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Numerical and experimental investigations on structural intensity in plates

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ABSTRACT

The need of reducing the vibration levels is one of the most important points in many engineering fields. Therefore, the knowledge of the vibrational field can be a useful and efficient tool in problems regarding acoustic and mechanical insulation. This paper is focused on the experimental measurements and numerical predictions of the structural intensity fields in rectangular plates. The method is applied by simulating finite plates and the effects of constraints, load conditions, damping, thickness and fibres orientation are investigated. Experimental measurements are carried out on both aluminium sandwich and composite (orthotropic) panels; the results are compared through a mixed numerical/experimental approach with purely numerical predictions. The mixed approach based on both experimental and numerical information is proposed since it can give good indications of the structural intensity fields, can offer information about the energy transmission paths and can fruitfully use the numerical generated information.

1. Introduction

Aircraft, ships, cars and all other existing vehicles are always subjected to external dynamic loads, which excite the structure in several frequency ranges depending on the sources of vibration. Vibrational energy can derive from engine operations, fluid–structure interaction, periodic contact between mechanical parts, etc. Therefore, these structures can be subjected to excitation forces at frequencies close to the structural resonances, hence exceeding the permissible vibration levels; this may result in fatigue failure, destruction of electronic and mechanical parts or very high noise levels (vibro-acoustic problem). The plates are among the most common structural configurations in the transportation engineering and thus in structural design the knowledge of their dynamic behaviour becomes of foremost importance as well as the transmission mechanisms and the vibrational fields.

One of the most effective tools for predicting and measuring energy distribution is the structural intensity (SI). It is a measurement of the energy flow that propagates within a structure due to the waves and it can be considered as the analogous of the power flow (PF) [1]. The interest in evaluating the SI has become attractive thanks to its capability to offer valuable informations on the strength and location of sources and transmission paths of structures-borne sound energy by plotting a vector map. SI is able to localise dampers in structures in an easy way and, for this reason, it can be a key for solving structure borne noise problems.

SI has been used for several years as a tool for the design of vibration and noise control systems and there is a good literature on this topic. In 1970 Noiseux and McDevitt measured the freefield flexural intensity with two accelerometers: one supplied the normal acceleration and the other supplied the rotational velocity at the point measured by positioning the accelerometer mounted on its side [1,2].

Pavic used a new approximation technique, called the *finite difference technique*, allowing the reconstruction of the SI field both in the free-field and near-field, also addressing flexural vibrations: briefly, spatial derivatives of the normal displacements, directly related to the forces in the classical Euler–Bernoulli plate theory, are obtained by a grid of accelerometers, [3]. The number of the accelerometers and their positioning is changed in order to improve the accuracy of that method, but in any case this contact method has several sources of error; the first is related to the direct attachment on the structure of the accelerometers, shakers, dampers, etc. For this reason, the researchers, in the ’80s, began to study non-contact methods for the measurable quantities, such as displacement, velocity and acceleration. These quantities are found by near-field acoustic holography (NAH) or by an optical method, with laser beams [4].

Although more accurate, also these methods have some problems: (i) the misalignment of the experimental set-up, (ii) the need of phase and magnitude matching and the cost of the instruments.

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Thanks to the continuous development of computers, it has been possible to build the intensity field only by FEM prediction [5,6]: in this case, the numerical model provides quickly all necessary data with low computational costs. These predictions can be made for isotropic, but also for composite materials. In particular, the latter have highly customizable properties and therefore they can be adapted to the type of loads to which they are subjected.

Other numerical methods, exploited the *wavenumber processing technique*; this can be used to determine SI from both contact and optical measurements, [7,8]. In these cases, the velocities and the wave-numbers are required instead of the displacements and the forces per unit length: the higher-order spatial derivatives, necessary to determine the SI, are computed from the wavenumber–frequency domain through a 2D Spatial Fourier Transform (SFT) of the velocities.

SI is a vector quantity consisting of magnitude and phase, its changes may be tracked to determine the relative health of structures. As consequence, in the recent years, structural intensity received a great emphasis also for the damage detection techniques [9,10].

In this work, the evaluation of SI of different panels is investigated numerically and experimentally. Firstly, an overview of the structural intensity with emphasis on the different techniques is reported. Section 2 is dedicated to illustrate the theoretical background and the equations used to calculate the SI field. In Section 3, numerical investigations of several panels are performed, (i) to validate the technique already presented by Gavric and Pavic [5,6], and (ii) to evaluate the effect of the main parameters, such as boundary conditions, materials, damper and structural damping coefficients, etc. on SI field. In Section 4 the numerical and experimental studies of the SI field on two different classes of panels, Aluminium Foam Sandwich panels and flax-PE panels, are presented. In this section, a mixed approach, based on numerical and experimental data, is proposed to enhance the technique presented by Gavric and Pavic [5,6]. Finally, in Section 5 some concluding remarks are given.

2. Theoretical background on structural intensity

Structural intensity (SI) is a vector field, described by magnitude and phase, which indicates the path and the amplitude of the mechanical energy flowing through a vibrating structural component [11].

The location, where the mechanical energy enters the structure, is generally called the energy source; the location, where the energy is extracted from the system, is called the energy sink. Multiple energy sources and sinks might coexist in the same structure. Aerodynamic loads, propulsion system, rotor and gearboxes and auxiliary power units are some examples of external and internal sources of excitation; vibration isolation systems and structural joints are examples of energy dissipation mechanisms.

In order to illustrate the capabilities of the SI and for the sake of simplicity, in this study only a pair of energy source and sink is considered in order to produce a well defined energy flow through the structure.

From a general point of view, the structural power is defined as the active part associated with the vibration energy. In analytical terms, the power, at a prescribed point, is represented by product of a force with the in-phase component of the velocity in the direction of the force and can be calculated as follows:

$$P(\omega, Q) = \frac{1}{2}\Re[F(\omega, Q)\,v^{*}(\omega, Q)] \tag{1}$$

where F is the applied force and v^{*} is the complex conjugate of the velocity; they both refer to a prescribed point, Q, in the structural domain Eq. (1); $\Re$ denotes the real part [12,13].

The spatial distribution of the energy propagated within the structure is defined with the structural intensity field which, in the case of plate type structures, represents the energy propagating through the unit length.

Hence, according to the principle of conservation of energy, the power injected to the plate can be deduced by integrating the normal component of the structural intensity vector ($\bar{I}$),along a closed curve L, enclosing the vibrational source:

$$P(\omega) = \oint_{L} \bar{I}\cdot\bar{n}\,dl \tag{2}$$

Vibrational power flow per unit cross-sectional area of a dynamically loaded plate is defined as the structural intensity, $\bar{I}$ ($\bar{n}$ denotes the normal vector) [14].

The total intensity in a thin vibrating plate is due to the combined action of shear, bending, and twisting waves (Fig. 1) and can be expressed with their orthogonal components as [15]:

$$I_x = -\frac{\omega}{2}\Im\left[N_x\tilde{u} + N_{xy}\tilde{v} + Q_x\tilde{w} + M_x\tilde{\theta}_y - M_{xy}\tilde{\theta}_x\right] \quad \left[\frac{\mathrm{W}}{\mathrm{m}}\right] \tag{3}$$

$$I_y = -\frac{\omega}{2}\Im\left[N_y\tilde{v} + N_{xy}\tilde{u} + Q_y\tilde{w} - M_y\tilde{\theta}_x + M_{xy}\tilde{\theta}_y\right] \quad \left[\frac{W}{m}\right] \tag{4}$$

$$I = \sqrt{I_x^2 + I_y^2} \tag{5}$$

where

- N_x, N_y and N_{xy} are complex membrane and in-plane shear forces per unit width,
- Q_y and Q_z are complex transverse shear forces per unit width,

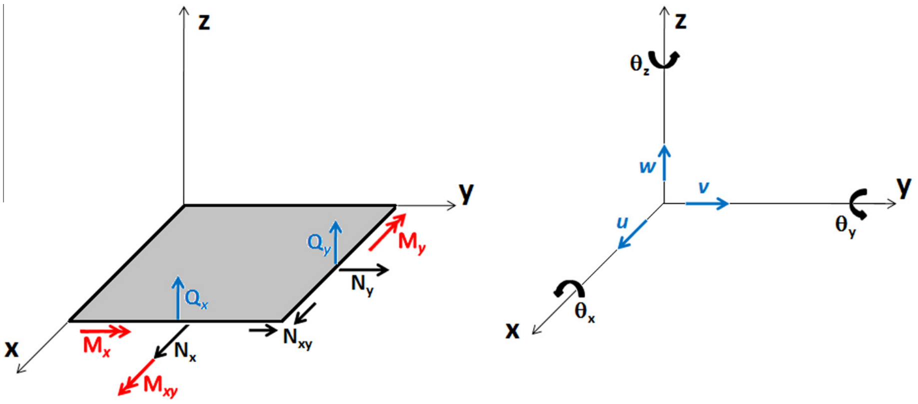

Fig. 1. Generalised forces per unit length and displacements in plate element.