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INVESTIGATION ON VIBRATION ENERGY FLOW CHARACTERISTICS IN COUPLED PLATES BY VISUALIZAITON TECHNIQUES

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INVESTIGATION ON VIBRATION ENERGY FLOW CHARACTERISTICS IN COUPLED PLATES BY VISUALIZAITON TECHNIQUES

Kai Li*, Sheng Li*, and De-you Zhao**

Key words: coupled plates, vibration intensity, visualization, energy flow.

ABSTRACT

The transmission and distribution of vibration energy flow in coupled plates are studied by the vibration intensity method together with visualization technique. Formulations for vibration intensity calculations and streamline representation, and the equations for energy flow are presented. The intensity vector, streamline map and energy distribution of coupled plates subject to a point force excitation are calculated and visualized to predict vibration energy transmission. The vibrational energy flows are very complex and dependent on the excitation frequencies, junction forms and boundaries. The energy sources, sinks, transmission paths and vortex fields are clearly shown with visualization technique. It is shown that the main flow of energy is not simply from force point to damper with increasing frequencies. When the energy flow reaches the boundaries at some frequencies, the vibration intensity is reflected and some virtual sources or sinks are formed. Vortex fields which indicate relatively amounts of energy can be observed in the coupled plates. The vibration intensity method together with visualization techniques provides a powerful tool for vibration control.

I. INTRODUCTION

Coupled plates are extensively used in many engineering applications, especially in ocean engineering, automotive and aerospace industries. In these fields the accurate investigation of vibration energy visualization for the energy transmission and distribution between coupled plates are of particular importance for noise and vibration control [4].

Vibration intensity is the vibration power flow per unit cross-sectional area in elastic medium, which is analogous to acoustic intensity in a fluid medium and was first introduced by Noiseux [14] and later developed by Pavic [15]. Vibration intensity indicates the magnitude and direction of vibrational energy flow at any point of a mechanical structure at frequencies of interest. Vibration intensity technique is not dependent on boundary conditions of the structures and enables to investigate the edge effects of vibration power transmission of structures [6, 7]. Vibration intensity field could be visualized by a vector map to show the particular information of energy flow transmission paths and positions of source and sinks of mechanical energy. Khun *et al.* [10] predicted the vibration intensity of a plate with multiple discrete and distributed dampers by the finite element method. Cieślik *et al.* [3] presented the formulations for structural vibration intensity calculation involving the external loads and moments based on the complex modal analysis by finite element method.

Energy flow in a plate has been investigated by many researchers. Bernhard [1] firstly developed a set of equations which govern the space and time averaged energy density in plates to investigate the mechanisms of energy generation, transmission and absorption. Further investigations of the energy model of plates proved that the vibration conduction equation is valid for the two-dimensional vibration field composed of plane wave components [2, 8].

As waves propagate through dynamically loaded mechanical structures, they encounter changes in structural junctions. Cuschieri and McCollum [5] used a mobility power flow (MPF) approach to study the structural energy flow through the junction between two flat plates coupled in an L-shaped configuration for both in-plane (longitudinal and shear) and out-of-plane (bending) waves' propagation. Li and Zhang [11] also used the mobility approach to study the input vibrational power flow and the transmitted vibrational power flow for an L-shaped stiffened plate excited by a concentrated harmonic force. Wang and Xing [17] formulated a substructure approach to investigate the power flow characteristics of an L-shaped plate. Kessissoglou [9] studied the power flow propagation in plates connected by an L-joint in both low and high frequency ranges, and derived an exact solution to describe the flexural, longitudinal and shear wave motions in the plates. Zhou and Zhao [21] calculated the vibration energy ratios of a stiffened

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panel in the mid and high frequency regions based on the dynamic stiffness method. Wu [18] gave the expressions for nodal force in complex frequency domain, and carried out the power flow calculation based on the finite element dynamic analysis. Xie [19] developed a module for structural power flow analysis on the basis of Msc/Nastran and integrated it into Nastran's solver.

Most of the previous works on vibration intensity were related to simple beams and plates structures and there were very few works on the energy flow within coupled plates. The aim of this study is to investigate the energy transmission paths and energy distribution within L-shaped plates by vibration intensity method and visualize energy wave phenomena in the plates and show the vibration energy flow characteristics.

II. THEORETICAL BACKGROUND OF VIBRATION INTENSITY

1. Instantaneous Structural Intensity

The time domain intensity equations are:

$$I(t) = -\begin{bmatrix} I_x \\ I_y \\ I_z \end{bmatrix} = -\begin{bmatrix} \overline{\sigma_{xx}v_x} + \overline{\tau_{xy}v_y} + \overline{\tau_{xz}v_z} \\ \overline{\tau_{yx}v_x} + \overline{\sigma_{yy}v_y} + \overline{\tau_{yz}v_z} \\ \overline{\tau_{zx}v_x} + \overline{\tau_{zy}v_y} + \overline{\sigma_{zz}v_z} \end{bmatrix} \quad (1)$$

where I_i is the intensity in direction i, υ_i the particle velocity in direction i, $\sigma_{ij}(t)$ the normal stress component.

The vibrational energy in structures is transmitted by shear forces (Q_x Q_x and Q_y), in-plane force (N_x, N_y and N_{xy}), and twisting moments (M_{xy} and M_{yx}). Hence, the vibration intensity component I_x in the x direction is written as

$$I_x = Q_x\frac{\partial\zeta}{\partial t} - M_x\frac{\partial^2\zeta}{\partial x\partial t} + M_{xy}\frac{\partial^2\zeta}{\partial y\partial t} + N_x\frac{\partial\xi}{\partial t} + N_{xy}\frac{\partial\eta}{\partial t} \quad (2)$$

These forces and moments are related to the transverse displacement as follows:

$$Q_x = -D\left(\frac{\partial^3\zeta}{\partial x^3} + \frac{\partial^3\zeta}{\partial x\partial y^2}\right) \quad M_x = -D\left(\frac{\partial^2\zeta}{\partial x^2} + \mu\frac{\partial^2\zeta}{\partial y^2}\right)$$

$$M_{xy} = -D(1-\mu)\frac{\partial^2\zeta}{\partial x\partial y} \quad N_x = \frac{Eh}{1-\mu^2}\left(\frac{\partial\zeta}{\partial x} + \mu\frac{\partial\eta}{\partial y}\right)$$

$$N_{xy} = \frac{Eh}{2(1+\mu)}\left(\frac{\partial\zeta}{\partial y} + \frac{\partial\eta}{\partial x}\right) \quad D = Eh^3/12(1-\mu^2) \quad (3)$$

2. Formulations of Vibration Intensity in a Plate

From thin plate theory, it is assumed that displacements perpendicular to the mid-plane of the plate are independent of the corresponding coordinate and that all structural points of a normal to the mid-plane remain on a straight line after the deformation. The I_x in (1) can be expressed in global coordinate system as follows

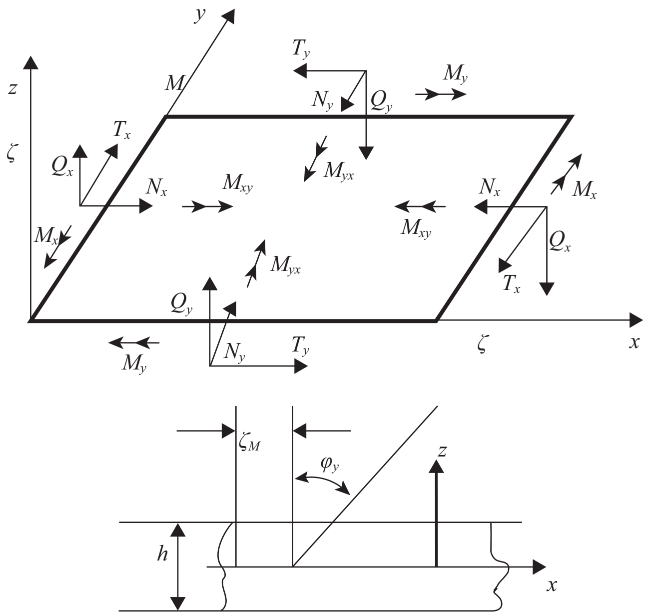


Fig. 1. Plate element with defined force and displacement.

$$I_x = -\overline{\frac{E}{1-\mu^2}\left(\frac{\partial\xi_M}{\partial x} + y\frac{\partial\varphi_x}{\partial x} + \mu\frac{\partial\zeta_M}{\partial z} + \mu\cdot y\frac{\partial\varphi_z}{\partial z}\right)\cdot v_x}$$

$$+ G\cdot\overline{\left(\varphi_x + \frac{\partial\eta}{\partial x}\right)v_y} + G\cdot\overline{\left(\frac{\partial\xi_M}{\partial z} + y\frac{\partial\varphi_x}{\partial z} + \frac{\partial\zeta_M}{\partial x} + y\frac{\partial\varphi_z}{\partial x}\right)\cdot v_z} \quad (4)$$

where: E denotes Young's elastic modulus, μ denotes Poisson's ratio, $G = E/(1-2\mu)$ denotes the shear modulus, φ_x and φ_y denote the rotational displacement about the x and y directions, v_x, v_y and v_z denote the velocity in the x, y and z directions. Figure 1 shows the positive orientations of internal forces and displacements.

Gavric and Pavic [6] developed equivalent structural vibration intensity algorithms that can be implemented both in the time domain and the frequency domain. Besides transverse deformations of the plate, the in-plane effect is also considered in the formulation of structural vibration intensity for shell elements. The x and y formulations of vibration intensity for a flat plate in frequency domain can be expressed as follows.

$$I_x = -(\omega/2)\,\mathrm{Im}[\tilde{N}_x\tilde{u}^* + \tilde{N}_{xy}\tilde{v}^* + \tilde{Q}_x\tilde{w}^* + \tilde{M}_x\tilde{\theta}_y^* + \tilde{M}_{xy}\tilde{\theta}_x^*]$$

$$I_y = -(\omega/2)\,\mathrm{Im}[\tilde{N}_y\tilde{u}^* + \tilde{N}_{yx}\tilde{v}^* + \tilde{Q}_y\tilde{w}^* + \tilde{M}_y\tilde{\theta}_y^* + \tilde{M}_{yx}\tilde{\theta}_y^*] \quad (5)$$

where $\tilde{N}_x$, $\tilde{N}_y$ and $\tilde{N}_{xy} = \tilde{N}_{yx}$ are complex membrane forces per unit width of the plate; $\tilde{M}_x$, $\tilde{M}_y$ and $\tilde{M}_{xy} = \tilde{M}_{yx}$ are complex bending and twisting moments per unit width of the plate; $\tilde{Q}_x$ and $\tilde{Q}_y$ are complex transverse shear forces per unit width of the plate; $\tilde{u}^*$, $\tilde{v}^*$, and $\tilde{w}^*$ are complex conjugate of translational displacements in the *x*, *y* and *z* directions; and $\tilde{\theta}_x^*$ and $\tilde{\theta}_y^*$ are complex conjugates of the rotational displacement about the *x* and *y* directions.

Streamline visualization technique [20] is a very useful tool to represent the transmission direction of a vector field. This technique is widely used in computer graphics flow visualization in fluid mechanics to display the vector field of the fluid flow. The velocity vector at any point of one streamline is tangent to that line. Up until the last decade the studies of sound flow visualization are rather seldom in the structural acoustical practice. The vibration intensity field is also a vector field representing the structural energy flow in a structure. Thus, this technique can show the energy transmission paths and indicate the vibration source and energy sinks. Based on the general fluid mechanics definition, the vibration intensity streamline can be similarly expressed as

$$dr \times I(r,t) = 0 \tag{6}$$

where *r* is an energy flow particle position. The cross product can be given by

$$\begin{vmatrix} i & j & k \\ I_x & I_y & I_z \\ dx & dy & dz \end{vmatrix} = 0 \tag{7}$$

For a 2-D plate, the vibration intensity streamline is written as

$$\frac{dx}{I_x} = \frac{dy}{I_y} \tag{8}$$

III. ENERGY FLOW IN PLATE STRUCTURE

In flat plate, bending waves take most of energy which are usually radiated as noise, therefore only out-plane wave is considered in (4). Making integration over the thickness of the plate, the energy flow per unit length can be stated in equation form as:

$$E = \frac{D}{2}\left\{\left[\frac{\partial^2\zeta}{\partial x^2}\right]^2 + \left[\frac{\partial^2\zeta}{\partial y^2}\right]^2 + 2\mu\frac{\partial^2\zeta}{\partial x^2}\frac{\partial^2\zeta}{\partial y^2} + 2(1-\mu)\frac{\partial^3\zeta}{\partial x^2\partial y}\right\} + \frac{\rho}{2}\left[\frac{\partial\zeta}{\partial t}\right]^2 \tag{9}$$

Table 1. Parameters of flat plate.

Poisson's ratio	0.3
Young's modulus	210 GPa
Density	7800 kg/m^3
Damping coefficient	100 Ns/m
Excitation force	1000 N

In-plane waves are of practical importance when considering the in-plane dynamic responses in coupled structures. In the case of coupled plate structures, which are joined at an angle and on which transverse exciting forces are applied, in-plane waves come out with the flexural waves, since the incident flexural waves are partially converted to the in-plane waves at the joint part. The in-plane waves act as efficient transmitters of flexural energy between plates connected at inclined and right angles [9]. Longitudinal waves and shear waves not only play important roles on energy flow in coupling structures but also induce the bending vibration into the adjacent components. Hence, when studying the energy distribution of a coupled L-shaped plate, the in-plane waves should be considered.

Expressions for the in-plane wave and out-plane wave energy in plate have been developed in the reference [13]. The symbol *E* stands for total mechanical energy that can be expressed as:

$$E = \frac{\rho}{2}\left[\frac{\partial\xi}{\partial t}\right]^2 C_L + \frac{\rho}{2}\left[\frac{\partial\zeta}{\partial t}\right]^2 C_B + \frac{\rho}{2}\left[\frac{\partial\eta}{\partial t}\right]^2 C_S \tag{10}$$

where $C_L = \sqrt{E/\rho\left(1-\mu^2\right)}$, $C_B = 0.535\sqrt{\omega C_l}\,h$ and $C_S = \sqrt{G/\rho}$ denote phase velocity of the longitudinal, bending and shear wave traveling in the elastic plate, ρ denotes the density of the plate per unit area.

IV. NUMERICAL RESULTS OF THE ENERGY FLOW WITHIN THE L-SHAPED PLATE

In this section the finite element software ANSYS software is used to calculate the stresses and displacements components of (1). Consecutively the APDL program language and MATLAB software are used to visualize the results in graphical forms.

1. Validation

Current vibration intensity analysis is firstly compared with previous result to validate the computational method. The same geometrical setup, boundary conditions, excitation frequency, material properties and loading conditions as the simulation carried out by Gavric and Pavic [6] was used. The properties and parameters of the plate are stated in Table 1 and Fig. 2.

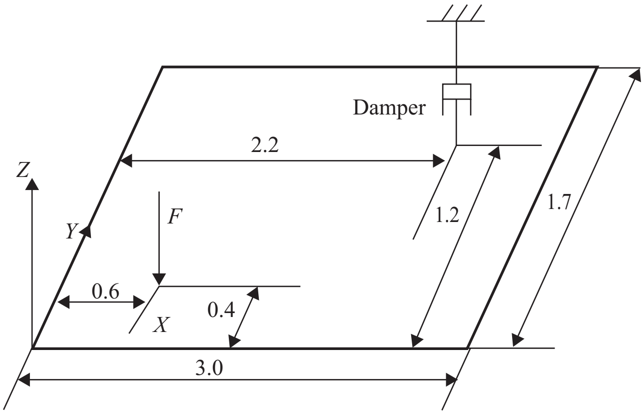
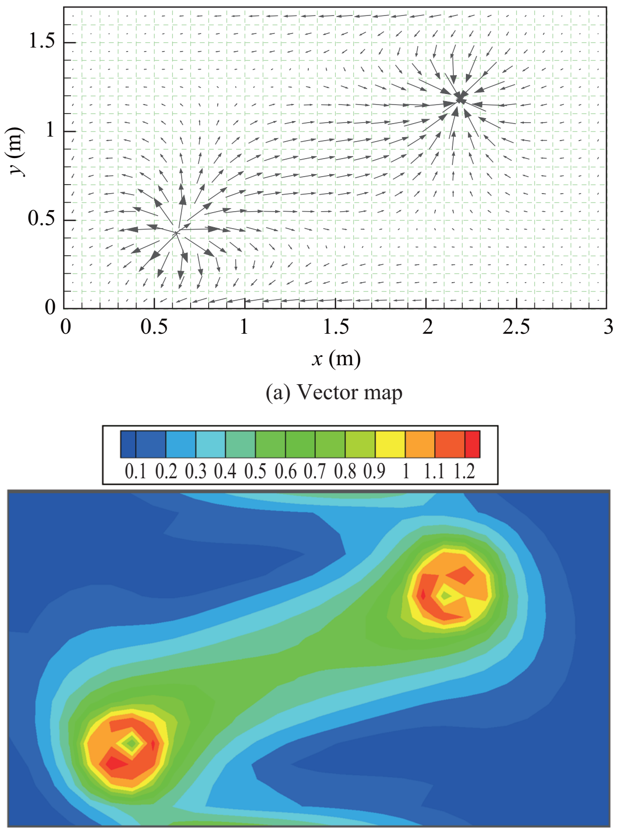


Fig. 2. Plate with defined force and damper in reference paper [6].



(a) Vector map

(b) Vibration energy distribution

Fig. 3. Representation of vibration intensity vector and energy distribution for a flat plate.

The plate is modeled using 510 eight-node isoparametric shell 93 element with 1625 nodes. The plate is assumed to be no structural damping. The plate is simply supported along the edges. The simulation of the vibration intensity vector flow result is shown in Fig. 3(a).

It can be seen that the energy flow from the excitation force point (energy source) to the damper location (energy concentration) can be clearly identified by structural vibration intensity vectors. This result is then compared with the results presented by Gavric and Pavic [6]. The comparison shows that the present results agree quite well with the published result. The bending wave energy flow shown in Fig. 3(b) is calculated based on (9).

Table 2. Parameters of L-shaped plate.

L-shaped plate	Coupling edge length/m	Other edges length/m	Thickness of plate/m	Damping ratio
Plate 1	1.0	1.2	0.004	0.01
Plate 2	1.0	1.6	0.004	0.01

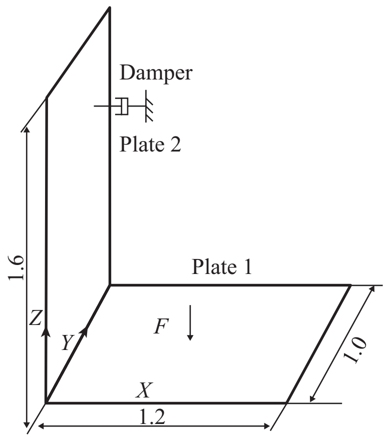


Fig. 4. L-shaped plate with defined force and damper (m).

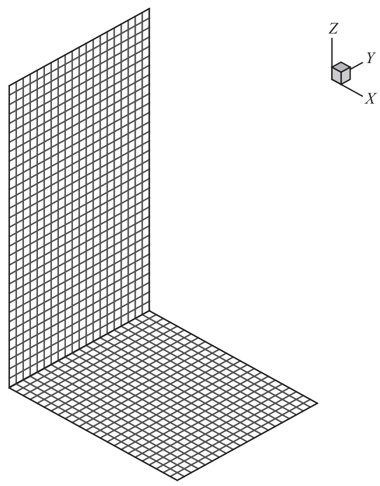
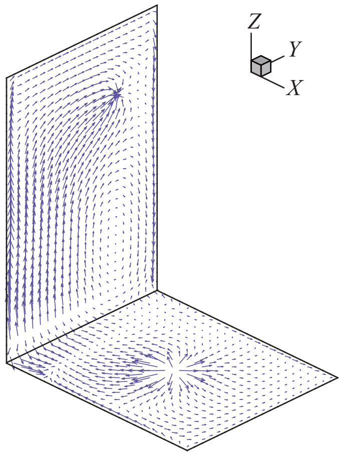


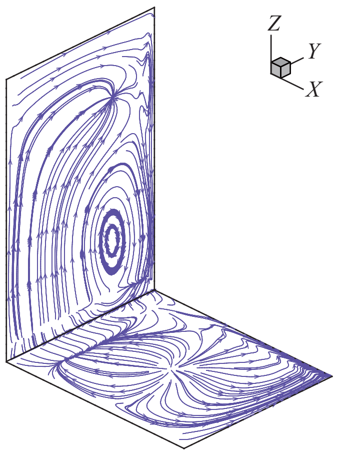
Fig. 5. Finite element mesh of L-shaped plate.

2. Energy Transmission Paths and Distribution

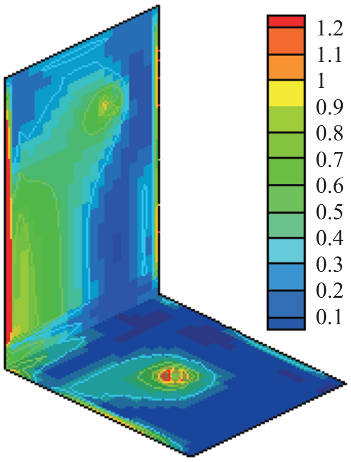
The parameters and sketch map of L-shaped plate are stated in Table 2 and Fig. 4. The finite element mesh for L-shaped plate is shown in Fig. 5. The plate is simply supported along the short edges, and free at the long edges and coupling boundary. The excitation point force with an amplitude of 1000 N is applied at x = 0.6 m and y = 0.5 m on the plate1 as shown in



(a) Vector map

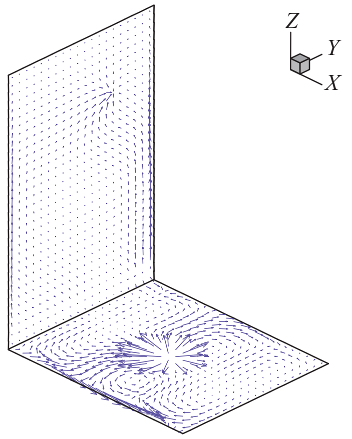


(b) Streamline map

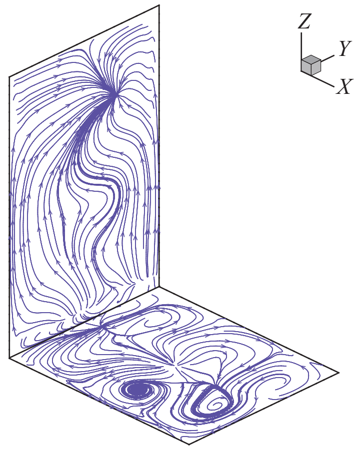


(c) Vibration energy distribution

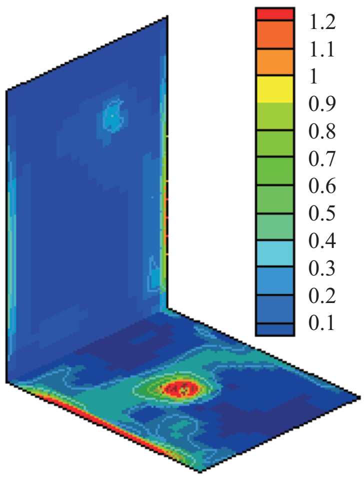
Fig. 6. Vector, Streamline of vibration intensity and vibration energy distribution representation for the L-shaped plate, *f* = 8.5 Hz.



(a) Vector map



(b) Streamline map



(c) Vibration energy distribution

Fig. 7. Vector, Streamline of vibration intensity and vibration energy distribution representation for the L-shaped plate, *f* = 32 Hz.

Fig. 4, an external damper with a damping rate of 100 Ns/m is attached to the plate 2 at $y = 0.7$ m and $z = 1.3$ m. The vibration intensity components are calculated for excitation frequencies of f = 8.5 Hz, f = 32 Hz, f = 69 and Hz, f = 94 which correspond to the natural frequencies of the L-shaped plate. Furthermore the total energy flow is calculated based on (10). The visualization energy flow results are shown in Figs. 6-9.

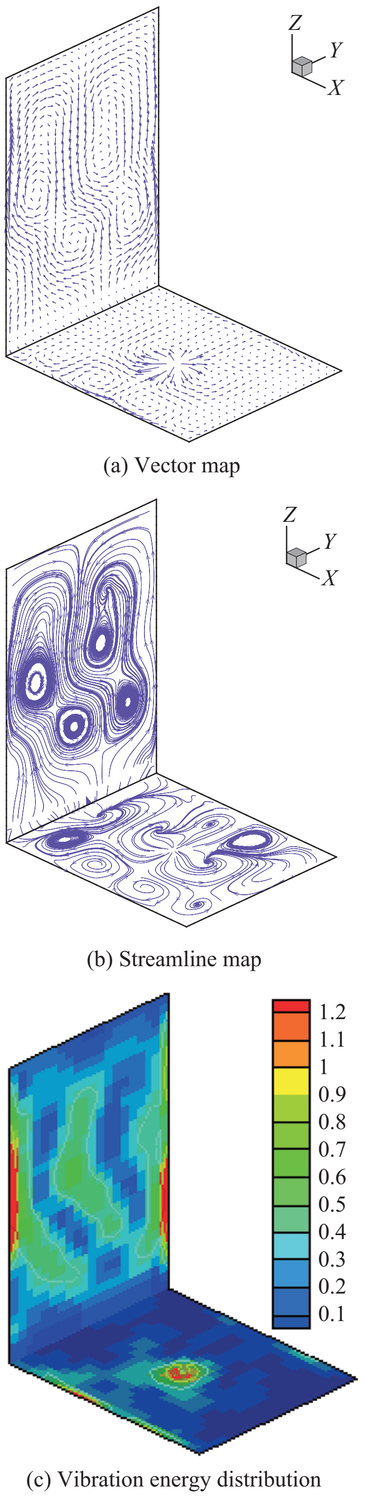


Fig. 8. Vector, Streamline of vibration intensity and vibration energy distribution representation for the L-shaped plate, f = 69 Hz.

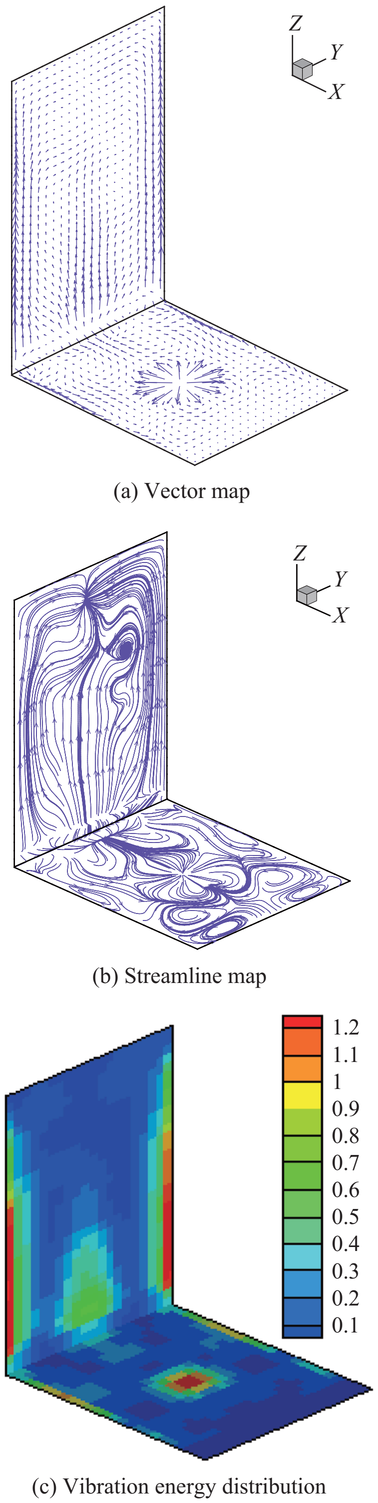


Fig. 9. Vector, Streamline of vibration intensity and vibration energy distribution representation for the L-shaped plate, f = 94 Hz.

The vibration intensity of the coupling plates with point force at the excitation frequency of 8.5 Hz is shown in Figs. 6(a) and 6(b). From these figures it can be found that the patterns of energy flow are quite identical. The positions of the energy source and sink can be identified for L-shaped plates. As indicated, force point acts as the energy source, damper location acts as the energy sink, and the main flow of energy is in a direct path from force point to the damper. It is clearly shown that energy vortex is present. A small amount of energy flow is also reflected on the coupling boundary of the L-shaped plate, while part of energy inject into the vertical free boundaries of plate 2 as shown in Fig. 6(c). The distributions of energy flow are displayed clearly, and energy flow distributions agree with the intensity vector field above quite well.

Structural energy flow can have both translational and vortex components. Vibration intensity distribution patterns also referred to as energy flow patterns may appear in a low damping planar structure (i.e., plate) in the form of straight, S-shape, or vortex patterns [12, 16]; While in coupled plates, the vibration energy does not flow straightly or S type to the damper due to the structural configuration and coupled connection. Theoretical and experimental studies have shown that structural energy flow can have both translational and vortex components [16]. In some instances the characteristics of the structural vibration energy are completely dominated by a vortex pattern.

By comparing Figs. 6 and 7, it shows a slight difference in the energy transmission paths, however, it exists some distinctions of the energy distributions between the two excitation frequencies. In Figs. 7(a) and 7(b), as the point force is applied on the plate 1, the vibrational energy is coming out from that point which is regarded as real energy source. When the energy flow reaches the boundary, the vibration intensity is reflected and some virtual sources or sinks can be constructed. Most of the vibrational energy is transmitting to the free boundaries of the plates, and part of the total energy is transmitted into the damper through the junction, where the energy is dissipated. Again it is shown how the energy distributes at the boundaries of the plates in Fig. 7(c).

As the excitation frequency increasing, the vibrational energy transmission paths become more complex as in Fig. 8. Vibration intensity vector and streamline map demonstrate that there exist the virtual energy sources or sinks. This phenomenon is due to vibration wave reflection from the boundaries of the plates. Most of the energy is not fully delivered to the damper position; the energy sinks by the damper can not be seen clearly in Figs. 8(a) and 8(b). Amount of energy flow are shown on the vertical free boundaries of plate 2 as shown in Fig. 8(c). Most of the energy densely distributes in the plate 2 and the free border. The phenomenon of vortex energy flow can also be shown clearly at the plate 2, which are not symmetric. Energy vortices indicate relative amounts of energy in the vertical plate.

When the excitation frequency up to 94 Hz, it can be seen from Fig. 9 that the vibration energy transfer paths become more complex and the vortices get to be more intensive. It has reported qualitatively that a pair of vibration modes whose resonance frequencies that are very close to each other are necessary to produce the vortex intensity pattern; if these vibration modes are excited simultaneously, the vortex intensity pattern takes place due to the superposition of these vibration modes [16]. Comparing the distributions of energy vortex, we notice that as frequency of excitation increases, higher order vibration modes make the energy flow more complex. The vortex means the circulation and conservation of the vibration energy in mechanic system. In the vortex field, the input energy is equal to the dissipated energy. The damping energy dissipation and the appearance of energy vortex separate the energy sinking at the damper. The energy transfer path from force point to the damper position is not clear, and the energy dissipation by the damper decreases significantly, most of the energy distribute at plate 2 and the coupling boundary.

V. CONCLUSIONS

The vibration energy flow and distribution of L-shaped plate using energy and vibration intensity visualization technique are studied in this paper. The main conclusions of this study can be summarized in the following three points:

(1) The transmission paths of the vibrational energy flow from plate 1 to plate 2 are very complex and dependent on the excitation frequencies, coupling junctions and boundaries conditions. At some frequencies closure vortex fields can be observed. The vibration intensity technique reveals energy flow paths and vortex flow clearly.
(2) The main flow of energy is in a direct path from force point to damper at the low frequencies. As the excitation frequency increasing, most of the energy is not fully delivered to the damper position, some energy flow concentration points and energy vortex field can be observed on other parts of L-shaped plate. When the energy flow reaches the boundaries, the vibration intensity is reflected and some virtual sources or sinks are constructed. Therefore, for vibrational energy flow control using external damper, the external damper should be put on the focal points of energy shown by the vibration intensity method.
(3) The energy distribution map can be used to show the vibrational energy within the L-shaped plate accurately, and is the complement for the vibration intensity technique to show vibrational energy distribution. Furthermore, the application of the vibration intensity technique together with visualization methods has improved the quality of structure-borne noise diagnostics and has made it possible to visualize energy wave phenomena (energy distribution) in a vibrating structure.

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