



Acoustic field reconstruction in the presence of masking objects

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Abstract – In acoustics, field reconstruction methods aim at retrieving acoustic fields (pressure, velocity and intensity) from acoustic measurements around a radiating source, which is often a vibrating structure of complex shape (pumps, engines...). If they are extensively used in laboratory conditions, their application to in situ characterization is not straightforward due to the presence of disturbing sources or masking objects, or to non-anechoic environments. The inverse Patch Transfer Function (iPTF) approach, thanks to the concept of virtual acoustic volume modelled by a finite element model, has already demonstrated its ability to deal with sources of complex shape and the presence of disturbing stationary sources in a non-anechoic acoustic environment. The objective of this article is to show how the presence of rigid masking objects can be easily and efficiently taken into account. A numerical experiment consisting of a thin, simply supported rectangular plate radiating noise in a semi-infinite acoustic field and partially masked by a rigid parallelepiped is presented. The acoustic fields identified and the directivity diagrams are compared with the reference and show that iPTF is able to cancel the presence of the masking object even if the latter completely covers the radiating plate. Finally, an industrial example consisting in an electric motor in operation is presented. Two configurations were tested: with and without the presence of a rigid object. Comparison of the results shows that the fields identified are in good agreement, demonstrating the ability of iPTF to cancel out the effect of masking objects.

Keywords: Inverse Patch Transfer Function method, Source identification, Source reconstruction, Inverse problem, Masking object, Masked source

1 Introduction

After air pollution, noise pollution is the second environmental element that can contribute to illnesses including hearing loss, sleep disorders, stress, and anxiety. Depression, high blood pressure, cardiovascular disease, or a stroke may result from this [1, 2]. For instance, the primary cause of noise pollution in cities is motor vehicle traffic [3]. To reduce noise output while meeting constraints like weight, volume, or new powertrain technologies, car manufacturers must create novel strategies to eliminate noise sources and assess the distribution of noise around cars.

The first step in optimizing the source vibro-acoustic effect of a source is to characterize it by determining the zones, parts and accessories responsible for radiated noise. A complete characterization of the source is defined by the knowledge of: the normal acoustic velocity field on the surface of the source, the surface pressure field, the active sound intensity field normal to the surface of the source, the radiated sound power and the radiation factor.

Among the experimental approaches for characterizing acoustic sources, the so-called direct and inverse methods

will be distinguished. By direct approach, we mean any experimental method for measuring one of the above-mentioned source features (velocity fields, sound power, etc.). The inverse approach refers to the estimation of the source features by measuring its acoustic radiation quantities. Many inverse experimental identification procedures have been published in the literature in the previous three decades [4–6]. Some have been created to answer specific applications, while others have evolved or even been combined to overcome theoretical restrictions.

There are now sophisticated source identification techniques that distinguish between source localization and field reconstruction techniques.

In 1976, Billingsley and Kinns [7] developed the Beam forming approach, which has since been refined to be useful in closed spaces or for detecting a moving source. It is determined using the Delay and Sum principle [8] and employs a microphone array located in the far field of the source. However, it has limited frequency resolution and is susceptible to the acoustic measuring environment. To counteract this, Pascal et al. [9] estimated the acoustic velocity from finite difference using a P-P probe (a microphone doublet). This method is a qualitative approach focused on source localization and visualization, and it does

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not allow for the reconstruction of fields on the surface of the sources.

In the 1980s, Maynard et al. [10, 11] pioneered Near-field Acoustic Holography (NAH). It is based on the 2D spatial Fourier transform of a complicated acoustic pressure field recorded in the nearfield by a microphone array on a hologram-like surface. This approach has limitations in an industrial setting as sophisticated as that of an engine test bench. In particular, it can only reconstruct sound fields on basic surfaces (planes, cylinders, spheres), it must be performed in a controlled acoustic environment, and it must be performed facing the source with no masking object between the source and the device of measurement (often a microphone array). Hu et al. [12] proposed a modification to work in a noisy environment using double pressure measurements and the knowledge of the source reflection coefficient. This technique recovers the field that would be emitted by the source if it was in a free field state. Chardon et al. [13] and Fernandez-Grande et al. [14] proposed methods to account for spatially sparse solutions.

Alternative methods were created to overcome the constraints of traditional NAH. These approaches are based on the representation of the acoustic field by elementary wave functions, and back-propagation is accomplished by solving an inverse problem without the need of a spatial Fourier transform. The HELS (Helmholtz Equation Least Squares) [15, 16] and SONAH (Statistically Optimized NAH) [17] approaches are the most well-known. Jacobsen et al. [18, 19] suggest SONAH formulations based on combined velocity and pressure measurements.

The iBEM (inverse Boundary Element Method) [20–22] corresponds to the inversion of a BEM formulation of transfer matrices between locations of measurements (pressure) and the nodes of the border elements discretizing the surface of the source. This numerical technique allows one to manage a complicated geometry of the source surface and reconstruct all acoustic fields directly on its geometry. Schuhmacher et al. [23] employed iBEM on a vehicle tyre, whilst Langrenne et al. [24, 25] used a double pressure measurement and the BEM formulation directly as a field separation technique. iBEM accepts the presence of an inhomogeneous environment around the structure. However, it is frequently used at the expense of a very high computing cost.

The Equivalent Source approach (ESM) was first introduced by Koopmann et al. [26] as a simplification of the iBEM approach (inverse BEM). Pereira [27] proposed an extension of ESM in closed acoustic volumes based on an interior problem formulation paired with the usage of a spherical antenna. The fundamental idea of the method is to represent the vibrating structure as a distribution of elementary sources positioned virtually inside the envelope surface of the structure. To manage noisy environments, Bi et al. developed a separation approach based on ESM from a double pressure measurement [28, 29] or a double measurement of particle air velocity [30]. Fernandez et al. [31] proposed a single-surface combined measurement of air pressure and particle air velocity to ensure field separation and to limit the amount of measurements.

Machine learning approaches constitute a quite recent alternative for source localization. Grumiaux et al. [32] proposed a survey of deep learning methods for single and multiple source localization mainly for indoor environments where reverberation and diffuse noise are present. Bianco et al. [33] reviewed machine learning applications in acoustics. Chaitanya et al. [34] introduced machine learning techniques in near-field acoustic holography based on the equivalent source method to improve its results in case of reverberant environments.

The iPTF (inverse Patch Transfer Functions) technique was developed by Aucejo et al. [35], Vigoureux et al. [36], and extended by Forget et al. [37]. It is based on the concept of virtual acoustic volume surrounding the source to characterize. Thanks to the use of a finite element model of the virtual acoustic volume with specific and virtual boundary conditions coupled to pressure and/or particle velocity measurements, iPTF is able to reconstruct any acoustic field (pressure, particle velocity, intensity) directly on the envelope surface of the source, even of complicated shape. As the underlying theory is based on the use of an integral formulation of the pressure field, the method is theoretically non sensitive to stationary disturbing sources outside the virtual acoustic volume. Previous applications have shown that iPTF can be used in non anechoic acoustic environments [38] and on sources with complex shapes [37, 39–41]. The iPTF method has many advantages over other reconstruction methods such as iBEM or NAH, but at a higher computational cost due to finite element solving.

The present article aims at demonstrating that iPTF is also able to handle the presence of rigid (infinite impedance) masking objects located in the virtual acoustic volume or passing through it, like mounting frames. The key point is the use of a finite element mesh with an empty acoustic footprint with Neumann's boundary conditions. It is thus possible to reconstruct the acoustic fields on the envelope surface of the source even if it is largely masked and if it is not possible to pick measurement points in between the source and the rigid masking object. A simple numerical experiment is first performed to explain the process and conduct parametric studies. Then, an industrial application on an electric motor demonstrates the ability of the iPTF approach to handle the presence of rigid masking objects, paving the way to in situ industrial use.

2 Handling the presence of masking objects in the iPTF framework

Consider a vibrating source surface Σ_s radiating noise in any acoustic environment. In the example of Figure 1a, two rigid surfaces Σ_o are located in the vicinity of the source: an infinite rigid baffle and a rigid rectangular box. In the iPTF framework presented in detail in [37], a virtual surface Σ_v delimiting a virtual acoustic volume Ω_v has to be defined. Consider a virtual acoustic volume that encompasses the source and the rigid rectangular box as presented in Figure 1b. In this example, the rigid baffle surface closes the virtual acoustic volume. The pressure $p(N)$ at point N

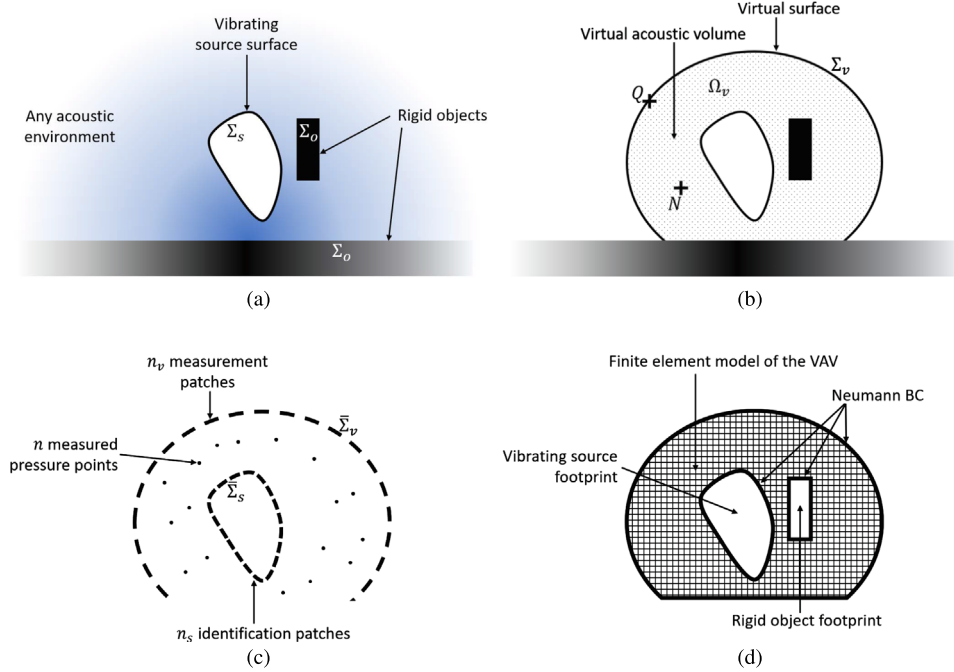


Figure 1. (a) Sketch of a vibrating source surface making noise in a semi-infinite acoustic domain in the presence of rigid objects; (b) Definition of the virtual acoustic volume Ω_v delimited by the virtual surface Σ_v , the vibrating source surface Σ_s and the envelopes of the rigid objects Σ_o ; (c) Localisation of measurement and identification patches and of measured pressure points inside the virtual acoustic volume; (d) Illustration of the Finite Element Model of the virtual acoustic volume (VAV) with Neumann Boundary Conditions.

in the virtual acoustic volume is driven by the the Helmholtz equation

$$\Delta p(N) + k^{*2} p(N) = 0 \quad \forall N \in \Omega_v, \quad (1)$$

where k^* is the complex acoustic wavenumber ($k^* = k(1 + i\eta)$, η being the damping factor of air). As presented in [37], the pressure at point Q can be expressed as a function of virtual mode shapes $\phi_n(Q)$ of the virtual acoustic volume,

$$p(N) = \sum_{n=1}^{\infty} \frac{\phi_n(N)}{\Lambda_n(k^{*2} - k_n^2)} \times \int_{\Sigma} \left(p(Q) \frac{\partial \phi_n(Q)}{\partial n} - \phi_n(Q) \frac{\partial p(Q)}{\partial n} \right) dQ, \quad (2)$$

where k_n is the natural wavenumber of mode n , Λ_n is the norm of mode n ($\Lambda_n = \int_{\Omega_v} \phi_n^2(N) dN$), $\frac{\partial}{\partial n}$ is normal derivative operator and $\Sigma = \Sigma_s \cup \Sigma_v \cup \Sigma_o$ is the enveloping surface of the virtual acoustic volume.

In addition, pressure $p(N)$ respects the Euler's continuity relations,

$$\frac{\partial p(Q)}{\partial n} = -i\omega\rho_0 v_n(Q) \quad \forall Q \in \Sigma_s \text{ or } \Sigma_v, \quad (3)$$

$$\frac{\partial p(Q)}{\partial n} = 0 \quad \forall Q \in \Sigma_o, \quad (4)$$

where ω is the angular frequency, ρ_0 is the air density and $v_n(Q)$ is the particle velocity normal to the surface.

Conversely, the virtual boundary conditions of the virtual acoustic volume can be chosen on purpose.

Considering Neumann boundary conditions for surfaces Σ_s , Σ_v and Σ_o ($\frac{\partial \phi_n(Q)}{\partial n} = 0$), one can write equation (2) as

$$p(N) = \sum_{n=1}^{\infty} \frac{i\omega\rho_0 \phi_n(N)}{\Lambda_n(k^{*2} - k_n^2)} \int_{\Sigma_s \cup \Sigma_v} v_n(Q) \phi_n(Q) dQ. \quad (5)$$

Therefore, the acoustic pressure in the virtual acoustic volume is only a function of normal velocities on surfaces Σ_s (source surface) and Σ_v (virtual surface). Discretizing surfaces Σ_s and Σ_v into elementary surfaces called patches as presented in Figure 1c, one can rewrite equation (5) as two pressure contributions, one coming from normal velocities of the identification patches (source surface Σ_s) and the other coming from normal velocities of measurement patches (virtual surface Σ_v).

$$\mathbf{p}_N = \mathbf{Z}_{Ns} \mathbf{v}_s + \mathbf{Z}_{Nv} \mathbf{v}_v, \quad (6)$$

where $\mathbf{v}_s$ and $\mathbf{v}_v$ are the vectors of normal velocities averaged on patches discretizing respectively the source surface Σ_s and the virtual surface Σ_v . $\mathbf{p}_N$ is the vector of n_N pressure points in the virtual acoustic volume. Finally, $\mathbf{Z}_{Ns}$ (dimension $n_N \times n_s$) is the acoustic impedance matrix between the n_s patches of the source surface and the n_N points in the virtual acoustic volume and $\mathbf{Z}_{Nv}$ (dimension $n_N \times n_v$) is the acoustic impedance matrix between the n_v patches of the virtual surface and the n_N points in the virtual acoustic volume. An element of these matrices giving

the relation between the pressure p_i at a point N_i , when a patch s_j is moving with an averaged normal velocity v_j , is

$$Z_{N_i s_j} = \frac{p_i}{v_j} = i\omega\rho_0 \sum_{n=1}^{\infty} \frac{\phi_n(N_i) \langle \phi_n \rangle_{s_j} S_j}{\Lambda_n(k^{*2} - k_n^2)}, \quad (7)$$

where $\langle \phi_n \rangle_{s_j} = \frac{1}{S_j} \int_{S_j} \phi_n(N) dN$ represents the space average of the mode shape on the surface of area S_j of patch s_j . It should be noted that equation (10) should be understood in a general sense, for any patch discretizing the virtual surface or the source surface.

Finally, one can rewrite equation (6) in an inverse form to express the velocity vector $\mathbf{v}_s$ as

$$\mathbf{v}_s = \mathbf{Z}_{Ns}^{-1}(\mathbf{p}_N - \mathbf{Z}_{Nv}\mathbf{v}_v). \quad (8)$$

Equation (8) is known as the underlying equation of the u-iPTF method (inverse Patch Transfer Function with uniform boundary conditions for the virtual acoustic volume). This equation remains exactly the same with or without the presence of rigid objects in the vicinity of the source to be characterized. The presence of these objects is intrinsically taken into account in the impedance matrices $\mathbf{Z}_{Ns}$ and $\mathbf{Z}_{Nv}$. This point is one of the main interests of the iPTF method as the closed virtual acoustic volume can be modeled using any finite element software as represented in Figure 1d. A rigid object, totally (like the rectangular box in Fig. 1) or partially (like the baffle plan in Fig. 1) included in the virtual acoustic volume, is introduced by removing its “acoustic footprint” (i.e. the volume occupied by the object is replaced by an empty space with Neumann boundary conditions) in the finite element model. The virtual and the real boundary conditions on surface Σ_o being identical, the integral in equation (2) on surface Σ_o is null and the presence of the masking objects is made invisible in equation (8). Thus, the source velocity field on the discretized surface $\bar{\Sigma}_s$ is obtained from equation (8) by computing the impedance matrices using a finite element model of the virtual acoustic volume with the footprints of the rigid objects and by measuring the acoustic pressure at n_N points in the virtual acoustic volume and the normal velocity of each of the n_v patches constituting the discretized virtual surface $\bar{\Sigma}_v$. This is an inverse problem as the matrix $\mathbf{Z}_{Ns}$ has to be inverted. This matrix being ill-conditioned, a regularization step is mandatory: in the following, a Tikhonov regularization associated with the RGCv criterion (Robust Generalised Cross-Validation method) will be used.

An alternative version of the u-iPTF method is introduced in [37] considering a different set of virtual boundary conditions. This other version is called m-iPTF for inverse Patch Transfer Function with mixed virtual boundary conditions. In m-iPTF, the Neumann boundary condition on the virtual surface Σ_v is replaced by a Dirichlet boundary condition. This choice permits expression of the source velocity vector $\mathbf{v}_s$ only as a function of acoustic pressure measurements

$$\mathbf{v}_s = \mathbf{Z}_{Ns}^{-1}(\mathbf{p}_N - \mathbf{Y}_{Nv}\mathbf{p}_v). \quad (9)$$

The counterpart is that the virtual mode shapes of the virtual acoustic volume have to be expressed in terms of pressure to compute $\mathbf{Z}_{Ns}$ and particle velocity to compute $\mathbf{Y}_{Nv}$. Indeed, an element of matrix $\mathbf{Y}_{Nv}$ is given by

$$Y_{N_i s_j} = i\rho_0 \sum_{n=1}^{\infty} \omega_n \frac{\phi_n(N_i) \langle \chi_n \rangle_{s_j} S_j}{\Lambda_n(k^{*2} - k_n^2)}, \quad (10)$$

where χ_n is the mode shape of the virtual volume expressed in velocity and given by Euler's relation:

$$\frac{\partial \phi_n(Q)}{\partial n} = -i\omega_n \rho_0 \chi_n(Q), \quad (11)$$

where $\frac{\partial}{\partial n}$ is the normal derivative operator and ω_n are the natural angular frequencies of the virtual acoustic volume. In any case, the presence of rigid objects follows exactly the same process as the one presented in the case of u-iPTF: a virtual Neumann boundary condition, compatible with the real boundary condition, makes invisible the presence of rigid objects and the underlying equation of m-iPTF remains unchanged. To illustrate this, the u-iPTF will be used in the numerical parametric study in Section 4 (the conclusion would be the same for m-iPTF) and the m-iPTF will be used in the industrial application in Section 6 as it only requires pressure measurements as can be seen from equation (9).

3 Regularization process

The iPTF method, defined by measured and modal input data, depends on the inversion of a direct radiation problem, in particular the inverse of the impedance matrix $\mathbf{Z}_{Ns}$ in equation (8). In regularization theory equation (8) is commonly written as

$$\mathbf{Ax} = \mathbf{y} \text{ with } \mathbf{A} \in \mathbb{C}^{n_N \times n_s}, \mathbf{x} \in \mathbb{C}^{n_s \times 1} \text{ and } \mathbf{y} \in \mathbb{C}^{n_N \times 1}, \quad (12)$$

where

$$\mathbf{A} = \mathbf{Z}_{Ns}, \quad (13)$$

and

$$\mathbf{x} = \mathbf{v}_s, \quad (14)$$

$$\mathbf{y} = \mathbf{p}_N - \mathbf{Z}_{Nv}\mathbf{v}_v. \quad (15)$$

$\mathbf{x}$ is then the quantity to be recovered from the observation of $\mathbf{y}$, given (12). In the iPTF context, matrix $\mathbf{A}$ is ill-conditioned (with or without the presence of masking objects) and a regularization step is mandatory to obtain meaningful results as discussed in [41]. There are many regularization methods available in the literature due to variety of applications and fields of study. In the following, a zero-order Tikhonov regularization will be used [42]. In that case, an estimate of $\mathbf{x}$ is returned by

$$\mathbf{x}_\lambda = \min \{ \|\mathbf{Ax}_\lambda - \mathbf{y}\|_2^2 + \lambda \|\mathbf{x}_\lambda\|_2^2 \}, \quad (16)$$

where λ is the Tikhonov regularization parameter, and $\|\bullet\|_2$ is the l_2 -norm of $\bullet$. The explicit expression of the regularized solution is

Table 1. Parameters values of the numerical experiment.

Parameter	Unit	Value
L_p	[m]	0.6
l_p	[m]	0.4
h_p	[mm]	2
E_p	[GPa]	210
ρ_p	[kg/m ³]	7800
ν_p	[-]	0.3
η_p	[-]	0.02
L_{obj}	[m]	0.7
l_{obj}	[m]	[0.1, 0.3, 0.5]
h_{obj}	[mm]	10
$(x_{obj}, y_{obj}, z_{obj})$	([m], [m], [m])	(0.05, -0.05, [0.01, 0.05, 0.1, 0.15])
(x_F, y_F, z_F)	([m], [m], [m])	(0.1, 0.1, 0.0)
c_{air}	[m/s]	340
ρ_{air}	[kg/m ³]	1.225
η_{air}	[-]	0.005
L_{virt}	[m]	0.8
l_{virt}	[m]	0.6
h_{virt}	[m]	0.2
$(x_{virt}, y_{virt}, z_{virt})$	([m], [m], [m])	(-0.1, -0.1, 0.0)

$$\mathbf{x}_\lambda = (\mathbf{A}^H \mathbf{A} + \lambda \mathbf{I})^{-1} \mathbf{A}^H \mathbf{y} = \mathbf{A}^\# \mathbf{y}, \quad (17)$$

where $\bullet^H$ is the Hermitian transpose of $\bullet$. The optimal regularization parameter λ will be chosen according to the Robust Generalised Cross-Validation method (RGCV) [43, 44] by seeking the minimum of the function

$$\text{RGCV}(\lambda) = \{\gamma + (1 - \gamma) [\text{Tr}(\mathbf{A} \mathbf{A}^\#)]^2\} \frac{\|\mathbf{A} \mathbf{x}_\lambda - \mathbf{y}\|_2^2}{[\text{Tr}(\mathbf{I} - \mathbf{A} \mathbf{A}^\#)]^2}, \quad (18)$$

where $\text{Tr}(\bullet)$ is the trace of $\bullet$, and $\gamma \in [0, 1]$ is the so-called robustness parameter. The regularization process is repeated for each frequency. The regularization parameter found using the RGCV method is therefore frequency-dependent.

4 Proof of concept: a numerical experiment

4.1 System under study

To evaluate the ability of iPTF to handle the presence of masking objects in the vicinity of the source, a simple test case has been set up. It consists in a simply supported rectangular thin plate of length L_p , width l_p and thickness h_p , radiating noise in a semi-infinite acoustic medium filled of air (of sound speed c_{air} , density ρ_{air} and damping factor η_{air}). The plate is made of an isotropic homogeneous material of Young's modulus E_p , density ρ_p , Poisson's ratio ν_p , and a viscous damping factor η_p . The critical frequency of the plate is 5860 Hz. The plate is excited by a point force F located at point $A = (x_F, y_F, 0)$. A multiview orthographic projection can be found in Appendix A. The plate is partially masked by a rigid rectangular box of length L_{obj} , width l_{obj} and thickness h_{obj} . A corner of the rigid object is located at point $C = (x_{obj}, y_{obj}, z_{obj})$. In this section, the

width l_{obj} and the distance to the plate, z_{obj} , are variable quantities. The values of each parameter are listed in Table 1.

4.2 Direct field computation

An example of the radiated pressure field at 900 Hz is given in Figure 2a: this is the numerical experiment used to pick inputs for iPTF (pressure vector p_N and velocity vector v_v in Eq. (8)). The numerical data are computed using the finite/infinite element MSC.Atran software in the frequency band [100:1000] Hz (frequency step of 2 Hz): a finite acoustic volume (different from the one used in iPTF), the shape of which can be seen in Figure 2a, is defined to discretize the acoustic nearfield, and a layer of infinite elements is added on its boundary to ensure Sommerfeld free field condition. A direct frequency response (DFR) was used in ACTRAN software for the calculation of the acoustic radiation. The model takes into account an air damping ratio $\eta_{air} = 0.5\%$ and the infinite elements are interpolated to order 10 to ensure the convergence of the solution.

4.3 Virtual surface and virtual volume

To apply iPTF a virtual surface consisting of five rectangular faces has been defined, as seen in Figure 2b. The virtual surface, the plate surface, the baffle surface and the rigid object surface define a virtual closed acoustic volume that completely encompasses the plate and the rigid object. The virtual acoustic volume is of length L_{virt} , of width l_{virt} and thickness h_{virt} (see in Appendix A and Tab. 1). A corner of the virtual volume is located at point $D = (x_{virt}, y_{virt}, z_{virt})$. The finite element mesh used to compute the virtual mode shapes of the virtual acoustic volume can be seen in Figure 2c. It is composed by tetrahedral linear elements of average size equal to 10 mm. The footprint

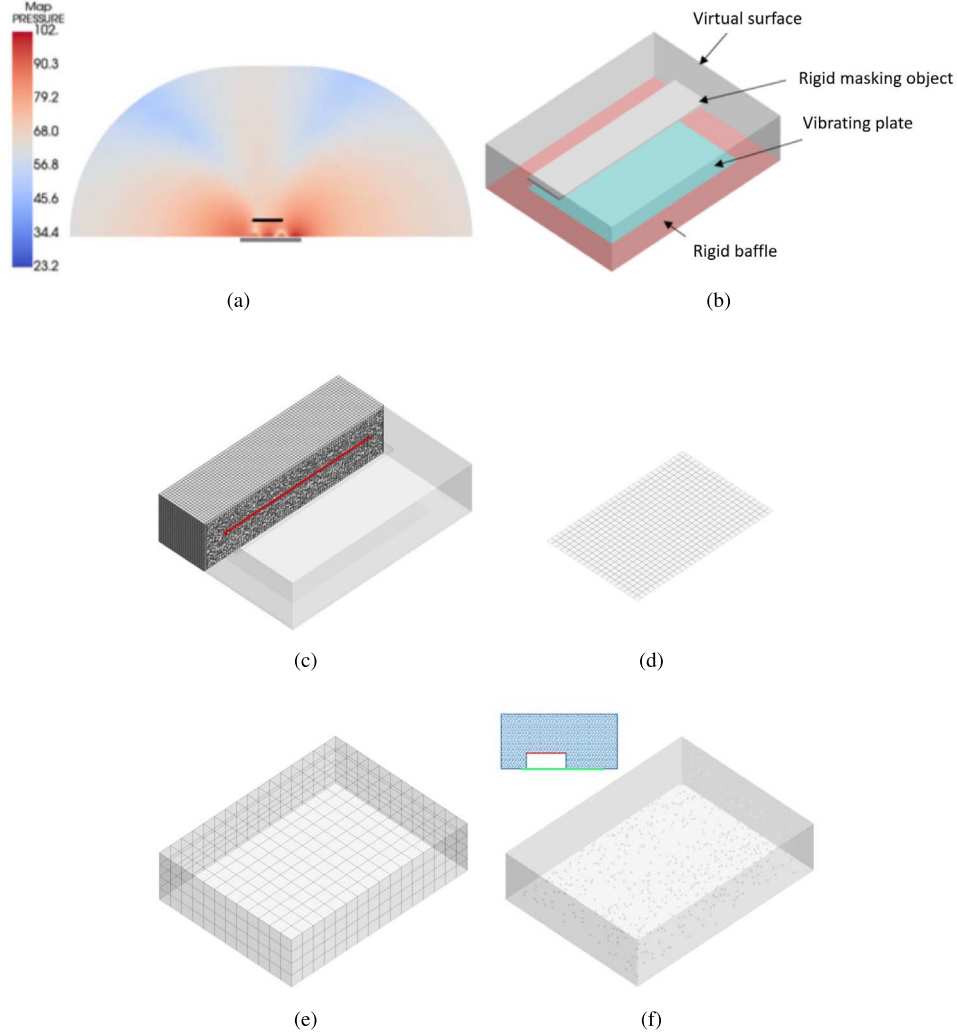


Figure 2. (a) Cut-section view of the acoustic pressure radiated from the excited plate in the presence of a 10 cm wide masking object positioned 10 cm away from the plate at 900 Hz; (b) virtual acoustic volume encompassing the plate and the rigid object; (c) cut-view of the finite element mesh of the virtual acoustic volume; (d) $n_s = 20 \times 30 = 600$ identification patches to reconstruct the acoustic fields; (e) $n_v = 416$ measurement patches on the virtual surface (with a 5 cm side length, which respects at least a four-elements-per-wavelength criterion up to 1000 Hz); (f) n_N pressure points randomly located in the virtual volume (avoiding the space in between the plate and the rigid object, depicted in white in the subfigure).

of the rigid object is visible (highlighted in red) in the cut-view of the mesh in Figure 2c. The plate surface is discretized into $n_s = 20 \times 30 = 600$ identification patches: the objective is to reconstruct the acoustic fields (pressure, velocity, intensity) on the mesh presented in Figure 2d. The virtual surface shown in Figure 2e is discretized into $n_v = 416$ square patches (with a 5 cm side length, which respects at least a 4-elements-per-wavelength criterion up to 1000 Hz). Considering an equally-determined case, $n_N = 600$ pressure points have been chosen randomly (but avoiding the space in between the object and the plate) to build the pressure vector p_N in equation (8) as shown in Figure 2f. Impedance matrices Z_{N_s} and Z_{N_v} in equation (8) are computed using equation (10) and the virtual mode shape extracted from the finite element model up to 6500 Hz (2905 modes).

4.4 Identified acoustic fields

For each frequency in between 0 and 1000 Hz (frequency step 2 Hz), equation (8) is applied following the regularization procedure detailed in Section 3. Thereby, the normal velocity field of each of the n_s patches of the plate surface is obtained: it is the primary unknown. Then, it is possible to retrieve the pressure field and the intensity field on the source surface using a direct formulation of equation (5). Then, one can easily obtain the radiated pressure field from the intensity field and thus also the radiation efficiency. Using the identified velocity field in a direct frequency computation (using a software like MSC.Atran for instance), one can compute the directivity of the source. Therefore, the source is completely characterized, with all the possible acoustic indicators.

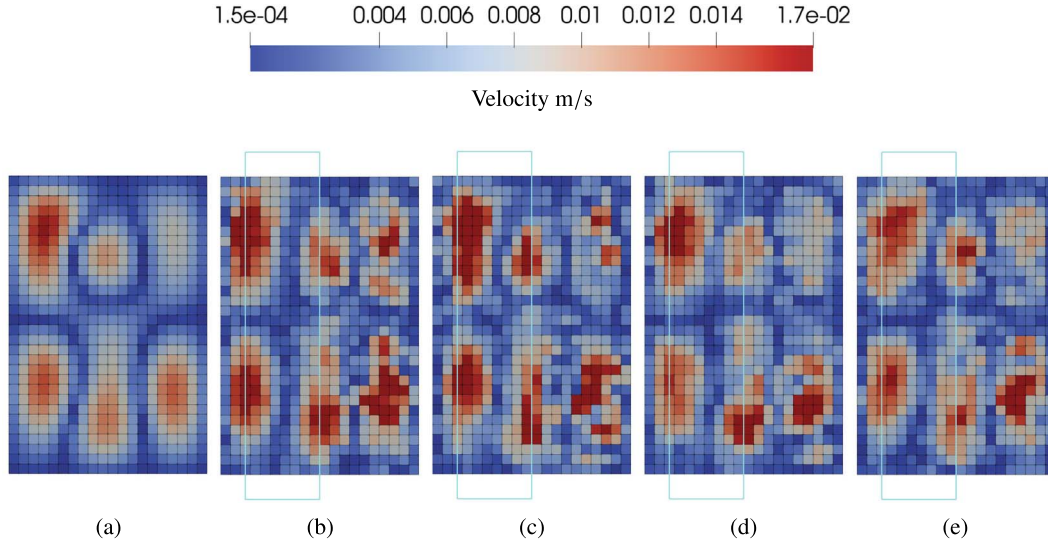


Figure 3. Normal velocity field at 332 Hz. (a) direct reference computation without object; (b)–(e) u-iPTF results with the presence of a 15 cm wide rigid obstacle at a distance of (b) 1 cm, (c) 5 cm, (d) 10 cm, and (e) 15 cm from the plate. The frames represent the shape of the rigid object in top view.

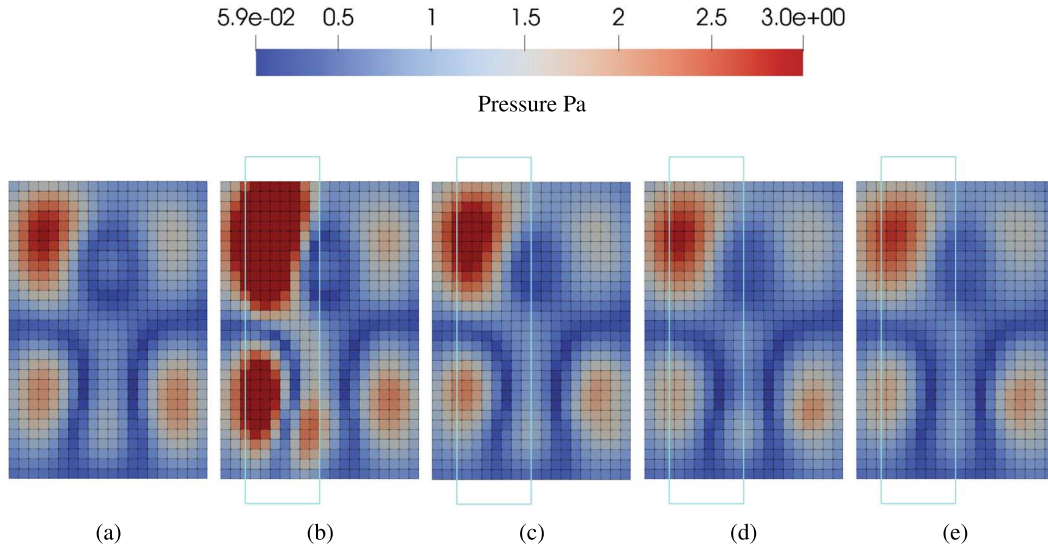


Figure 4. Pressure field at 332 Hz. (a) direct reference computation without object; (b)–(e) u-iPTF results with the presence of a 15 cm wide rigid obstacle at a distance of (b) 1 cm, (c) 5 cm, (d) 10 cm, and (e) 15 cm from the plate. The frames represent the shape of the rigid object in top view.

In the following, for sake of conciseness, only the velocity fields, the wall pressure fields and the directivity will be compared to the reference (computed using a direct frequency response with MSC.Actran).

Figures 3 and 4 compare respectively the identified velocity fields and the identified pressure fields to the reference field at a particular frequency of 332 Hz when the rigid object is at a distance z_{obj} equal to 1 cm, 5 cm, 10 cm and 15 cm, the object width being $l_{\text{obj}} = 15$ cm.

Figure 3 shows that the identified velocity fields are comparable to the reference in terms of spatial distribution whatever the distance of the rigid object even when very

close to the plate. Analyzing Figure 4 shows an even better comparison of the identified pressure fields compared to the reference (the smoothing effect observed on the identified pressure fields has already been observed in [37]) except for the very close distance of 1 cm for which a pressure amplification is observed. This point will be discussed below.

To evaluate the quality of the reconstruction on a large frequency range, the closeness index $\mathcal{CI}$ between two vectors $\mathbf{v}$ and $\mathbf{w}$ given by equation (19) is used.

$$\mathcal{CI} = 1 - \frac{\|\mathbf{v} - \mathbf{w}\|^2}{\|\mathbf{v}\|^2 + \|\mathbf{w}\|^2}, \quad (19)$$

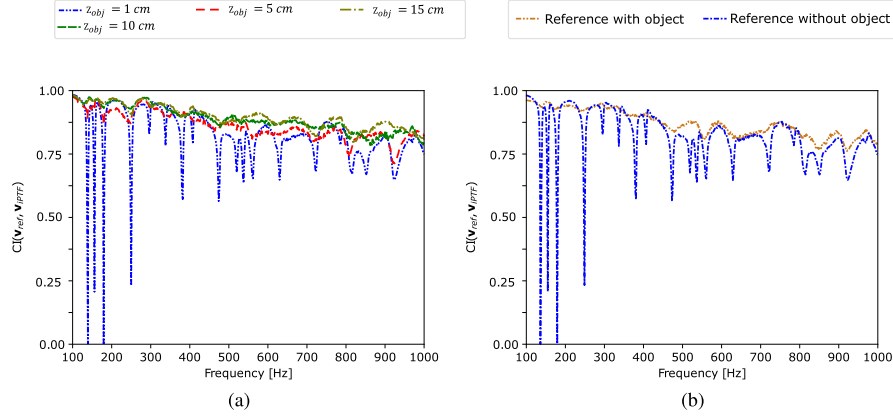


Figure 5. (a) Closeness index between the identified and the reference fields for different z_{obj} values (1 cm, 5 cm, 10 cm, and 15 cm) and for a object width $l_{obj} = 15$ cm. The reference field is the same for each comparison, i.e. the direct computation without rigid object. (b) Closeness index between the identified field obtained for $z_{obj} = 1$ cm and the reference field obtained without or with the presence of the rigid object.

where $\|\mathbf{v}\|$ is the norm of vector $\mathbf{v}$. $CI = 1$ if vectors $\mathbf{v}$ and $\mathbf{w}$ are identical in amplitude and phase, $CI = -1$ if vectors $\mathbf{v}$ and $\mathbf{w}$ are identical in amplitude but opposite in phase and $CI = 0$ if vectors $\mathbf{v}$ and $\mathbf{w}$ are orthogonal. The closeness index thus ranges from -1 to 1 , the objective being to have a closeness index between the identified and reference vectors as close as possible to 1 for all the frequencies in the frequency range under study. Figure 5a presents the closeness indices for the velocity fields identified with the varying distance z_{obj} . In that case, the reference is always the same: the direct computation without object. As can be seen, the quality of the results hardly depends on the distance of the object, except in the case for which $z_{obj} = 1$ cm. For distances ranging from 5 cm to 15 cm, the closeness index is higher than 0.8 in the whole frequency range indicating a good agreement between the identified fields and the reference. This is a unique feature of the iPTF method: in our knowledge, no other field reconstruction method is able to handle the presence of rigid masking objects.

Results for $z_{obj} = 1$ cm presented in Figure 4b (pressure identification) and Figure 5a (velocity identification) suggest that the quality of the reconstruction decreases when the rigid object is too close to the plate: this impression is only due to the choice of the reference to compare with (here the velocity and pressure fields on the surface of the plate in the case without the presence of the rigid object). Indeed, the presence of the rigid object so close to the plate has two effects:

- a pressure increase in the space between the plate and the rigid object as can be seen in Figure 6a;
- a slight frequency shift of the resonances of the plate as can be seen from the mean square velocity spectra plotted in Figure 6b.

The pressure increase observed from the identified maps in Figure 4 actually represents the reality of the pressure field when the object is close to the plate. The sudden drops in the CI observed in Figure 6b at certain frequencies are

due to the mismatch between the resonance frequencies of the plate with and without the presence of the rigid object. Indeed, the frequencies of the sudden drops correspond to the resonance frequencies of the plate and Figure 5b shows that when the identified velocity fields are compared with the right reference (the field computed with the presence of the object thus taking into account the frequency shift), the closeness index is higher than 0.8 and is completely equivalent to the ones obtained for the other distances. Therefore, it means that even for very close objects and without measuring anything in between the plate and the object (in the shadow zone where the pressure field is amplified), iPTF gives good results for all acoustic indicators. Figures 7 and 8 compare respectively the identified velocity fields and the identified pressure fields to the reference field at a particular frequency of 254 Hz when the rigid object width l_{obj} is equal to 15 cm, 30 cm and 50 cm, the object distance being $z_{obj} = 10$ cm. For these three cases, the masking object covers respectively 37.5%, 75% and 100% of the surface of the plate. Once again it is worth noting that no information (pressure points) has been taken in space between the plate and the object. Therefore, only few pressure points are in the direct field of the plate, at least for the two last cases. For the fields presented in Figures 7 and 8 the quality of the reconstruction slightly decreases with the width of the masking object, but it remains surprisingly good even when the plate is completely covered by a rigid object placed at 10 cm from it, even though velocity reconstruction always gives rougher results than pressure reconstruction.

Figure 9 shows the closeness index for frequencies in between 100 Hz and 1000 Hz. As seen in Figure 7, at 254 Hz the closeness index is high, around 0.75. However, the quality of the reconstruction strongly decreases with frequency when the width of the masking object increases. This is due to a lack of information, most of the pressure points being taken on the other side of the object. Therefore, for the extreme case of a masking object bigger than the source to identify itself, no information is captured in

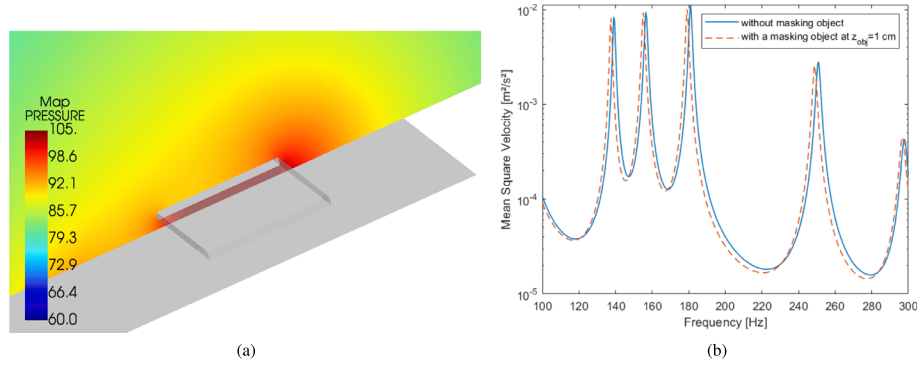


Figure 6. Effects of the presence of a rigid object very close to the plate ($z_{\text{obj}} = 1$ cm). (a) Pressure amplification in the small space between the plate and the rigid object; (b) Slight frequency shift of the plate resonances observed on the mean square velocity of the plate compared to the case without rigid object.

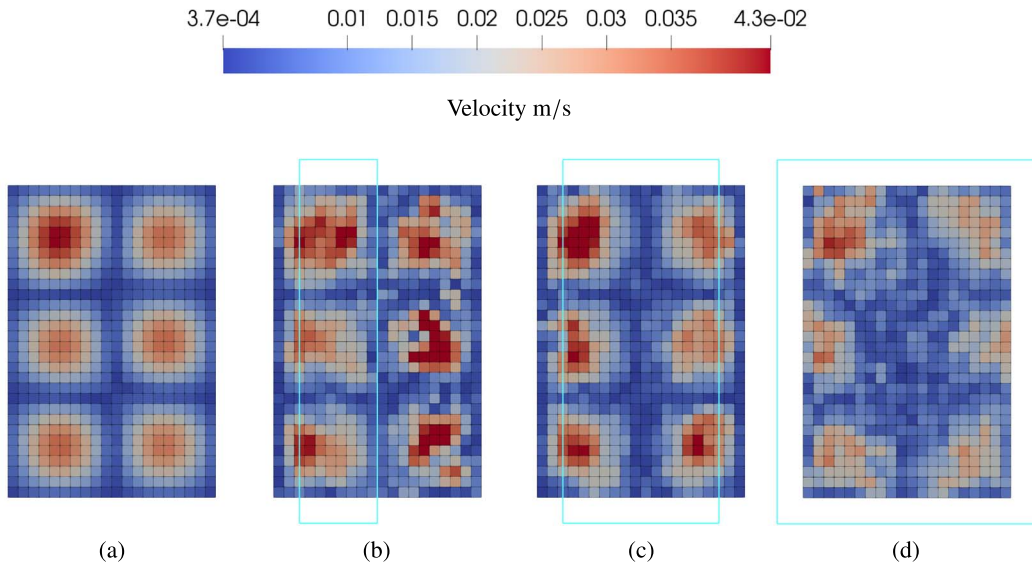


Figure 7. Normal velocity field at 254 Hz. (a) direct reference computation without object; (b)–(d) u-iPTF results with the presence of a rigid obstacle at a distance of 10 cm from the plate and a width of (b) 15 cm, (c) 30 cm, and (d) 50 cm. The frames represent the shape of the rigid object in top view.

the vicinity of the source and most of the microphones are almost isolated from the source. But even for this extreme case, the identified maps are not meaningless as can be seen in Figures 7 and 8. Indeed, the fields are somehow distorted, producing a low $\mathcal{CI}$ value, but the spots and the maximum values of velocity and pressure agree relatively well with the reference. Such interesting results were not expected when setting up this test case. This shows how iPTF is robust and that it can be used in configurations for which no other method can be applied.

However, putting some microphones in the shadow zone clearly improves the quality of the results as demonstrated by Figure 9b (note that placing microphones in between the plate and the object which is not very practical experimentally). The effect of putting microphones in the masked zone is clearly beneficial but not mandatory, which paves the way to an experimental applicability of iPTF even in a presence of large masking objects.

Lastly, Figures 10 and 11 demonstrate that the iPTF results can be used to estimate the source directivity even if it is masked by an object. Figures 10b and 11b show the directivity plots computed from the direct frequency responses using MSC.Actran with and without the presence of the masking objects: these plots demonstrate that the acoustic field is modified by the presence of the rigid object, as expected. Figures 10c and 11c plot the directivity obtained when the identified velocity fields are used as an input of a direct frequency response in a semi-infinite medium (without object). In Figure 10c, the identified directivity plots are clearly equivalent to the reference one without the masking object: iPTF can thus be used for an in-situ estimation of the directivity of a source even if it is masked by objects. It has the ability to cancel the influence of the masking object on the directivity plots.

The directivity plots drawn in Figure 11c present some discrepancies especially when the object is 30 cm or 50 cm

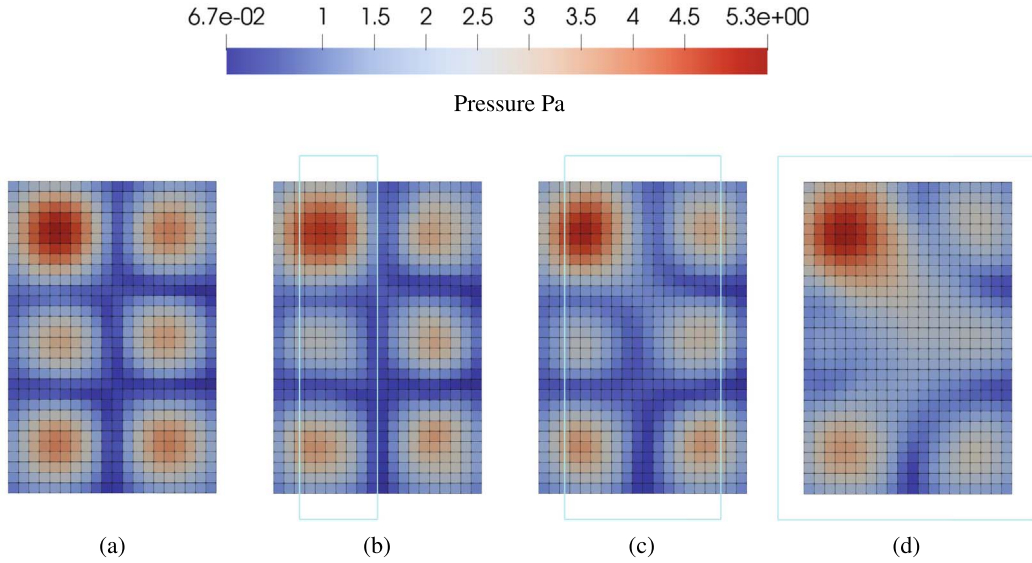


Figure 8. Pressure field at 254 Hz. (a) direct reference computation without object; (b)–(d) u-iPTF results with the presence of a rigid obstacle at a distance of 10 cm from the plate and a width of (b) 15 cm, (c) 30 cm, and (d) 50 cm. The frames represent the shape of the rigid object in top view.

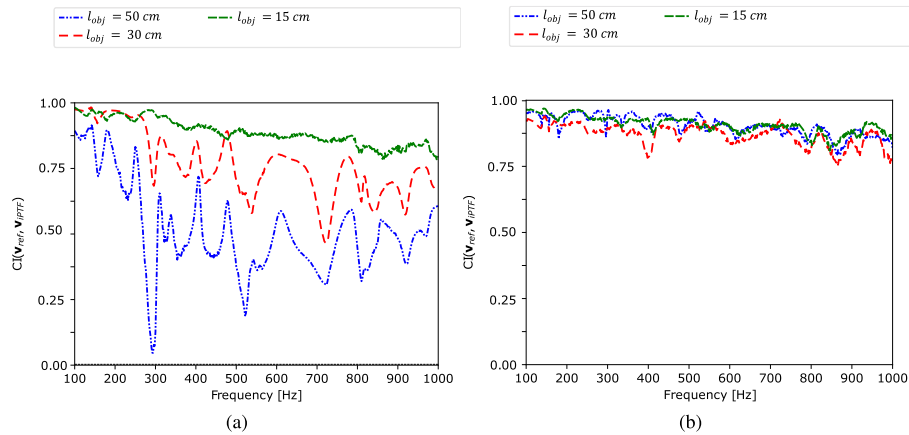


Figure 9. Closeness index between the identified and the reference fields for different l_{obj} values (15 cm, 30 cm and 50 cm) and for a distance $z_{obj} = 10$ cm. The reference field is the same for each comparison, i.e. the direct computation without rigid object. (a) By avoiding picking pressure points in the shadow of the object; (b) by authorizing picking pressure points in the shadow of the object.

wide. Again, it is due to the fact that when no pressure point is taken in between the plate and the object, the identified velocity fields are distorted as seen in Figure 7. When leaving the possibility of taking some pressure points in between the plate and the object (Fig. 9b), the identification of the directivity is almost perfect as shown in Figure 11d.

5 Industrial application

5.1 System under study

The system under study is the Siemens XiL test rig [45] shown in Figure 12a. It is composed of an electrical motor, the so-called SimRod e-motor, coupled to a load motor

through a coupling unit. A load is applied to the SimRod e-motor using the load motor. The whole system is rigidly mounted on a heavy frame uncoupled from the rest of the workshop. There is no special acoustic treatment in the workshop and thus the acoustic environment is not anechoic. Also, electric cabinets (one of them is visible in Fig. 12a) placed in the vicinity of the system emit some stationary disturbing noise. During the test, the speed is increased during 5 s from 0 to 2500 rpm and then is kept constant for approximately 17 s. During this constant speed step, the corresponding torque remains in between 10 and 14 Nm. Then, the speed is linearly decreased to 0 in approximately 5 s. In all the runs, the cooling fan visible on the SimRod e-motor in Figures 12a and 12c was off.

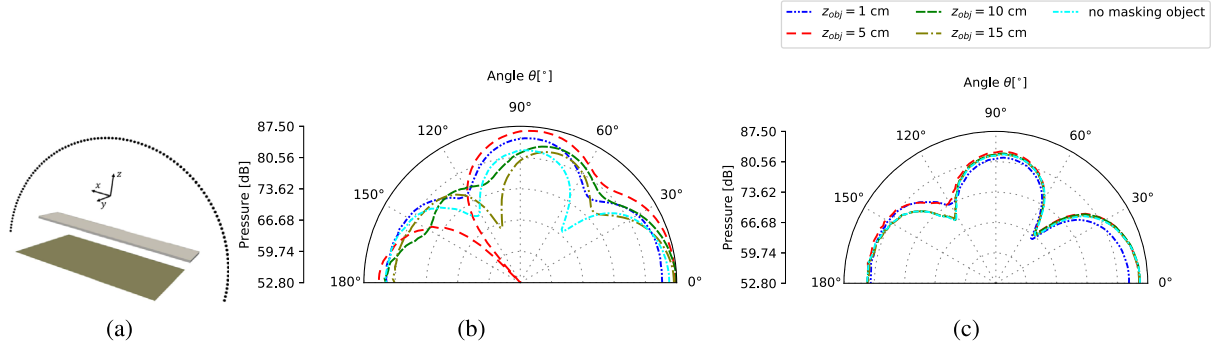


Figure 10. Directivity of the source at 636 Hz in the case of a rigid object of width $l_{obj} = 15$ cm located at distances z_{obj} equal to 1 cm, 5 cm, 10 cm and 15 cm. (a) sketch of the microphone positions on a semicircle in the ZX plan; (b) directivity plots obtained from the direct computation with the rigid masking object; (c) directivity plots obtained from the velocity fields identified by iPTF with the rigid masking object.

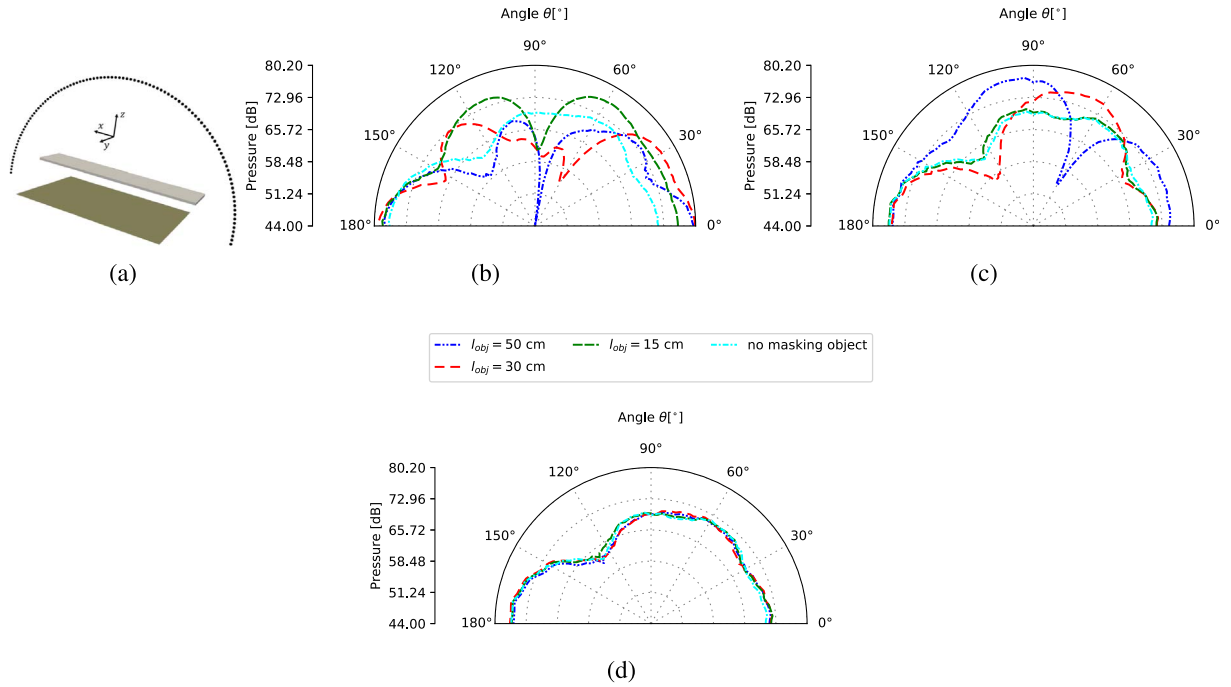


Figure 11. Directivity of the source at 1000 Hz in the case of a rigid object of width l_{obj} equal to 15 cm, 30 cm, and 50 cm located at a distance $z_{obj} = 15$ cm. (a) sketch of the microphone positions on a semicircle in the ZX plan; (b) directivity plots obtained from the direct computation with the rigid masking object; (c) directivity plots obtained from the velocity fields identified by iPTF with the rigid masking object without any pressure points taken in the shadow of the object; (d) directivity plots obtained from the velocity fields identified by iPTF with or without the rigid masking object with pressure points also taken in the shadow of the object.

The acquisitions used as an input for iPTF were performed only during the step with a constant speed of 2500 rpm and an applied torque ranging in between 10 and 14 Nm.

5.2 Definition of the virtual acoustic volume

5.2.1 Identification patch mesh

The identification patch mesh presented in Figure 12d consists of triangular elements of 30 mm side to respect at

least a $\lambda/4$ criterion (four elements per wavelength) in the $[0 \dots 2000]$ Hz frequency range. In addition, this size allows a correct description of the 3D shape of the SimRod e-motor without too much details. The identification patch mesh is then composed of 716 patches.

5.2.2 Virtual surface patch mesh

The virtual surface surrounding the SimRod e-motor is composed of four planar measurement surfaces on the right, left, front and top sides. The four surfaces comprise square

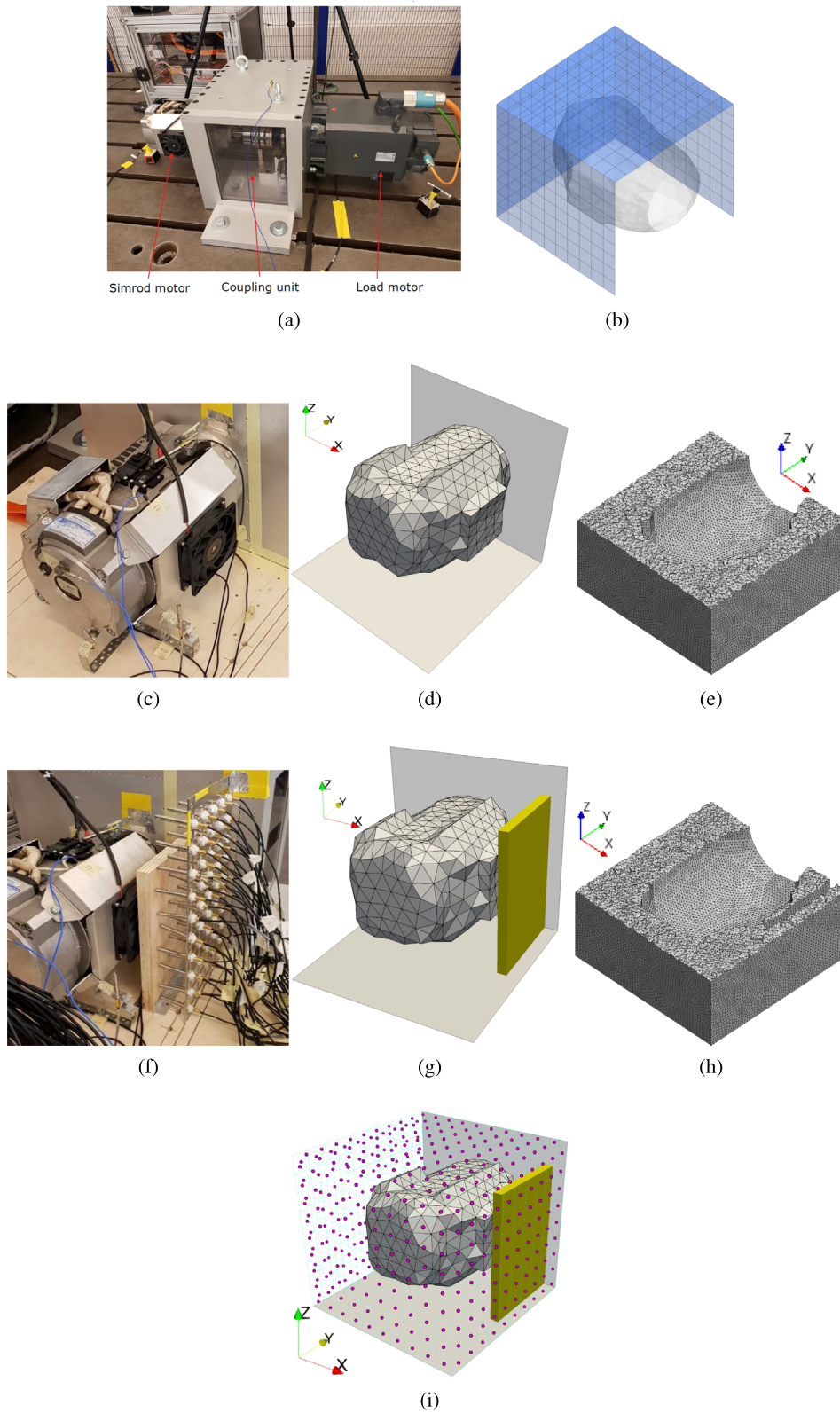


Figure 12. (a) Picture of the complete system; (b) surfaces of measurement patches and shape of the SimRod e-motor; (c) picture of the SimRod e-motor; (d) identification patch mesh; (e) FE mesh of the virtual acoustic volume; (f) picture of the SimRod e-motor with the presence of a masking object; (g) position of the masking object with respect to the identification patch mesh; (h) FE mesh taking into account the footprint of the masking object; (i) positions of the microphones inside the virtual acoustic volume (for both configurations).

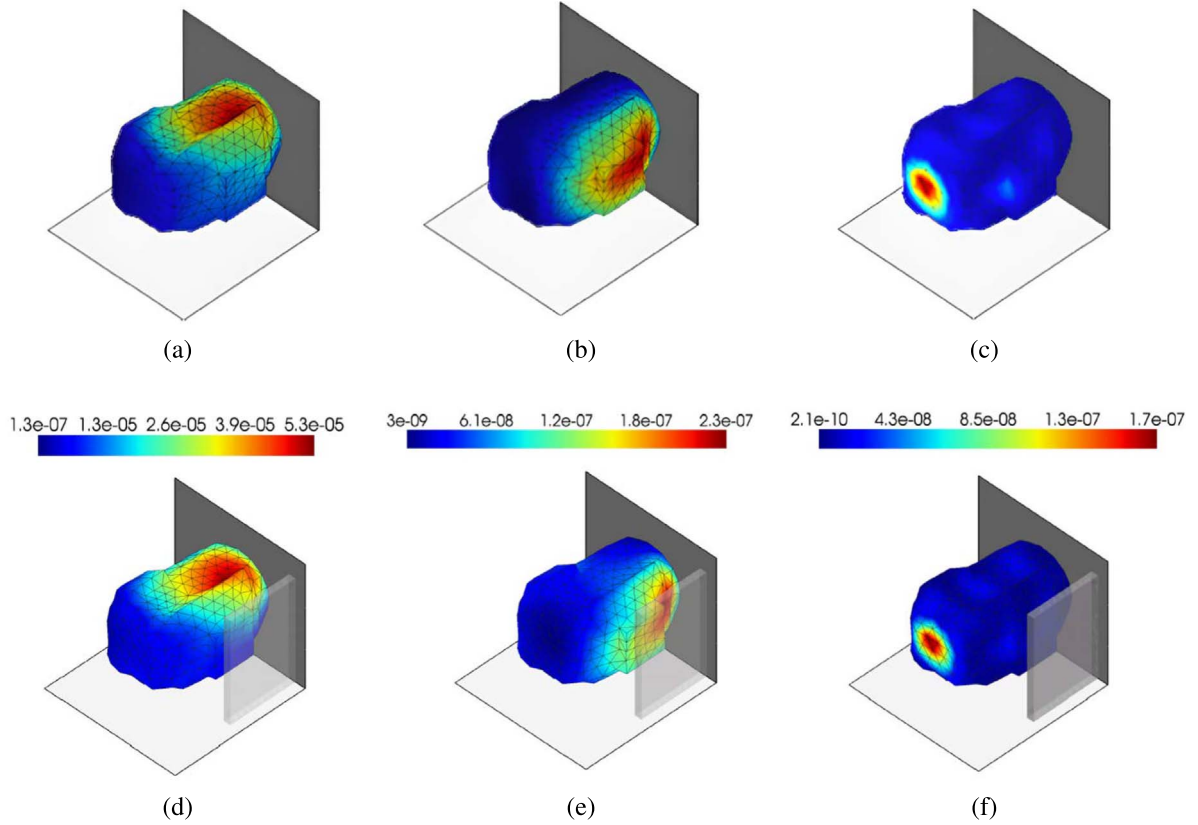


Figure 13. Intensity [W/m^2] fields identified with m-iPTF at (a) and (d) 453 Hz, (b) and (e) 544 Hz, and (c) and (f) 1992 Hz. (a)–(c) Identification without the presence of rigid masking object; (d)–(f) Identification with the presence of rigid masking object.

patches of dimensions 40×40 mm as can be seen in Figure 12b. This patch size allows the use of iPTF up to 2 kHz with a $\lambda/4$ criterion. The left, right and front surfaces are divided into 10 (horizontal) $\times$ 9 (vertical) patches. The top surface is divided into 10×10 patches. The total number of patches is 370. The ground and the surface of the coupling unit will be considered as two physically rigid surfaces and, as such, will not be discretized into patches.

5.2.3 Virtual volume mesh

The virtual volume is defined as the acoustic volume surrounded by the union of the four planar measurements surfaces composing the virtual surface described previously and two physically rigid surfaces (ground and surface of the coupling unit). The virtual volume consists then of a box with the footprint of the SimRod e-motor whose shape is described by the virtual surface patch mesh, as can be seen in Figure 12e. The orange wires, visible in Figure 12c were not taken into account in the virtual volume and, as such, their influence is assumed to be negligible.

To compute natural frequencies and mode shapes of the virtual acoustic volume up to 8 kHz, an average side length of approximately 8 mm is set for the tetrahedral elements. 2102 mode shapes are then extracted for the virtual volume between 0 and 8 kHz and will be used in

equation (10) to compute the impedance matrices. Finally, 694 field points are located inside the virtual acoustic volume (see Fig. 12i).

Another configuration presented in Figures 12f–12h consists in the same configuration as previously described but with an additional rigid object inside the virtual acoustic volume. The object is a wooden 200 mm wide, 300 mm high and 20 mm thick rectangular panel placed at some centimeters in front of the fan, as can be seen in Figures 12f and 12g. It is considered rigid, so no patch is defined on its surface and its footprint is taken into account in the FE mesh (Fig. 12h). Except for one removed position of the microphone antenna, the rest of the configuration and the operating conditions are the same as in the previous case. The objective is here to verify that the presence of the rigid object doesn't affect the acoustic maps identified on the surface of the source.

5.3 Acoustic measurements

The m-iPTF approach (Eq. (9)) has been used in this experiment. This choice was driven by the available sensors: an array of microphones. However, u-iPTF and m-iPTF have the same tendencies when dealing with the presence of a masking object. The array, specially designed for the application (see Fig. 12f), is constituted of 5×10 microphones with a spacing of 4 cm in both directions. The acoustic

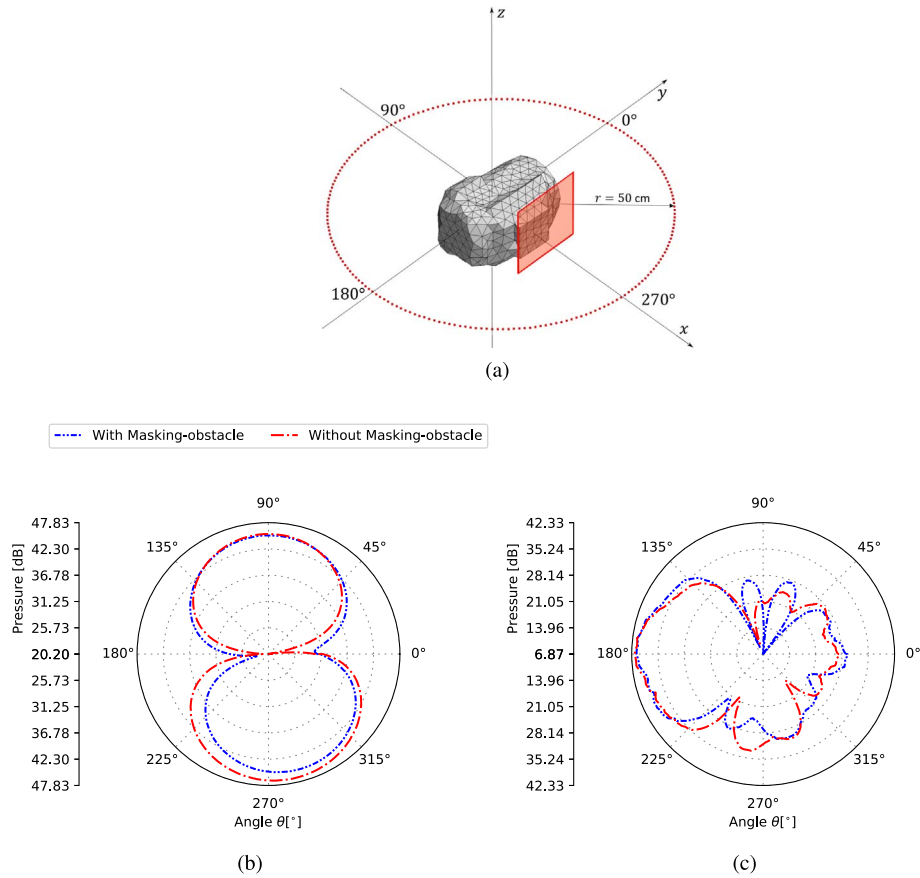


Figure 14. (a) Sketch of the virtual microphone positions on a circle in the XY plan with respect to the position of the SimRod e-motor and the approximate location of the masking object (red rectangle). Directivity plots at (b) 544 Hz and (c) 1992 Hz.

pressure at the centroids of the virtual surface patches has been measured by moving the array sequentially (2 positions per face, 8 positions in total). As the measurements were sequential, some fixed references were defined: 5 microphones located close to the SimRod e-motor and 2 triaxial accelerometers glued directly on the e-motor.

To measure the acoustic pressure at the 694 field points inside the virtual cavity, the array was moved toward the center of the virtual volume at two different positions spaced by 2 cm. The slots used to put the array in position are visible in Figure 12f.

The signals of the sensors were recorded during the whole run, but only 10 s in the steady state were kept, with a sampling frequency of 40.960 kHz. The signals acquired for the different positions of the array were synchronized on the same event analyzing the signal of one of the microphones used as a fixed reference. The signals were then cut in 10 windows of 1 s, weighted by a Hanning window. Then a temporal-to-frequency conversion was done using a fast Fourier transform. Finally, a phase reference was chosen for all the positions of the array and the spectra were averaged. It resulted in 370 spectra for the measurements on the virtual surface and 694 spectra for the measurements at the field points inside the volume. Each spectrum has a

frequency range from 0 to 2000 Hz with a frequency step of 0.5 Hz.

5.4 Field reconstruction and directivity results

Figure 13 presents the comparison between the intensity fields identified for both configurations (with and without the rigid object) at three different frequencies (453, 544 and 1992 Hz). As in Section 2, it is here expected to obtain the same intensity fields, independently of the presence of the object. Figure 13 demonstrates that the identified fields agree well for the three frequencies. However, at 453 and 1992 Hz, considering the position of the object with regards to the position of the spots of acoustic intensity, one can argue that the presence of the rigid object might not affect the radiated field. Indeed, the masking object is actually not masking the zones with high intensity. It is not the case at 544 Hz. At this frequency, the spot of maximum intensity is located just behind the masking object, itself positioned at only some centimeters from the SimRod e-motor. In addition, no pressure measurements were performed in the shadow zone in between the rigid object and the source. This configuration is very challenging and no other method, to our knowledge, is able to reconstruct this kind of acoustic

fields in such a cluttered environment. Figure 13e proves that iPTF has this powerful feature, as the reconstructed field is in good agreement with the one obtained without the masking object.

Figure 14 shows the directivity plots at frequencies 544 Hz and 1992 Hz. They were obtained using the velocity fields identified in both configurations as an input for a direct frequency response computation using MSC.Actran (in free field condition). Here again, the two estimates of the directivity plot are in good agreement. In particular, for 544 Hz, the identified main lobes are oriented in the direction of the rigid object: this proves that the effect of the rigid object is canceled in the estimation of the directivity.

6 Conclusion

The presence of rigid objects like mounting frames often makes complicated the in situ acoustic characterization of vibrating structures with field reconstruction methods like NAH-like or iBEM approaches. Thanks to the concept of virtual acoustic volume, the inverse Patch Transfer Function can be used to face this issue. Indeed, the rigid objects can be part of the virtual acoustic volume and no additional measurements are required: the presence of the object is taken into account in the finite element mesh of the virtual acoustic volume as an empty footprint with Neumann's boundary conditions.

This procedure was evaluated in a numerical experiment in which a simply supported rectangular thin plate is partially masked by a rigid parallelepiped. It was demonstrated that the identified acoustic fields were in accordance with the reference ones, obtained without the presence of the object. Then, the identified velocity fields could be used to evaluate the directivity plots as if the source was placed in an anechoic environment: the presence of the rigid object was canceled.

The approach was then tested on a real industrial application consisting of an electric motor in operation. The reconstructed acoustic fields obtained with a masking object intentionally placed in the vicinity of the motor were compared to those obtained without the object. The accordance of results demonstrated that the iPTF approach is able to handle the presence of rigid object directly in the vicinity of a complex source, a unique feature.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

The data corresponding to numerical applications are available from the corresponding author on request.

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Appendix A. Multiview ortographic projection of the numerical experiment

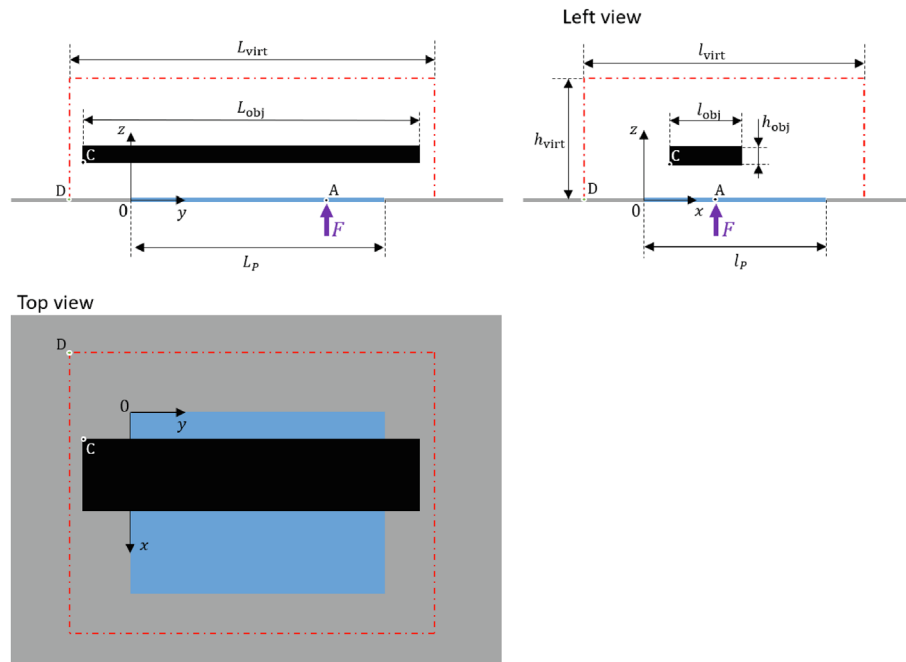


Figure A1. Normal velocity reconstruction of a plate in a noisy environment in the presence of an obstacle.

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