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Vibration sources identification in coupled thin plates through an inverse energy method

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ABSTRACT

This paper addresses the problem of vibration sources identification in coupled thin plates at high frequency range. An energy-based method called Simplified Energy Method (MES) is used for that purpose. It was initially developed to predict the distribution of structural energy density in mid- and high frequency ranges regarding injected power. This paper extends this energy method to solve inverse structural problems to identify vibration sources acting on coupled structural subelements. Thanks to this inverse formulation, the forces in a structure are obtained from the energy density data. Numerical simulations were performed to test the validity of the present formulation using different positions of external forces and measurement points. Numerical as well as experimental results show that the inverse MES (IMES) method has an excellent performance in estimating the input forces applied to a complex structure modeled with a set of assembled plates from the density energy measurements.

1. Introduction

The localization and quantification of structural forces acting on structures from operating measurements is an important topic that has been treated by several researchers. Nevertheless, direct measurements of sources to quantify the input loads position and magnitude, are not feasible. An inverse process to estimate the exciting sources is often employed to solve this problem.

Many approaches have been developed in the literature in order to localize vibration sources and identify acting forces. Among these approaches, the Force Analysis Technique (FAT), also known as the RIFF method, is an alternative experimental method developed by Pezerat and Guyader [1,2]. It consists in defining the vibration source acting on the structure, through the knowledge of displacement field distribution. In particular, the input force is obtained through vibration equation of the motion where the spatial derivatives are determined by Finite Difference Method [3]. In the last decade, several studies have been developed with this approach for a beam [1], plates [2,4] and cylindrical shells [5]. In a recent study, Pezerat et al. [6] coupled this approach with near field acoustic holography in order to identify the structure displacement field with a movable antenna. Leclere et al. [4] offered an improvement to this method where the filtering by a convolution product was suppressed.

Still, other approaches have been used by some researches in order to identify the vibration sources. The Finite Element method, for example, has been used by Ibrahim et al. [7] to estimate the forces applied at measured and unmeasured positions in the structure through data about the possible forces locations. This method was also used by Corus et al. [8] to identify the vibration sources applied to the structure by a compressor. Another method, called the Kalman Filter has been used by Ji et al. [9] to estimate a time wise variation rod force source on the rod end with free boundaries. Moreover, Liu et al. [10] proposed to apply of Kalman's Filter with a recursive estimator to determine the input force of a mechanical grey-box model. An inverse method based on this approach and a recursive least-squares algorithm were used in Ma et al. [11] to estimate input forces on a beam structures.

It has been noted that the most proposed investigations in the literature were limited on the low frequency band, characterized by a weak overlaps model and dominated by a resonant behavior, and for simple rather than complex structures. Most of them become ineffective when frequency increases, i.e. precisely at high frequency range. The greatest limitation of these methods comes from the prohibitive explosion of degree of freedom's number and increased response sensitivity to the slightest variations of systems. Generally, in this frequency band, the use of these methods are time consuming and require very high calculation costs. To

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solve this problem, a second numerical model, called Energy Methods, appeared relying on the energetic variables. The use of these approaches provides an efficient tool for the evaluation of averages energy levels at high frequency range. The Statical Energy Analysis (SEA) [12] is one of these approaches. It consists in subdividing the system into connected subsystems, and assuming that the energy fields are diffused, in order to determine a global estimation of the average value energy distribution in each subsystem. Several investigations have been conducted to improve the SEA. In fact, they tried not only to predict the energy density, but also to estimate the power flow fields and the energy distribution inside systems. Among these developments, the local energy formulation was devised by Nefske and Sang [13] and developed by Bernhard et al. [14,15] and also discussed in references [16,17]. These improvements further lead to a Simplified Energy Method (MES) for the medium and high frequency ranges. The direct theory formulation has been applied in various domains including beam [18], membrane and plates [19,17] and acoustic applications [20]. An inverse energy flow method has been developed for acoustic applications [21] and structures [22], but it is still for specific and simple applications.

The main novelty of this paper is the application of the inverse MES formulation for a complex system (coupled multi-plates) in order to identify the structural sources through a direct measurement of the energy density field. However, the Inverse MES formulation (IMES) is general and can be applied for complex structure modeled with many assembled plates.

First, the assumption of the Simplified Energy Method will be reviewed and the direct formulation will be presented. The new IMES formulation for assembling plates was proposed. Next, the numerical validations will be detailed to show the efficiency of the method and validate the proposed IMES formulation. Finally, experimental results were presented in order to validate the technique and to extend it to industrial test cases.

2. Overview of the direct simplified energy flow formulation

2.1. Assumptions

The simplified energy method is a vibro-acoustic approach in medium and high frequency ranges, based on the analysis of wave propagation. This method is based on the description of two local energy quantities: the energy density W is defined as a sum of the kinetic and potential energy densities, and the energy vector $\vec{I}$ which is the energy flow inside the system. The energy flow balance in a local region can be written as follows:

$$\Pi^{in} = \Pi^{diss} + \vec{\nabla} \cdot \vec{I} \tag{1}$$

where $\vec{\nabla}$ is the gradient operator, Π^{in} is the local input density and Π^{diss} is the local dissipated power density. The MES adopts the same damping model as that in SEA [12] with:

$$\Pi^{diss} = \eta\omega W \tag{2}$$

where η is the hysteretic damping factor and ω is the circular frequency. The MES propagative waves are characterized by a simple equation depending on the energy density W and energy flow $\vec{I}$ such that:

$$\vec{I} = c_g W \vec{n} \tag{3}$$

where c_g is the group velocity. This expression is valid for undamped system and in the far field for outing traveler waves.

2.2. Energy fields formulation

Several researches have explained the development of the MES approach. Here, we suggest a short summary of them, and for more details readers may refer to [17,18,21].

The MES formulation used the non-correlation of the propagating waves. These waves are symmetric and correspond to the propagating fields from a point source s in the n-dimensional (nD) space. Therefore, their fields depend only on the distance r between the source s and the measurement point m. The energy balance can then be written as follows:

$$\frac{1}{r^{n-1}}\frac{\partial}{\partial r}(r^{n-1}\vec{I}) + \eta\omega W\vec{n} = 0 \tag{4}$$

where n is the space dimension (n =1D, 2D or 3D). In our work, n =2D space is considered.

In addition, this equation can also be written by substituting Eq. (3) into the energy balance Eq. (4), such that:

$$\frac{1}{r^{n-1}}\frac{\partial}{\partial r}(r^{n-1}W) + \frac{\eta\omega}{c_g}W = 0 \tag{5}$$

The solutions of this equation in terms of energy density and active intensity are expressed G and $\vec{H}$, respectively:

$$G(s,m) = \frac{1}{c_g}\frac{e^{-(\eta\omega/c_g)r}}{2\pi r}, \quad \vec{H}(s,m) = \frac{e^{-(\eta\omega/c_g)r}}{2\pi r}\vec{u}_{sm} \tag{6}$$

where $r = \|\vec{sm}\|$ is the distance between the source s and the measurement point m and $\vec{u}_{sm}$ is the unit vector from m to s.

The total energy field is constructed as the superposition of a direct field (primary source) coming from the input power in the system surface Ω and a reverberant field (secondary sources) coming from the fictitious sources localized in the system boundaries $\partial\Omega$, as shown in Fig. 1. All these considerations summarize the following relationships:

$$W(r) = \int_{\Omega} P^{in}(s)G(s,m)ds + \int_{\partial\Omega}\sigma(p)\vec{u}_{sm}\cdot\vec{n}_p G(p,m)dp \tag{7}$$

$$\vec{I}(r) = \int_{\Omega} P^{in}(s)\vec{H}(s,m)ds + \int_{\partial\Omega}\sigma(p)\vec{u}_{sm}\cdot\vec{n}_p \vec{H}(p,m)dp \tag{8}$$

where σ is the secondary source located at the boundaries and P^{in} is the injected power derived from the infinite thin plate solution [23] and written as follows:

$$P^{in} = \frac{F^2}{16\sqrt{D\cdot h\cdot\rho_s}} \tag{9}$$

where F is the applied force, D is the plate stiffness defined by $D = Eh^3/12(1-\upsilon^2)$ and ρ_s is the density.

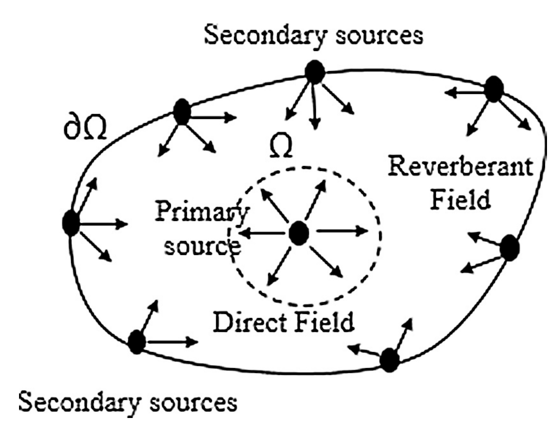

Fig. 1. Sources description.