the sound pressure levels which depend on the source power levels, the absorption coefficients and the geometry of the enclosure. This relationship may be expressed mathematically as follows:

$$\mathrm{SPL}_f(\mathbf{r}) = F\left(\mathrm{SWL}_{jf}, \mathbf{r}_j, \alpha_{kf}, AA\right), \tag{1}$$

where F is a general function and $\mathrm{SPL}_f(\mathbf{r})$ is the sound pressure level at a position $\mathbf{r} = (x, y, z)$ which depends on the sound power level SWL_{jf} for the source j, the coordinates of the source j ($\mathbf{r}_j$), the absorption coefficient α_{kf} of each interior surfaces k, and the geometrical features of the enclosure symbolised as AA. Sub-index f means that the magnitudes correspond to the frequency f. Expression (1) represents an acoustic model. The explicit form of the function F depends on the kind of the theoretical model (Helmholtz equation, geometrical methods, etc.) and numerical technique used. This acoustic model allows one to obtain SPLs if the variables of the argument given are known. This is known as direct problem.

The inverse problem corresponds to the determination of the sound power levels, SWL_{jf}, and the absorption coefficients, α_{kf}, from the knowledge of the SPL_f values at a number of monitoring points i. The latter are obtained by means of direct measurements. This inverse problem (identification task) can be formulated as follows (Luzzato, Lecointre, 1986):

$$\left(\mathrm{SWL}_{jf}, \alpha_{kf}\right)_{\mathrm{opt}} = \arg\min\ OF, \tag{2}$$

where $(...)_{\mathrm{opt}}$ indicates the set of the optimal variables (to be identified) and OF is the objective function defined as the following root mean square error function:

$$OF = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\overline{\mathrm{SPL}}_{if} - \mathrm{SPL}_f(\mathbf{r}_i)\right]^2}, \tag{3}$$

where N is the total number of monitoring points, $\overline{\mathrm{SPL}}_{if}$ is the measured sound pressure level and SPL_f is given by expression (1). According to this formulation, the actual values for the sound power levels and absorption coefficients are those that minimise the difference between the measured and calculated SPLs. From the mathematical point of view, expressions (2) and (3) constitute an optimisation problem. Accordingly, the identified magnitudes will be mentioned as optimal values.

The OF minimisation is subject to the following constraints:

$$\begin{cases} \mathrm{SWL}_{jf}^{[\min]} \le \mathrm{SWL}_{jf} \le \mathrm{SWL}_{jf}^{[\max]}, \\ \alpha_{kf}^{[\min]} \le \alpha_{kf} \le \alpha_{kf}^{[\max]}, \end{cases} \tag{4}$$

where $\mathrm{SWL}_{jf}^{[\min]}$, $\mathrm{SWL}_{jf}^{[\max]}$, $\alpha_{kf}^{[\min]}$, and $\alpha_{kf}^{[\max]}$ represent the minimum and maximum sound power levels and absorption coefficients, respectively. It has to be noted that the formulation takes into account point sources assuming they are of small dimensions.

3. Acoustic model

The diffusion model allows one to estimate the SPLs in rooms with non uniform reverberant conditions. It is based on an analogy between the sound propagation in enclosures with diffusely reflecting surfaces and particles propagation in a diffusing medium. In this section, a brief explanation of both the full diffusion model and the corresponding simplified two-dimensional version is given. Detailed theoretical foundations can be found in the cited references (Valeau *et al.*, 2006; Billon *et al.*, 2012; Sequeira, Cortínez, 2012).

3.1. Acoustic diffusion model

The stationary and reverberant sound energy density $w_f(\mathbf{r})$ in a room of volume V_r, is obtained as the solution of the following equations (Valeau *et al.*, 2006):

$$-D\nabla^2 w_f(\mathbf{r}) + \sigma_f w_f(\mathbf{r}) = q_f(\mathbf{r}) \qquad \text{in} \quad V_r, \tag{5}$$

$$-D\frac{\partial w_f(\mathbf{r})}{\partial \mathbf{n}} = A_f c w_f(\mathbf{r}) \quad \text{on} \quad \partial V_r, \tag{6}$$

where ∇^2 is the Laplace operator, D is a diffusion coefficient, σ_f is a coefficient of volumetric absorption, $q_f(\mathbf{r})$ is the source power per unit volume, $\mathbf{n}$ is the exterior normal to the boundaries, A_f is an absorption factor, and c is the speed of sound. The diffusion coefficient $D = K \cdot 4cV_r/(3S_r)$, depends on the volume of the room, the inner surface area S_r, the speed of sound, and the function $K = 2.238\ln(s) + 1.549$. This function allows to include mixed specular and diffuse reflections on room surfaces, with s being the scattering coefficient used to determine the proportion of sound energy that is reflected in a specular manner and the proportion that is scattered (Foy *et al.*, 2009). In particular, for $s = 1$ (completely diffuse reflections), $K = 1$. Moreover, the coefficient $\sigma_f = m_f \times c$, depends on the atmospheric attenuation in the room, being m_f the absorption coefficient of air (Billon *et al.*, 2008). In addition, the mentioned expression can be modified to take into account the possible presence of fittings (Valeau *et al.*, 2007).

Equation (6) corresponds to the boundary conditions, where the absorption factor A_f is given in terms of the surface absorption coefficients by means of the following expression (Jing, Xiang, 2008):

$$A_f = \frac{\alpha_f}{2\,(2-\alpha_f)}. \tag{7}$$

The total sound pressure level is obtained by adding the direct sound field contribution to the reverberant one (Valeau *et al.*, 2006):

$$\mathrm{SPL}_f(\mathbf{r}) = 10\log_{10}\left\{\frac{\rho c}{P_{\mathrm{ref}}^2}\left[\int\limits_{V_s}\frac{q_f(\mathbf{r})}{4\pi r^2}\,\mathrm{d}V_S + c w_f(\mathbf{r})\right]\right\}, \tag{8}$$

where $r = \|\mathbf{r}-\mathbf{r}_j\|$ is the distance from a monitoring point to an arbitrary source point $\mathbf{r}_j$, ρ is the air density, and $P_{\mathrm{ref}} = 2\cdot 10^{-5}$ Pa. In this paper, only omnidirectional point sources with a constant power Ws_f are adopted. Then, $q_f(\mathbf{r}) = Ws_f\delta(\mathbf{r}-\mathbf{r}_j)$.

3.2. Simplified acoustic diffusion model

The simplified two-dimensional diffusion model (SADM) is obtained from the full model by making use of the Kantorovich method (Sequeira, Cortínez, 2012). Accordingly, the reverberant energy density (w) is approximately represented as the product of two functions, one corresponding to the variation on the plane domain and the other considering the variation in height:

$$w_f(\mathbf{r}) \approx \widetilde{w}_f(\mathbf{r}) = P_f(x,y)\times Z(z), \tag{9}$$

where P_f is an unknown function and Z is a preselected function constructed from a second order polynomial $Z = 1 + a_1 z + a_2 z^2$. The latter represents the simplest way to characterise the vertical energy variation. The idea behind this simplification is that the vertical distribution of the reverberant field is assumed to be much simpler than that of the plane variation. The corresponding polynomial coefficients are determined from the boundary conditions defined in both floor and ceiling planes:

$$D\frac{\mathrm{d}Z}{\mathrm{d}z} = \pm A_f Z. \tag{10}$$

Substituting the expression (9) into Eqs. (5) and (6), multiplying by Z, and integrating along the vertical direction, the following system of equations, corresponding to the simplified acoustic diffusion model SADM, is obtained (Sequeira, Cortínez, 2012):

$$-\nabla_p^2 P_f \int\limits_0^H DZ^2\,\mathrm{d}z - P_f\int\limits_0^H\left[D\left(\frac{d^2Z}{\mathrm{d}z^2}\times Z\right) - \sigma Z^2\right]\mathrm{d}z = \int\limits_0^H q_f Z\,\mathrm{d}z \quad \text{in } \Omega, \tag{11}$$

$$-\frac{\partial P_f}{\partial \mathbf{n}}\int\limits_0^H DZ^2\,\mathrm{d}z = P_f\int\limits_0^H A_f c Z^2\,\mathrm{d}z \quad \text{on } \partial\Omega, \tag{12}$$

where ∇_p^2 is the Laplace operator in the plane (x, y), H is the height of the room, Ω symbolises the plane domain, and $\partial\Omega$ is the perimeter.

Equations (11) and (12) can be conveniently solved by means of the finite element method. For this task the commercial software FlexPDE was employed. The total sound pressure level is obtained by means of expression (8), once the approximated reverberant energy density is achieved as the solution of the previous equations. That is to say, in this paper the specific form for the acoustic model (1) is given by (8) along with Eqs. (9) to (12).

4. Optimisation technique: Simulated Annealing method

In order to solve the identification problem (Eqs. (2)–(4)), it is first necessary to determine SPL_f by means of the SADM along with the finite element method, as described above, for different trials of the admissible values (verifying inequalities (4)) for the variables to be indentified $\mathbf{X} = (\mathrm{SWL}_{jf},\ \alpha_{kf})$. Then, the objective function may be evaluated. This procedure is repeated iteratively according to the Simulated Annealing SA algorithm.

The latter is a probabilistic technique for finding quasi-optimal solutions to global optimisation problems (Kirkpatrick *et al.*, 1983). The algorithm starts by defining an initial trial for an array having the desired variables (sound power levels and absorption coefficients) $\mathbf{X}_0$ within the feasible domain of the problem. Then, it successively generates, in a reduced domain of the neighbourhood of the actual array $\mathbf{X}$, new trials $\mathbf{X}'$ which are accepted as current according to the change in the objective function $\Delta OF = OF(\mathbf{X}') - OF(\mathbf{X})$. If this change is negative, the new trial is accepted as the new current array. If the change is positive, the acceptability is decided according with the probability of Boltzmann distribution. The latter depends on a parameter T, known as *temperature* (due to the physical analogy between the technique and a thermodynamic process), which directs the convergence of the algorithm, as it approaches to zero. So, initially, when the parameter T is high, there is a large probability of accepting configurations with a greater OF value, but as the procedure advances and T decreases, the probability of acceptance becomes considerably smaller, until it finally converges to the optimal solution. The conventional cooling scheme $T_{a+1} = \beta\times T_a$ is used here, where β is the decreasing rate (Dreo *et al.*, 2006).

The identification procedure is computationally implemented in Matlab by linking finite element solutions of the SADM, using the software FlexPDE, with the simulated annealing (SA) technique in an iterative manner (Sequeira, Cortínez, 2016).

5. Study of the SADM accuracy

Considering the fact that the identification procedure depends especially on the appropriate accuracy of the SADM, a comparison of SADM results against values obtained with other acoustical models and experimental determinations is performed. In particular, the sports hall 1, depicted in Fig. 1, is analysed. This existing unoccupied enclosure was previously studied by Hornikx *et al.* (2015) who obtained sound pressure levels at different points by means of the commercial software CATT-Acoustic and by direct measurements. Calculations and measurements are presented for the octave-frequency band of 500 Hz. The estimated absorption coefficient values of the hall are (Hornikx *et al.*, 2015): 0.02 (surface 1, 2, and 5); 0.65 (surface 3); 0.06 (surface 4); and 0.57 (surface 6).

For the described situation, the SADM predictions of sound pressure levels are compared with the following values:

- SPLs determined by means of finite element solution of the ADM (three dimensional equation system (5), (6), and (8)).
- SPLs determined by means of the well-known ray tracing (RT) technique (Hornikx *et al.*, 2015).
- SPLs obtained by means of measurements (Hornikx *et al.*, 2015).

To apply SADM and ADM approaches, reflections on the surfaces are considered mixed specular and diffuse. The scattering coefficient value of 0.1, as proposed by Hornikx *et al.* (2015), is chosen (this value leads to $D = 5813.9$ m^2/s for the diffusion coefficient). Moreover, the coefficient of volumetric absorption takes the value $\sigma = 0.17$ s^{-1} (with $m_{500\text{ Hz}} = 5 \cdot 10^{-4}$ m^{-1}). The comparison study is performed for the sound pressure level related to the level at 1 m from the sound sources in free field, $\text{SPL}_{\text{re, free, 1 m}}$.

Figure 2 shows this comparison for the SPL distribution along the receiver lines 1 and 2 generated for each of the considered sources (S1, S2, and S3) at height $z = 1.5$ m. A finite element mesh of about 580 triangular elements and 7700 tetrahedral elements were used to solve the SADM and ADM, respectively. A general good agreement between predicted and measured values is observed. The SADM presents an averaged mean absolute error of 1 dB, while the RT shows an averaged mean absolute error of 0.7 dB. In particular, a very close similarity is found between results from the SADM and ADM (with a maximum error of 0.2 dB). From this example, it can be concluded that

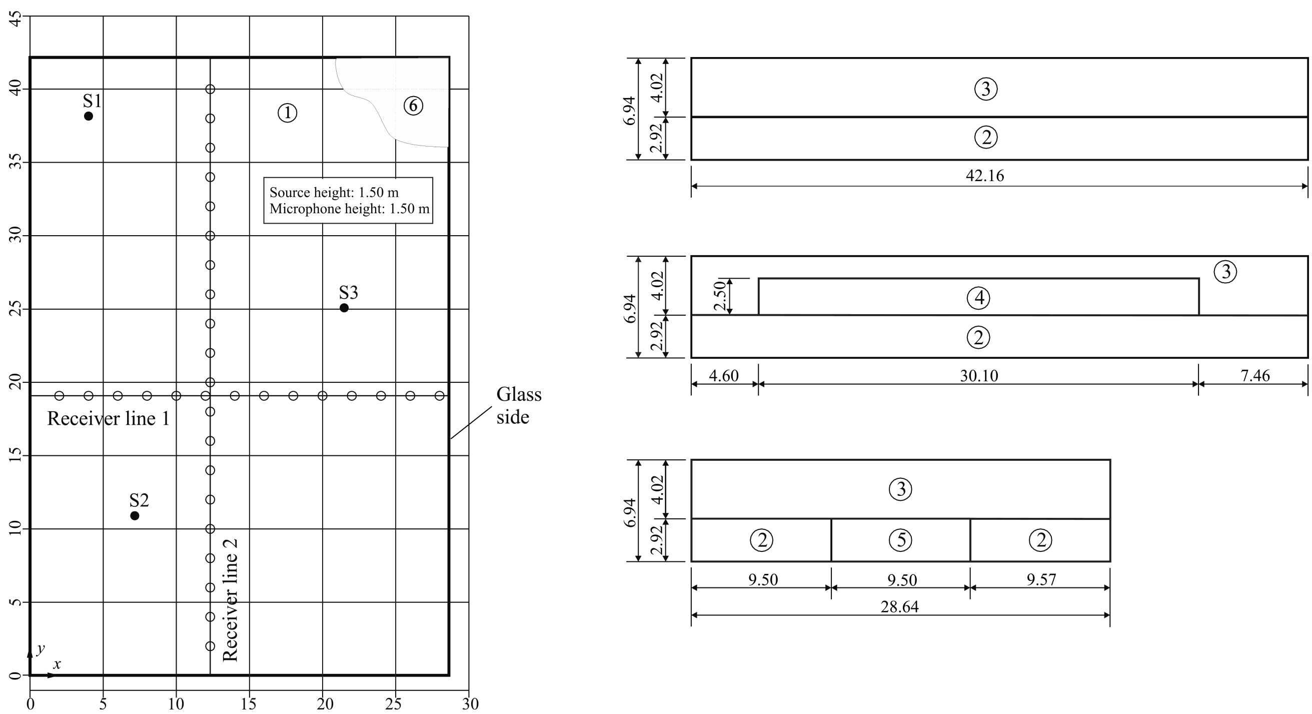

Fig. 1. Scheme of the Sports hall 1 (units in m). Left figure: calculation and measurement grid used at a height of 1.5 m above the floor. Source positions are marked by S1, S2, and S3, receiver positions by lines 1 and 2. Right figure: surface dimensions: (upper) side wall at $y = 0$ m; (middle) side wall at $x = 28.64$ m; (lower) cross wall at $x = 0$ m; and $y = 42.16$ m. Material distribution: (1) sports floor, (2) smooth concrete blocks, (3) open lath construction on a 0.14 m deep cavity, filled with 0.03 m mineral wool at the position of the laths, (4) lightweight partition wall with windows, (5) soft pad, (6) open lath ceiling construction on 2.0 m deep cavity, filled with 0.03 m mineral wool (Hornikx *et al.*, 2015).

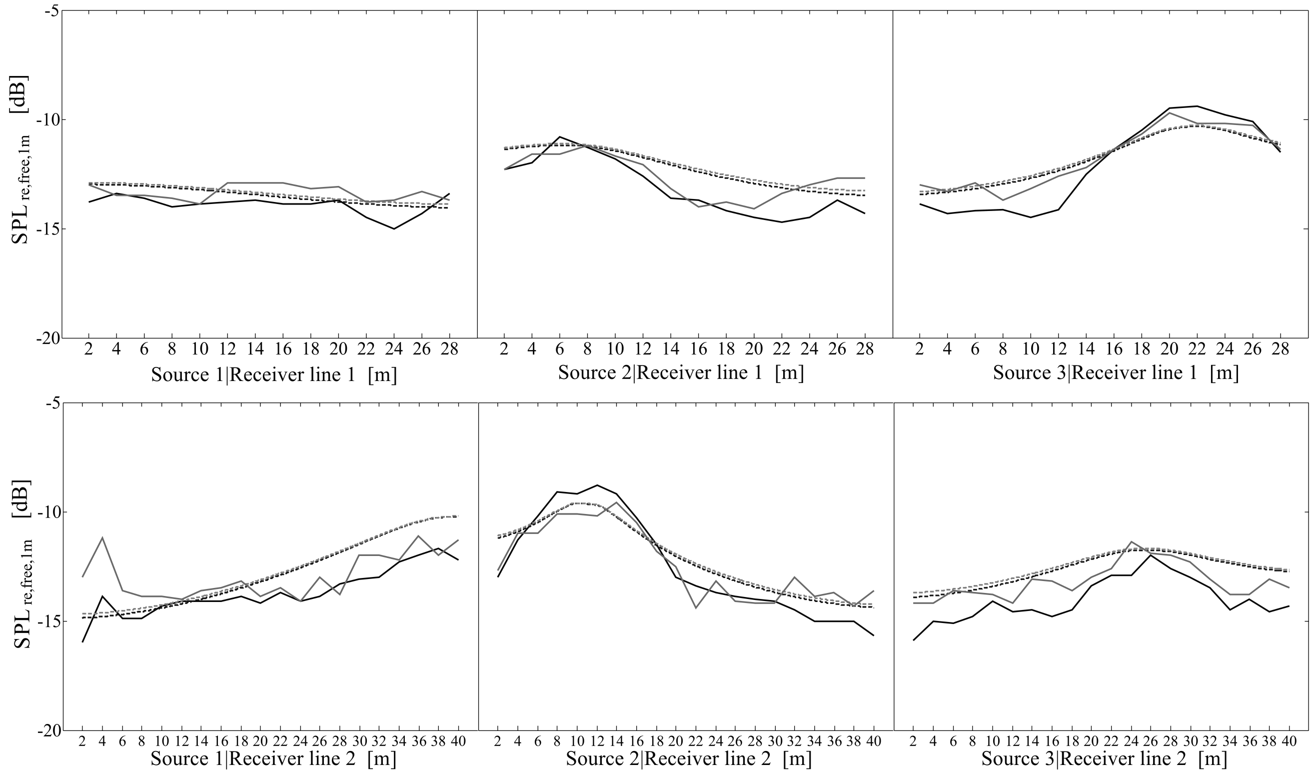

Fig. 2. $\mathrm{SPL}_{\mathrm{re,\,free,\,1\,m}}$ results of the hall. Solid black: experimental (Hornikx *et al.*, 2015); dashed black: ADM; dashed grey: SADM; and solid grey: CATT-Acoustic (Hornikx *et al.*, 2015).

the proposed simplified diffusion model has an acceptable precision for predicting the SPL variations in the identification approach.

6. Identification example

6.1. Analysed enclosure

The 5-m high coupled workroom shown in Fig. 3 is studied. Ten omnidirectional point sources with a height of 1.2 m are considered. The locations and actual power level values of the sources are given in Table 1. The actual absorption coefficients of the surfaces are: 0.45 for ceilings 1, 0.70 for ceiling 2, 0.02 for floor, 0.25 for the partition, and 0.05 for all the remaining walls.

For this example, the $\overline{\mathrm{SPL}}$ values are not obtained from measurements but simulated with the help of a theoretical acoustic model (ADM in this case, with the diffusion and volumetric absorption coeffi-

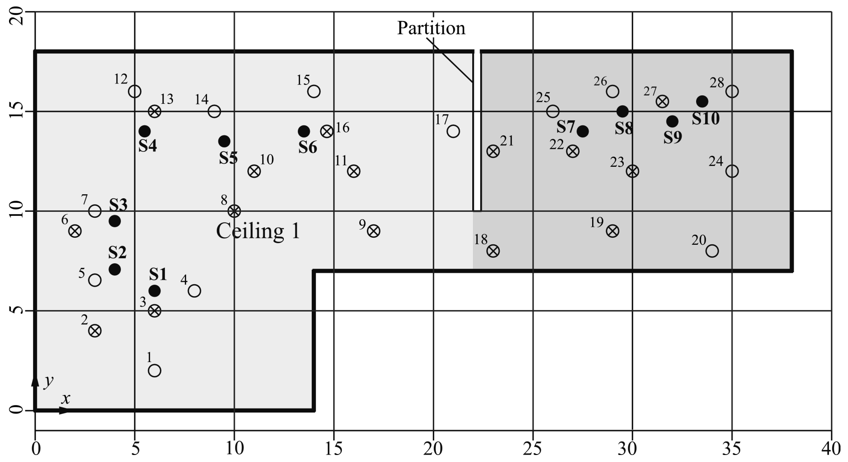

Fig. 3. Scheme of the workroom (units in m) with locations of the sources (S). Two sets of monitoring points are considered: set 1 (○) and set 2 (⊗).

Table 1. Actual sound power levels and coordinates of the sources.

Sound source	Coordinate [m]		SWL [dB re 10^{-12} W]
	x	y	
S1	6	6	102
S2	4	7	105
S3	4	9.5	114
S4	5.5	14	101
S5	9.5	13.5	117
S6	13.5	14	100
S7	27.5	14	106
S8	29.5	15	102
S9	32	14.5	100
S10	33.5	15.5	110

cients given in the following sub-section). Moreover, in order to consider the unavoidable errors existing in the theoretical model or the measurement techniques, random errors are added over the theoretical predictions. These pseudomeasured values will be mentioned as "measured" values. Thus, two classes of $\overline{\text{SPL}}$ measured values are considered:

A. The "measured" $\overline{\text{SPL}}$s are assumed to be coincident with those determined by means of the acoustic diffusion model (ADM) as a function of the actual sound power level and absorption coefficient values. In fact, no errors are involved.
B. The "measured" $\overline{\text{SPL}}$s are assumed to be related, just in an imperfect (although approximate) form, with the acoustic model (ADM) predictions because of errors in modelling or measuring. Accordingly, random errors of $\pm\,0.50$ dB over the theoretical SPLs are added in order to obtain the measured $\overline{\text{SPL}}$ values.

6.2. Identification procedure

The SWLs of every source and the absorption coefficients of the ceiling 1 (α_{ceiling1}), ceiling 2 (α_{ceiling2}), and the partition ($\alpha_{\text{partition}}$), described above, are the variables to be identified. Only the octave-frequency band of 1000 Hz is considered. However, it is clear that the same methodology can be applied to any octave band within the range of mid and high frequencies where the diffusion model is valid (Billon *et al.*, 2006).

To perform the procedure, an appropriate number of monitoring points should be used. However, in order to show the robustness of the present methodology, two monitoring point configurations from sets 1 and 2 are selected (see Fig. 3): configuration I, with 28 monitoring points (set 1 + set 2) and configuration II, with 13 monitoring points (set 1). These configurations are used for the two kinds of measured sound pressure levels defined above. Accordingly, four cases are studied: Cases A.I and A.II, considering configurations I and II, respectively, without errors in the "measured" $\overline{\text{SPL}}$s and Cases B.I and B.II, considering configurations I and II, respectively, taking into account random inherent errors in the $\overline{\text{SPL}}$ values.

Considering the fact that the present example involves a coupled enclosure, it is first necessary to determine the diffusion coefficient D for each sub-volume (Billon *et al.*, 2006). Accordingly, assuming completely diffuse surface reflections, the following values are determined: $D_1 = 2019.4\ \text{m}^2/\text{s}$ (for the sub-volume with the ceiling 1) and $D_2 = 1563.3\ \text{m}^2/\text{s}$ (for the sub-volume with the ceiling 2). The coefficient of volumetric absorption takes the value $\sigma = 0.24\ \text{s}^{-1}$ (with $m_{1000\ \text{Hz}} = 7 \cdot 10^{-4}\ \text{m}^{-1}$).

On the other hand, before implementing the identification procedure, it is mandatory to define the variable limits to obtain the feasible search region. Generally, in real situations, *a priori* knowledge of the sound power ranges is possible (i.e., by using manufacturer approximate information), so a reasonable bounded limit set can be considered. Then, a range variation of $\pm\,8$ dB relative to the actual SWLs is selected. Moreover, the absorption coefficient variables are limited to values from 0.05 to 0.9. Due to the heuristic nature of the SA algorithm, the entire procedure has been carried out ten times (with a total of 10 000 iterations) for each case and the best results have been accepted. The decreasing rate used in the cooling scheme in SA algorithm was $\beta = 0.98$.

Table 2 shows the results of the proposed identification methodology. For Cases A.I and A.II, predictions are acceptable, having mean errors of 0.43 dB (configuration I) and 0.88 dB (configuration II), for the SWL values and 0.04 (configuration I) and 0.09

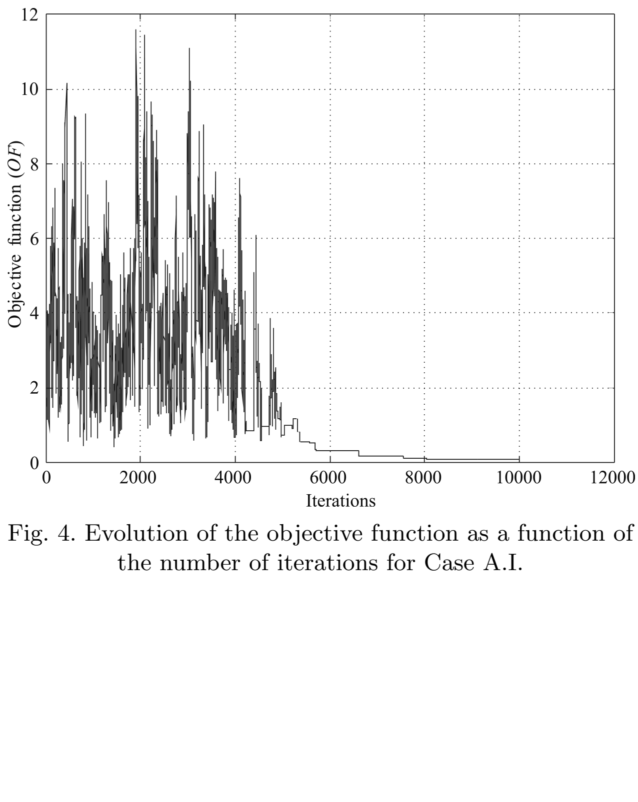

Fig. 4. Evolution of the objective function as a function of the number of iterations for Case A.I.

Table 2. Results from the identification approach. Cases A.I and A.II consider configurations I and II, respectively, without errors in the $\overline{\text{SPL}}$ values. Cases B.I and B.II consider configurations I and II, respectively, taking into account random inherent errors in the $\overline{\text{SPL}}$ values.

Variable	Actual value	Identified value		Identified value	
		Case A.I	Case A.II	Case B.I	Case B.II
SWL_{S1} [dB]	102	101.4	100.5	100.3	101.8
SWL_{S2} [dB]	105	104.0	104.9	106.5	106.9
SWL_{S3} [dB]	114	113.9	114.0	113.2	113.4
SWL_{S4} [dB]	101	101.1	98.7	100.8	103.9
SWL_{S5} [dB]	117	116.9	117.1	116.8	116.8
SWL_{S6} [dB]	100	100.5	101.2	98.0	101.2
SWL_{S7} [dB]	106	105.9	106.4	103.3	104.9
SWL_{S8} [dB]	102	102.1	101.7	103.1	102.3
SWL_{S9} [dB]	100	98.7	102.8	101.3	103.5
SWL_{S10} [dB]	110	109.6	109.9	108.4	108.2
$\alpha_{\text{ceiling 1}}$	0.45	0.42	0.42	0.39	0.42
$\alpha_{\text{ceiling 2}}$	0.70	0.74	0.62	0.63	0.50
$\alpha_{\text{partition}}$	0.25	0.30	0.41	0.40	0.40
OF [dB]		0.064	0.024	0.148	0.102
Mean absolute SWL error [dB]		0.43	0.88	1.31	1.37
Max absolute SWL error [dB]		1.30 (SWL_{S9})	2.80 (SWL_{S9})	2.70 (SWL_{S7})	3.50 (SWL_{S9})
Mean absolute α error		0.04	0.09	0.09	0.13
Max absolute α error		0.05 ($\alpha_{\text{partition}}$)	0.16 ($\alpha_{\text{partition}}$)	0.15 ($\alpha_{\text{partition}}$)	0.20 ($\alpha_{\text{ceiling 2}}$)

(configuration II), for the α values. As expected, results for configuration I (with the greatest number of monitoring points) are the most accurate. For Case B, general results are also satisfactory. Again, calculations for configuration I (Case B.I) are the most accurate. The mean errors for the SWL and α values are less than 1.4 dB and 0.13, respectively. As it can be seen, the majority of the variables are identified with a good accuracy from the practical point of view, excepting for the sound power level of one of the sources (SWL_{S9}, for Case B.II) for which the estimation error is greater than 3 dB. Figure 4 illustrates, for Case A.I, the evolution of the objective function as a function of the number of iterations until the optimal solution ($OF = 0.064$ dB) is reached. Similar graphical reports can be obtained from the rest of the cases studied.

6.3. Reconstruction of the acoustic field

Once the source powers and the surface absorption coefficients have been identified, it is possible to estimate the acoustic field with the SADM. Obviously, this calculation should reproduce with acceptable accuracy the "measured" $\overline{\text{SPL}}$s. In order to illustrate this fact, Fig. 5 shows the noise map generated by means of SADM with the identified variables for Case A.I. In the same figure, one can observe a comparison between the "measured" $\overline{\text{SPL}}$s and predicted SPLs. The former corresponds to discrete numerical values (located near each symbol ○ and ⊗), while the latter are represented by the noise map. A good correspondence is observed.

Finally, to confirm the efficiency of the proposed acoustic diffusion model for the workroom adopted in the example, the SPL values predicted by the SADM are compared with those obtained by the RT technique with the same identified values for the sound power levels and absorption coefficients. Software Catt-Acoustic was employed by the authors for the RT calculations considering $10 \cdot 10^4$ sound rays (for each source). Comparison shown in Table 3, for Case A.I, provides a satisfactory agreement, with a mean and maximum error of about 0.8 dB and 1.9 dB, respectively. Similar results were found for the rest of the cases.

It is important to mention that the use of the SADM for the example presented, involved computation time of less than 1 s for each trial. On the other hand, the corresponding times, when using the ADM and RT technique, are approximately 22 s and 1200 s, respectively. In this way, the overall elapsed time to perform 10 000 iterations, in order to complete the identification, would be of about 2.6 h ($10\,000 \cdot 1$ s), 60 h ($10\,000 \cdot 22$ s), and 3300 h ($10\,000 \cdot 1200$ s), when using SADM, ADM, and RT technique, respectively. This fact represents an important advantage in the context of the identification methodology proposed.

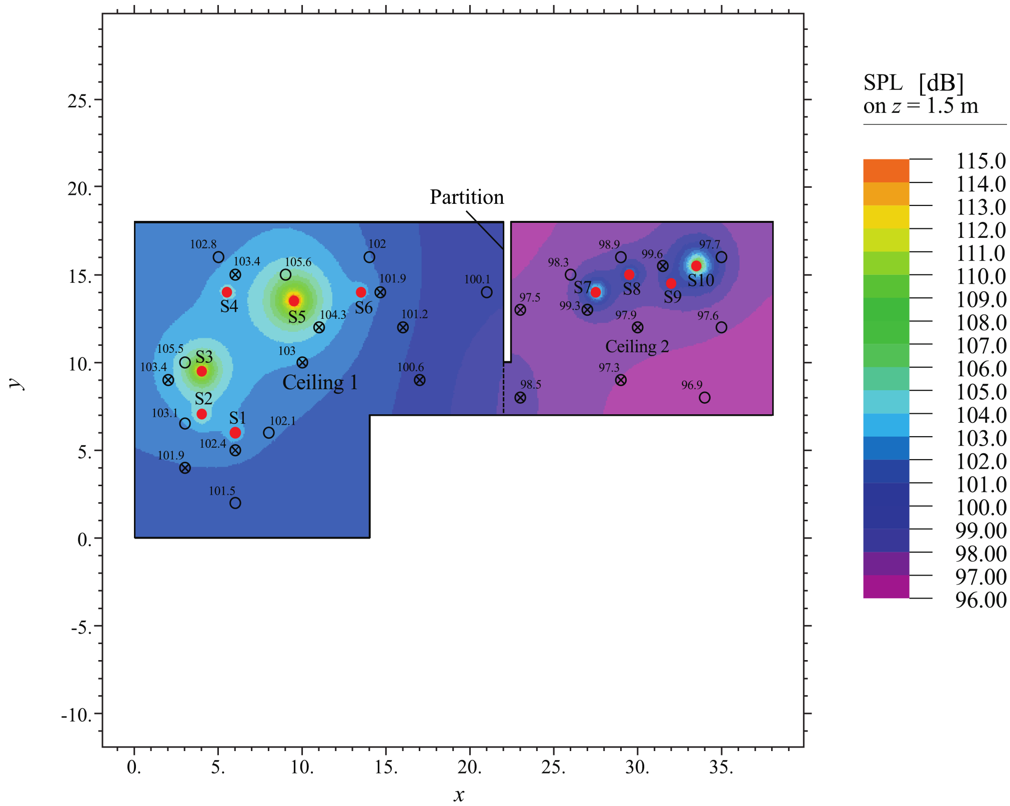

Fig. 5. "Measured" and predicted SPL distribution for Case A.I. The former corresponds to discrete numerical values (located near each symbol ○ and ⊗), while the latter are represented by the colour noise map.

Table 3. Comparison of SPL at the monitoring points for Case A.I (units in dB).

Point	1	2	3	4	5	6	7
SADM	101.5	101.9	102.4	102.1	103.1	103.3	105.4
RT	100.9	101.4	101.7	101.6	102.8	103.6	105.8
Point	8	9	10	11	12	13	14
SADM	102.9	100.7	104.2	101.2	102.8	103.3	105.5
RT	102.3	99.5	104.0	100.2	102.8	103.4	105.0
Point	15	16	17	18	19	20	21
SADM	102.0	101.9	100.2	98.6	97.2	96.7	97.3
RT	101.4	101.3	99.3	97.3	96.3	95.4	95.4
Point	22	23	24	25	26	27	28
SADM	99.2	97.8	97.6	98.1	98.8	99.6	99.7
RT	97.7	96.9	96.5	96.9	97.4	98.5	98.9

7. Conclusions

The important problem of estimating the sound source powers and the absorption coefficients of interior surfaces in multi-source industrial workrooms, from acoustic pressure measurements, was studied. A simple and effective approach for this problem, based on a combination of the simplified acoustic diffusion model (SADM), the finite element method, and the simulated annealing optimisation algorithm, has been presented. The methodology has demonstrated to be accurate and robust enough for its application in industrial environments. The improvement of the SADM over the ADM and RT techniques, in terms of the computation time, has been verified. This fact is the major advantage in the identification procedure because of the large number of iterations needed before an acceptable convergence may be found.

Other important aspects, such as the study of large scale sound sources with directivity and the problems of determining the optimal location and number of monitoring points to employ, will be presented in a future research contribution.

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