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Sound source localization by an inverse method using the measured dynamic response of a cylinder

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ABSTRACT

This work presents an experimental study to localize an acoustic source inside a cylindrical shell which is applied without contact with the structure. Since this source cannot be detected by direct measurements, the proposed method is based on the measurement of the velocity at some discrete points on the external surface of the shell by a Scanning Laser Vibrometer. The displacements integrated from the measured velocities will be injected into the equation of motion using finite difference schemes. First, some numerical simulations will be presented starting from exact data and then with uncertainties to simulate measurements. Before the regularization process was applied, the distributions resulting from measured velocities cannot be able to locate the acoustic source whenever the measurement uncertainties are present. In this case, a regularization technique based on the filtering of the wavenumber domain which is infected by the noise is applied. The regularization criterion has been applied to the distributions as results of measurements and there the localization of the acoustic source is clearly improved.

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1. Introduction

The localization of excitation sources in mechanical structures is a recently interesting scientific domain which is developed to operate a preventive maintenance. The localization of mechanical, thermal and acoustic sources exciting structures by direct measurement is extremely difficult and sometimes impossible to realize because of the ignorance of application point of the source. Following of the direct method limits, the indirect ones known as inverse problems are considered as efficient and robust tools for the localization of the sources. They are based on the measurement of some accessible quantities such as accelerations, velocities, displacements, acoustic pressure and so on to make a good diagnosis. However, the main difficulty is that the solution of the inverse problem is often unstable due to the presence of uncertainties in the experimental data [1]. The first application of the inverse methods in the vibroacoustic domain relate to near-field acoustical holography (NAH), introduced by Williams et al. [2] with the idea is to measure the sound pressure field on an hologram surrounding the source in order to go up with the acoustic source. Maynard et al. [3] introduced a regularization technique based on the use of the filtering to limit the spatial FFT obtained in a stable field. Langrenne et al. [4] solved the acoustic inverse problem to calculate the velocity field on the source surface. The boundary element method is used to recover the loudspeaker positions with a fairly good accuracy. The applied technique requires the knowledge of both measured acoustic pressure and the predicted velocity fields on a closed surface surrounding the source. Layou et al. [5] proposed a method where a Laser vibrometer is used for the measurement of the vibration to estimate the mode shapes of the plates. Another technique based on the structural intensity was used to localize sources in vibrating structures by analyzing the way traversed by the energy of vibration. Zhang et al. [6,7] compared two formulations of the structural intensity by introducing terms relating to rotational inertia and shear. The calculation of the intensity and the force distribution starting from the measured data on a plate is carried out after the application of a windowing followed by a filtering in the wavenumber domain. Pezerat et al. [8,9] proposed the RIFF method to locate mechanical forces applied on beams and plates starting from the equation of the motion using finite difference schemes. The present method is relatively local because the measurement of the response of the entire structure is not needed and the boundary conditions can be unknown. The measurement noise, amplified by the fourth derivatives, led to the bad conditioning of the inverse problem. Therefore, the proposed regularization consists in filtering the wavenumbers highly infected by the noise. Weber et al. [10] presented an approach

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based on an inverse finite element method to reconstruct sound pressure and particle velocity on the boundary in 2D cavity. This procedure requires sound pressure measurements which are associated to the nodes of an acoustic finite element model of the cavity. The IFEM is applied in a two-dimensional laboratory experiment by means of regularization techniques and a loudspeaker included in the boundary of a test facility can be identified. Chen et al. [11] used a window function to regularize the divergent problem which occurs in the Laplace equation with over specified boundary conditions in an infinite strip region. To deal with this ill-posed problem, the corner of the L-curve is chosen as the compromise point to determine the optimal alpha of the Gaussian window, so that the high wavenumber content can be suppressed instead of engineering judgement using the concept of a cutoff wave-number. A reasonable solution of the unknown boundary potential can be reconstructed and divergent results can be avoided by using the proposed regularization technique. In another work of Chen et al. [12], the desingularized meshless method has been applied to deal with the problems with over-specified boundary conditions. The inverse problem is remedied by using the Tikhonov regularization method and the truncated singular value decomposition method. To verify the accuracy of the method, several numerical examples are given by the comparison with the results of analytical solutions.

In comparison with the works done on beams and plates, only a limited number of published papers dealing with the use of indirect methods in the source identification were applied to the case of the cylindrical shells and complex structures. In the Reference [13], the author employed the cylindrical shell vibration intensity to locate sources. De-Araújo et al. [14] and Antunes et al. [15] proposed a method in order to locate impact forces starting from spaced measurements of the dynamic response of a beam, afterward they proposed the experimentation in order to regularize the problem by a signal processing technique which makes possible the separation of the reflective waves of direct ones using the information provided by a limited number of accelerometers. However, when subject to flow-induced vibrations, the loosely supported tubes display very complex rattling motions with the impact generated primary waves completely immersed in countless wave reflections travelling between the tube boundaries. As a consequence, the multiple impact patterns of tube support interaction are much more difficult to identify than isolated forces. Leclère et al. [16] focus their interest to the low frequency amplitude modulation of the noise generated by an engine operating at idle. Spectral analysis tools are applied on multi-channel measurements to identify the source. A virtual source analysis shows that several uncorrelated sources are contributing to the operating response, particularly on frequencies for which a high amplitude modulation is observed. Kletschkowski et al. [17] applied a novel approach based on a combined measurement and calculation technique to reconstruct the boundary values of both sound pressure and particle velocity. The solution of the inverse problem is found by minimizing a cost function that corresponds to the acoustic energy of the enclosure. This inverse approach has been applied to sound source localization in an aircraft fuselage using internal as well as external sources to excite cabin noise. Internal sources have been localized with success. Djamaa et al. [18,19] make an extension of the RIFF method to the cylindrical shells. Using some assumptions by neglecting of the deformations supposed too small, they show that the localization of the mechanical sources is possible using radial displacements only in the case above the ring frequency. This case is very interesting because the measurement can be easily processed by a Laser vibrometer.

In this work and in opposition of the excitation by direct contact with the structure, we try to localize an acoustic excitation without contact. The pressure developed by this source is distributed on the internal surface of the cylinder. From the experimental view point, the measurement of the velocity in the three directions is impossible especially if we have a high number of measurement points. This technique proves to be important to localize acoustic sources whose frequencies are generally higher at the ring frequency of the cylinder starting from the radial velocities which are easily measurable.

2. Principle of the method

Let us consider a cylindrical shell with a finite length L and radius a excited by an acoustic source along the radial direction (Fig. 1). The cylinder vibrated along the radial direction according to a, along the axial direction according to Z and along the angular direction according to θ.

The differential equation of motion is given by the following developed form:

$$\frac{Eh}{1-\nu^2}\left(-\left(\frac{\nu}{a}\frac{\partial u}{\partial z}+\frac{1}{a^2}\frac{\partial v}{\partial \theta}+\frac{w}{a^2}\right)+\frac{h^2}{12}\nabla^4 w\right)+\rho h\omega^2 w=-P \qquad (1)$$

With $\nabla^4=\frac{\partial^4}{\partial z^4}+\frac{2}{a^2}\frac{\partial^4}{\partial z^2\partial\theta^2}+\frac{1}{a^4}\frac{\partial^4}{\partial\theta^4}$

Where: E is the Young modulus, ν is Poisson ratio, ρ is the density, h is the thickness, (u, v, w) are the displacements, ω is the excitation frequency and P is the unknown pressure of the acoustic source.

The proposed method allows the approximation of the forth order derivatives of the radial displacement of the Eq. (1) by finite difference schemes centered at the point indexed (i, j).

$$\begin{aligned}
\frac{\partial^4 w}{\partial z^4} &\Longleftrightarrow \frac{1}{\Delta_z^4}\left(w_{i+2,j}-4w_{i+1,j}+6w_{i,j}-4w_{i-1,j}+w_{i-2,j}\right)\\
\frac{\partial^4 w}{\partial \theta^4} &\Longleftrightarrow \frac{1}{\Delta_\theta^4}\left(w_{i,j+2}-4w_{i,j+1}+6w_{i,j}-4w_{i,j-1}+w_{i,j-2}\right)\\
\frac{\partial^4 w}{\partial z^2\partial \theta^2} &\Longleftrightarrow \frac{1}{\Delta_z^2}\frac{1}{\Delta_\theta^2}\begin{pmatrix} w_{i+1,j+1}-2w_{i+1,j}+w_{i+1,j-1}-2w_{ij+1}+4w_{i,j}\\ -2w_{i,j-1}+w_{i-1,j+1}-2w_{i-1,j}+w_{i-1,j-1}\end{pmatrix}
\end{aligned} \qquad (2)$$

Δ_z and Δ_θ represent the distance between two consecutive points along the longitudinal and angular directions, respectively.

Substituting Eq. (2) into Eq. (1) and by introducing the structural damping, the pressure distribution can be calculated by the following expression:

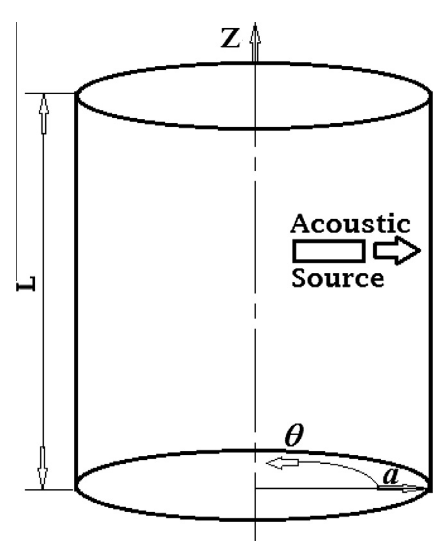

Fig. 1. Schematic configuration of the problem.

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