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Reconstruction and separation of vibratory field using structural holography

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A B S T R A C T

A method for reconstructing and separating vibratory field on a plate-like structure is presented. The method, called "Structural Holography" is derived from classical Near-field Acoustic Holography (NAH) but in the vibratory domain. In this case, the plate displacement is measured on one-dimensional lines (the holograms) and used to reconstruct the entire two-dimensional displacement field. As a consequence, remote measurements on non directly accessible zones are possible with Structural Holography. Moreover, as it is based on the decomposition of the field into forth and back waves, Structural Holography permits to separate forces in the case of multi-sources excitation. The theoretical background of the Structural Holography method is described first. Then, to illustrate the process and the possibilities of Structural Holography, the academic test case of an infinite plate excited by few point forces is presented. With the principle of vibratory field separation, the displacement fields produced by each point force separately is reconstructed. However, the displacement field is not always meaningful and some additional treatments are mandatory to localize the position of point forces for example. From the simple example of an infinite plate, a post-processing based on the reconstruction of the structural intensity field is thus proposed. Finally, Structural Holography is generalized to finite plates and applied to real experimental measurements

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1. Introduction

Since decades, source localization and identification is a very important topic in both academic and industrial projects. Many methods have become an increasingly powerful research tool and allow today to understand and predict the structure behavior. However, for most of the methods, characterizing a surface requires measurements on this entire area. In this paper, a new approach in the vibratory domain is proposed to know the entire vibratory behavior of a plate with a maximum of 4 sensor lines. This method is based on the propagation and back-propagation principles, performed in the wave number domain, developed in acoustics by Williams and Maynard and called Near-field Acoustical Holography (NAH) [1].

Much research has been done to characterize and identify the vibration source acting on a structure. In the middle of 70 s, Pavic [2] and Noiseux [3] developed the structural intensimetry, defined from acoustic analogy, to analyze the flexural waves propagation in simple structures. Many publications which followed were concentrated on the structural intensity approach because the energy flow distribution gives information about the energy transmission paths, the sources positions

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and the sinks of mechanical energy. Zhang and Mann showed that the force distribution can be calculated directly in the wavenumber domain using the two-dimensional fast Fourier transform [4], and used the measured structural intensity and the force distribution function to study vibrating plates [5]. Gavric showed the potentiality of numerical calculation of structural intensity [6] and demonstrated that this approach can be used for modal models obtained from experimental modal analysis [7,8]. Another method for localizing the excitation source is the Force Analysis Technique (FAT) introduced by Pézerat [9,10], also known as the RIFF technique, which uses a finite difference scheme to discretize the equation of motion and reconstruct the force distribution acting on structures like beams [11], plates [10] and shells [12,13]. Thereafter, FAT had also been coupled with NAH to identify vibration sources from radiated noise measurements [14]. As the Force Analysis Technique, the Virtual Fields Methods has been developed by Berry et al. [15,16] to identify and quantify the local dynamic transverse forces and distributed pressures acting on the surface of a thin plate from vibratory measurements. The main difference compared to FAT is the use of virtual fields to extract information on a part of the structure.

Initially developed for acoustic signals emitted by stationary sources [1,17,18], NAH allows now to solve more complex problems [19] and can be used for continuously visualizing nonstationary acoustic fields through RT-NAH (Real-Time Near-field Acoustic Holography) [20] or TDH (Time Domain Holography) for reconstructing sound data blocks in the time domain [21]. NAH is a powerful method to reconstruct the velocity distribution of a vibrating plate or recover the sound field of an acoustic system from the acoustic pressure hologram measured from a microphone array in the near-field. It makes it possible to visualize the spatial pressure field radiated by the system for any frequency of interest. NAH uses a specialized processing technique performed in the wavenumber domain to back-propagate the pressure field. Overcoming the ill-posed inverse problem is satisfactory done using a regularized procedure [22].

This paper presents a new reconstruction and separation vibratory field method, called Structural Holography. It is based on the back-propagation process performed in the k-space domain by using the Spatial Fourier Transform. The theory of the method leads to four coefficients identified with only four 1D sensor lines (holograms). These four coefficients allow to propagate and back propagate the wave number spectrum on the entire plate. The displacement field is obtained by applying the Inverse Spatial Fourier Transform on the wave number spectrum. If the holograms are positioned between two sources, considering the sources as forth waves or back-waves allows to separate them using Structural Holography. A source separation technique has already been applied in acoustics by Cheng et al. to separate the incident and the scattered sound fields [23]. This method is based on the principle that any waveform can be decomposed using the two-dimensional spatial Fourier transform into wave components that propagate in a known manner. The approach proposed in Structural Holography is different. The measurements are realized outside the area where the forces are localized.

In this paper, theoretical background of Structural Holography is first presented. Numerical studies and experimental results illustrate the validity of the source separation technique. A structural intensity approach is used subsequently on the reconstructed displacement to increase the accuracy of the source localization.

2. Theoretical background of structural holography

The theoretical background of Structural Holography is based on the plate bending theory. For thin plates, it is shown that the Kirchhoff theory yields accurate results. According to the Kirchhoff theory, the forced flexural vibration is governed by the following fourth-order differential equation [24]:

$$\frac{Eh^3(1+j\eta)}{12(1-\nu^2)}\left(\frac{\partial^4 w(x,y,t)}{\partial x^4}+\frac{\partial^4 w(x,y,t)}{\partial y^4}+2\frac{\partial^4 w(x,y,t)}{\partial x^2\partial y^2}\right)+\rho h\frac{\partial^2 w(x,y,t)}{\partial t^2} = F(t)\delta(x,y), \tag{1}$$

where E is the Young modulus, h the thickness of the plate, η the damping, ν the Poisson's ratio, and $w(x,y,t)$ the transverse displacement. Let us consider the example of a point force $F(t)$ located at (0,0) as expressed in Eq. (1) so that the force distribution is null anywhere else. As a consequence, Eq. (1) can be rewritten for a harmonic regime e^{jwt}:

$$\nabla^4\overline{w}(x,y) - k_f^4\overline{w}(x,y) = 0, \quad (\forall\, y \neq 0) \tag{2}$$

where $\overline{w}(x,y)$ is the transverse displacement at the angular frequency ω, $k_f^4 = \frac{\omega^2\rho h}{D}$ and $D = \frac{Eh^3(1+j\eta)}{12(1-\nu^2)}$. The 1D Spatial Fourier transform (SFT) is applied to Eq. (2) in x direction to obtain a 4th order differential equation:

$$\frac{\partial^4}{\partial y^4}W(k_x,y) - 2k_x^2\frac{\partial^2}{\partial y^2}W(k_x,y) + (k_x^4 - k_f^4)W(k_x,y) = 0, \tag{3}$$

which admits the general solution:

$$W(k_x,y_i) = \mathrm{C}^{\mathrm{B}}_{\mathrm{eva}}(\mathrm{k}_x)\mathrm{e}^{k_x^+ y_i} + \mathrm{C}^{\mathrm{F}}_{\mathrm{eva}}(\mathrm{k}_x)\mathrm{e}^{-k_x^+ y_i} + \mathrm{C}^{\mathrm{B}}_{\mathrm{mix}}(\mathrm{k}_x)\mathrm{e}^{k_x^- y_i} + \mathrm{C}^{\mathrm{F}}_{\mathrm{mix}}(\mathrm{k}_x)\mathrm{e}^{-k_x^- y_i}, \tag{4}$$

where $k_x^+ = \sqrt{k_x^2 + k_f^2}$, $k_x^- = \sqrt{k_x^2 - k_f^2}$ and y_i is the reconstruction position on the plate. This solution has four coefficients

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