The 32nd International Congress and Exposition on Noise Control Engineering
Jeju International Convention Center, Seogwipo, Korea,
August 25-28, 2003

[N382] Acoustic Source Localization based on Pressure and Particle Velocity Measurements

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ABSTRACT

Inverse source identification techniques are used to find the acoustic sources on the surface of a sound radiating object. One of the most general applicable methods is the inverse frequency response function method (IFRF). The standard IFRF technique uses acoustic pressure measurements performed on a measurement grid in the nearfield of an acoustic source to determine the corresponding normal velocities on the surface of the source. To relate the measured field pressures to the surface vibrations, a transfer matrix is calculated with a boundary element solver (BEMSYS). In the source localization process, this matrix needs to be inverted in order to predict the original surface normal velocities. Generally, the transfer matrix is ill-conditioned and can only be solved by applying regularization techniques.

In this paper, apart from conventional pressure measurements, it is investigated whether the nearfield particle velocities, measured with a Microflown sensor, can be used to reconstruct the original source vibrations. By means of an experimental setup, a comparison is made between pressure based and velocity based IFRF.

KEYWORDS: Acoustic source localization, BEM, IFRF, Inverse problems, Microflown

INTRODUCTION

Exterior structural acoustics focuses on the relation between vibrations on the surface of a structure and the radiated sound field. In the IFRF source localization technique, the vibration patterns at the source surface are unknown and have to be determined from the sound field measured at several points near the source surface.

Conventionally, these source localization methods are based on acoustic pressure measurements. However, due to recent developments in sensor technology it is possible to directly measure acoustic particle velocity with the so-called Microflown sensor (www.microflown.com). In an earlier study [8] it was shown by means of numerical simulations that the IFRF method based on particle velocity measurements would, from a theoretical point of view, lead to improved reconstructions of the surface vibrations. This paper deals with the experimental validation of this novel IFRF method in order to confirm these numerical findings.

EXPERIMENTAL SETUP

The experimental setup, as shown in figure 1, consists of a hollow aluminum box with 30 mm thick walls. A flexible aluminum plate (1.1 mm thick) is clamped to the box by means of reinforcement strips that are bolted to the box. The top of box is covered with a 30 mm thick plate. Inside the box a loudspeaker generates an interior sound field, in the frequency range 200-1200 Hz, that causes the flexible plate to vibrate. Eventually, this plate vibration results in a sound field outside the box.

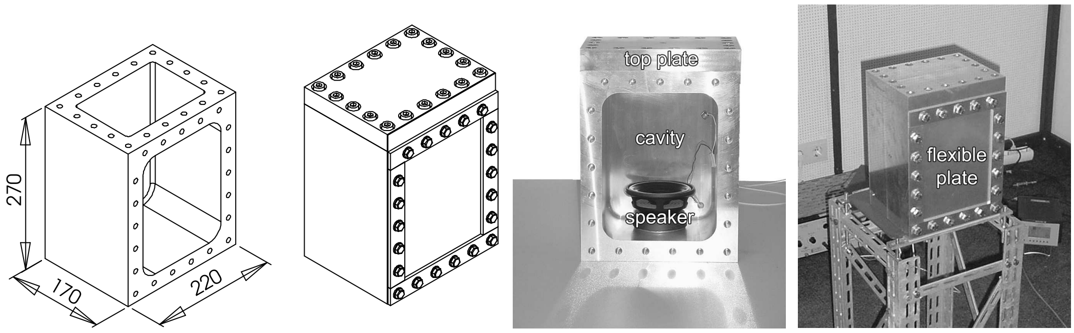


Figure 1: The experimental setup consists of an aluminum box with 30 mm thick walls. This study focuses on the configuration where a rigid and a flexible plate are attached to the top and front of the box respectively.

In order to obtain the relation between the acoustic quantities surrounding the box and the structural normal velocity of the box, a boundary element model is made as shown in figure 2. The source mesh of the model consists of 898 linear triangular elements with a total of 463 nodes. On a plane at a distance of 30 mm from the flexible plate an exterior field mesh consisting of 256 nodes is defined.

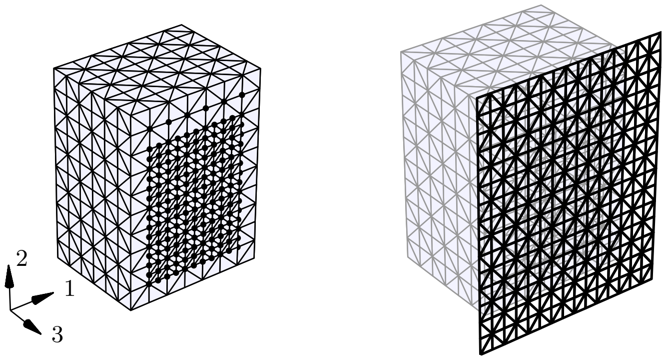


Figure 2: Source surface mesh of the box (left) and field mesh at a distance of 30 mm in front of the box (right). The field grid consists of 16x16 measurement points.

To obtain a reference solution for the source localization methods, a laser vibrometer is used to measure the surface normal velocity of the flexible plate at 171 nodes of the BEM mesh (see dots in left side of figure 2). In the considered frequency range, it is allowed to assume that the thick walls of the box have a negligible surface velocity compared to the flexible front plate. As a consequence, all the radiated sound originates from the front plate. Both the positioning and data acquisition of the sensors is completely automated under the Matlab environment.

BASIC RELATIONS

Conventional pressure based IFRF

In conventional IFRF methods [3, 4, 6] the task is to obtain the unknown surface velocities in normal direction ($\mathbf{v}_n$) from the acoustic pressures ($\mathbf{p}_f$) measured at the field grid. This is done by solving $\mathbf{v}_n$ from the following system of equations

$$\mathbf{p}_f = \mathbf{H}_p \cdot \mathbf{v}_n \tag{1}$$

where transfer matrix $\mathbf{H}_p$ represents the discretized equivalent of the Helmholtz integral equation [1, 5, 7].

Unfortunately, system (1) is a discrete ill-conditioned problem, which implies that arbitrary small perturbations in the measured pressure signal result in large errors in the solution of the surface velocities. Nevertheless, a meaningful solution can be found in both physical and mathematical terms with the help of regularization methods. It is known [3, 6] that standard regularization techniques like truncated singular value decomposition or Tikhonov regularization give adequate solutions in IFRF techniques. In this paper, a more efficient iterative least squares method (LSQR) was used to solve the system of equations [2].

Novel particle velocity based IFRF

In contrast with the conventional pressure based IFRF method, the proposed novel source identification method uses the acoustic particle velocities instead of pressures as measured field quantity. According to Euler's equation of motion, the particle velocities can be calculated by taking the gradient of the Helmholtz integral equation. The developed boundary element solver BEMSYS is then used to derive the transfer matrices from surface normal velocity to acoustic particle velocity in the field grid.

Once the transfer matrices are known, the surface velocity can be reconstructed in several ways by separately solving each of the following systems

$$\mathbf{v}_1 = \mathbf{H}_{v_1} \cdot \mathbf{v}_n \qquad \mathbf{v}_2 = \mathbf{H}_{v_2} \cdot \mathbf{v}_n \qquad \mathbf{v}_3 = \mathbf{H}_{v_3} \cdot \mathbf{v}_n \tag{2}$$

where $\mathbf{v}_1, \mathbf{v}_2$ and $\mathbf{v}_3$ are the three mutually perpendicular field velocity components as indicated in figure 2.

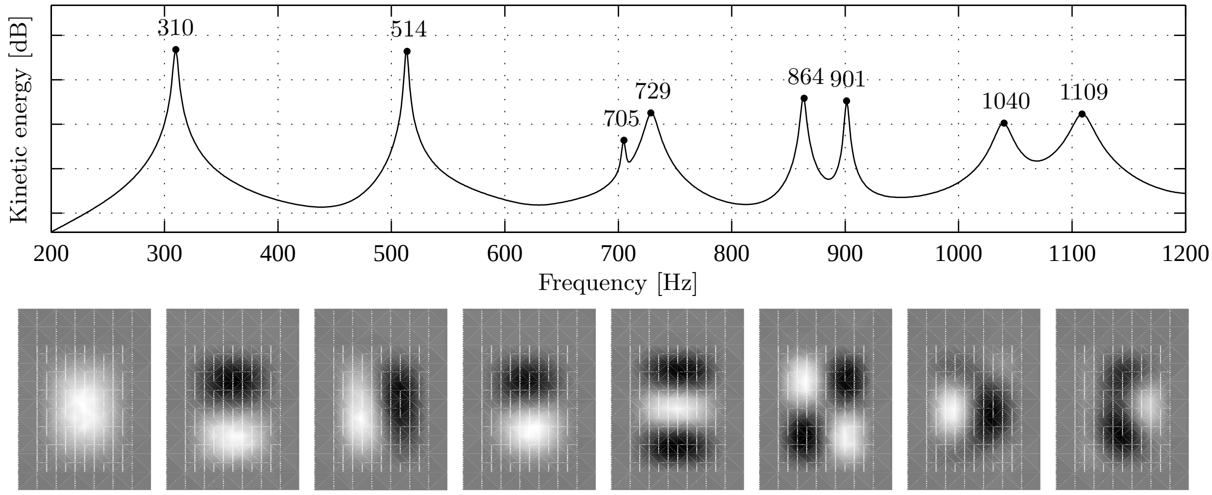
Of course when multiple sensors are applied simultaneously, it is possible to solve combinations of the (sub)systems (1) and (2), for example

$$\begin{Bmatrix} \mathbf{p}_f \\ \mathbf{v}_3 \end{Bmatrix} = \begin{bmatrix} \mathbf{H}_p \\ \mathbf{H}_{v_3} \end{bmatrix} \cdot \mathbf{v}_n \tag{3}$$

Like in the conventional IFRF method, the systems of equations based on particle velocity are also ill-conditioned and require regularization [6].

RESULTS

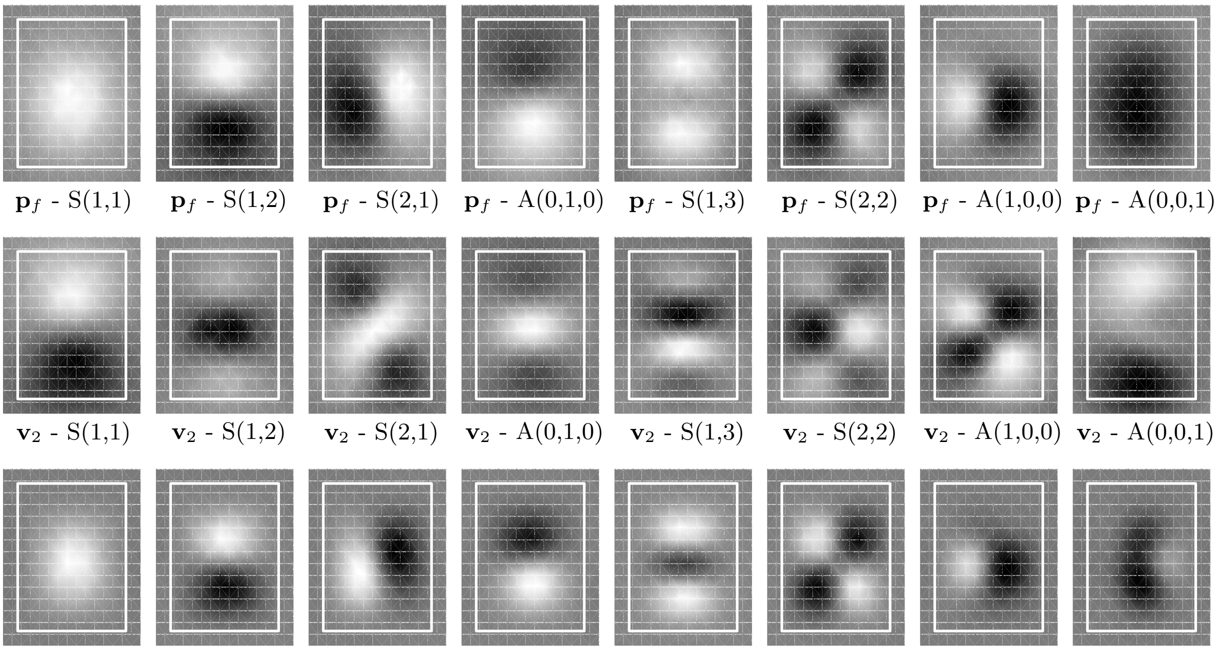
Figure 3 shows the results of the laser vibrometer scan which forms the reference solution for the source localization methods. The upper part of the figure gives the computed mass-normalized kinetic energy ($E_k = \frac{1}{2} \oint_S v_n^{\mathrm{H}} v_n \, \mathrm{d}S$) based on the measured surface velocities of the plate. It is clear that eight resonance frequencies can be observed in the considered frequency range. The lower part of figure 3 illustrates the corresponding plate vibrations at the successive resonances.



S(1,1) S(1,2) S(2,1) A(0,1,0) S(1,3) S(2,2) A(1,0,0) A(0,0,1)

Figure 3: Results obtained by a laser Doppler scan of the plate: normalized kinetic energy (upper) and surface normal velocity of the plate (lower) at the resonance frequencies. Capital S indicates a structurally dominated mode and A stands for acoustically dominated mode. Colors are scaled between +1 (white) and -1 (black).

Note that only the surface velocities on the flexible front plate are shown. The vibration levels of the remaining walls are much lower and hence they have a negligible contribution to the exterior acoustic field. Figure 4 illustrates the measured acoustic quantities in the field grid. These measured distributions are input for the different types of source localization methods.



$\mathbf{p}_f$ - S(1,1) $\mathbf{p}_f$ - S(1,2) $\mathbf{p}_f$ - S(2,1) $\mathbf{p}_f$ - A(0,1,0) $\mathbf{p}_f$ - S(1,3) $\mathbf{p}_f$ - S(2,2) $\mathbf{p}_f$ - A(1,0,0) $\mathbf{p}_f$ - A(0,0,1)

$\mathbf{v}_2$ - S(1,1) $\mathbf{v}_2$ - S(1,2) $\mathbf{v}_2$ - S(2,1) $\mathbf{v}_2$ - A(0,1,0) $\mathbf{v}_2$ - S(1,3) $\mathbf{v}_2$ - S(2,2) $\mathbf{v}_2$ - A(1,0,0) $\mathbf{v}_2$ - A(0,0,1)

$\mathbf{v}_3$ - S(1,1) $\mathbf{v}_3$ - S(1,2) $\mathbf{v}_3$ - S(2,1) $\mathbf{v}_3$ - A(0,1,0) $\mathbf{v}_3$ - S(1,3) $\mathbf{v}_3$ - S(2,2) $\mathbf{v}_3$ - A(1,0,0) $\mathbf{v}_3$ - A(0,0,1)

Figure 4: Acoustic quantities measured in field grid at a distance of 30 mm from the front plate. The white rectangle indicates the outer contour of the box.

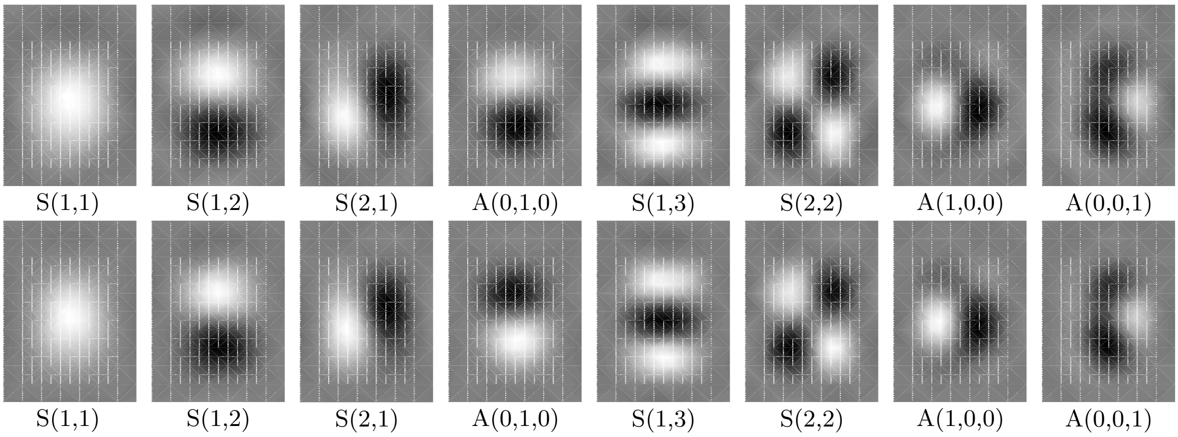


Figure 5: Reconstructed plate vibrations by means of the IFRF method, (upper) the conventional pressure based method and (lower) the novel method based on particle velocity measurement ($\mathbf{v}_3$). S indicates a structural mode and A stands for acoustic mode.

Figure 5 shows the reconstructed surface normal velocities with the IFRF method based on pressure measurements ($\mathbf{p}$) and based on particle velocity measurements in the direction perpendicular to the field grid ($\mathbf{v}_3$). It is obvious that good agreement is found between the vibration patterns measured with the laser vibrometer and the results obtained with the source localization methods.

To compare the quality of the reconstructed surface vibrations, the associated acoustic power $\Pi = \frac{1}{2} \oint v_n^{\mathrm{H}} p \, \mathrm{d}S$ is evaluated. The acoustic power based on the laser scan method is considered to be the most accurate and consequently it is used as reference for the results obtained with the different types of IFRF methods. Figure 6 shows the reconstructed narrow band acoustic power predicted by the different methods.

The differences between the total acoustic power based on the reconstructed surface normal velocities and the power based on the directly measured surface normal velocities are collected in table 1. From the table it becomes clear that a very acceptable deviation in total sound power of about 1 dB is found for the various types of IFRF methods.

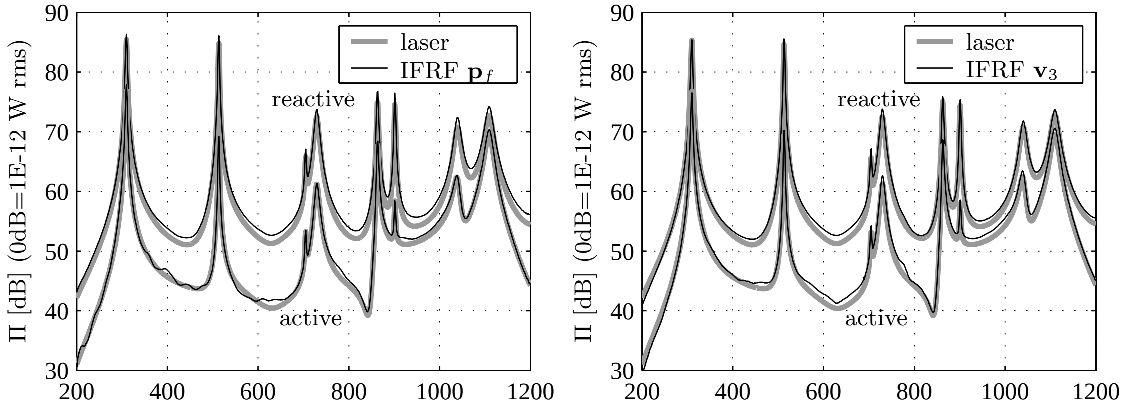


Figure 6: Comparison of acoustic power between direct laser measurement and IFRF method based on pressure (left side) and particle velocity (right side). The upper lines represent the reactive power (imaginary part) whereas the lower lines represent the active power (real part).

IFRF method	Active power [dB rms]	Reactive power [dB rms]
$\mathbf{p}_f$	0.72	1.25
$\mathbf{v}_2$	0.02	0.53
$\mathbf{v}_3$	0.58	0.67

Table 1: Difference in total sound power based on IFRF reconstructions versus laser vibrometer measurement.

Furthermore it can be noticed that the results based on particle velocity measurements are slightly better than those based on pressure measurements.

CONCLUSIONS

In this paper the practical application of different formulations of the IFRF source localization method was investigated. By means of an experimental setup it was shown that very good agreement was found between the direct laser Doppler measurements of the source surface velocities and the reconstructed surface normal velocities with the IFRF methods. From a theoretical point of view it was expected that the novel source localization method based on particle velocity would result in slightly better reconstructed surface velocities compared to the conventional pressure based IFRF method [8]. The validation experiments presented in this paper confirmed these theoretical findings.

ACKNOWLEDGEMENTS

This research is supported by the Dutch Technology Foundation (STW). The author would like to thank his supervisor Henk Tijdeman and his other colleagues for their cooperation, valuable suggestions and critical comments.

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