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A judging principle of crucial vibrational transmission paths in plates

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ABSTRACT

This paper developed a judging principle of crucial vibrational transmission path (VTP) in plates. Novel generalized definitions of VTPs are given referred to the meaning of streamlines. And by comparing governing equations, the similarity between energy flow and fluid motion is firstly found so that an analytic method of VTPs in plates is proposed by analogy with fluid motion. Hereafter, the crucial VTP is defined for energy flows at objective points and relative judging criteria is given. Finally, based on two numerical experiments of passive control, the judging principle is indirectly verified by comparing the reduction effects of energy flows at focused points and relative judgment results of crucial VTPs. This paper is meaningful for analyzing and applying the VTPs in plates to guide the control design in future.

1. Introduction

The structural intensity (SI) [1], which is equivalent to power flow [2] and energy flow [3], can indicate the vibrational transmission paths(VTPs) and positions of sources and sinks of mechanical energy in structures [4]. So, it has received more and more attentions from vibration engineers for minimizing vibration or noise levels in last decades.

The SI was firstly introduced by Noiseax [5] in 1969. Since then, different methods are proposed to analyze the SI and corresponding VTPs in structures. Gavric [1] proposed a finite element method for numerical computation of SI by the normal mode approach in the low frequency range. Energy finite element analysis [6] is used for the analysis of SI at high frequencies. Moreover, a hybrid finite element formulation [7] and power flow boundary element method [8] are developed for computing SI in the mid-frequency region. In addition, a streamline technique is introduced by Xu [9] to visualize the SI vector fields. Based on that technique, the VTPs are shown clearly and legibly by streamlines at discrete points in a space. Till now, considerable work has been done for the analysis of SI and VTPs in various structures, such as beams [10–12], plates [13–19], shells [20–22], and built-up structures [23–25].

Usually, only vibrations of several points/positions are focused to be controlled. For guiding the control designs, the VTPs which have crucial effect on vibrations at objective points should be discerned from the whole VTPs in structures which are usually composed of plates. However, studies on the judgment of VTPs in plates are poor at present. Nam [26], Won [27], Gibbs [28] and Audrain [29] took the magnitudes of focused SIs as cost functions so as to evaluate the optimal control forces. In their work, VTPs are entirely not considered while deciding the exciting points of control forces. Pan [30], Koh [31] and

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Gardonio [32] investigated the power transmitted to a beam- or plate-like receivers through several distributed mounts, and controlled the unwanted vibrations on the receivers by using active isolators. They regarded those discrete mounts as crucial VTPs from sources to receivers, and the whole VTPs in those structures are not considered yet. Besides, Liu [24] applied the SI approach to identify the interior noise sources and predominant vibration panels for a box structure, and determined the proper control positions according to the VTPs in the box structure. Despite that, the placements of dampers and control forces are still determined empirically without any analysis or judgment of VTPs, so it cannot be generalized for other applications. Totally speaking, studies on VTPs in plates are still insufficient at present. And to the best of authors' knowledge, the judging principle of crucial VTPs in plates are not reported yet. As a result, researchers are confused on how to analyze and apply the obtained VTPs to vibration reductions. Thus, more studies are needed to deal with this problem.

In order to apply the obtained VTPs to conduct vibration control designs, a judging principle of crucial VTPs in plates is addressed in this paper. Firstly, novel generalized definitions of VTPs are given referred to the meaning of streamlines. Secondly, the similarity between energy flow and fluid motion is found and then an analytic method of VTPs in plates are proposed by analogy with fluid motion. Thirdly, based on theoretical deductions, the crucial VTP, effective VTPs and crucial effective region are defined for energy flows at focused points, and their detailed judging method is given. Finally, two numerical experiments of passive control are designed to indirectly verify the judging principle of VTPs, and results show that the judging principle is reasonable and meaningful for control designs.

The rest of this paper proceeds as follows: Section 2 describes the SI approach and streamline technique; Section 3 expounds the proposed judging principle of crucial VTPs in plates; Section 4 verifies the judging principle indirectly by using two numerical experiments of passive control; Section 5 summarizes the paper and draws relevant conclusions.

2. Theories of SI and streamline representation

The transient SI is a time-dependent vectorial quantity equal to the outflow of energy density in an infinitesimal control volume. Its jth component in time domain can be defined as [1]

$$i_j(t) = -\sigma_{ij}(t)\cdot v_j(t), i,j = 1,2,3 \tag{1}$$

where $v_j(t)$ is the velocity in the j-direction at time t, and $\sigma_{ij}(t)$ is the ijth component of the stress tensor (i,j=1,2,3 corresponding to x, y, and z directions in a Cartesian coordinate).

The temporal mean of transient SI represents the net energy flow through structures. And for a flat plate, the two components of SI integrated over the plate thickness are [1]

$$\begin{cases} I_x = -\omega/2\mathrm{Im}\left[\tilde{N}_x\tilde{u}_0^* + \tilde{N}_{xy}\tilde{v}_0^* + \tilde{Q}_x\tilde{w}_0^* + \tilde{M}_x\tilde{\theta}_y^* - \tilde{M}_{xy}\tilde{\theta}_x^*\right] \\ I_y = -\omega/2\mathrm{Im}\left[\tilde{N}_y\tilde{v}_0^* + \tilde{N}_{yx}\tilde{u}_0^* + \tilde{Q}_y\tilde{w}_0^* - \tilde{M}_y\tilde{\theta}_x^* + \tilde{M}_{yx}\tilde{\theta}_y^*\right] \end{cases} \tag{2}$$

where N_x, N_y and $N_{xy} = N_{yx}$ are membrane forces, M_x, M_y and $M_{xy} = M_{yx}$ are internal moments, Q_x and Q_y are shear forces, u_0, v_0 and w_0 are translational displacements of the mid-surface, θ_x and θ_y are rotational displacements about the x and y directions. The superior $\sim$ means complex values, and the asterisk * denotes a complex conjugate.

The streamline representation technique illustrates the flow as lines parallel to its velocity field everywhere. As SIs are also vectors distributed in the space, the streamline representation technique can be used to interpret the VTPs of mechanical energy in structures. A streamline can be mathematically expressed as [9]

$$\mathrm{d}\mathbf{r} \times \mathbf{I}(\mathbf{r}) = 0 \tag{3}$$

where $\mathbf{r}$ is the energy flow particle position. That is, the SI vector at any point of one streamline is tangent to that line, as is shown in the following Fig. 1.

The cross product in Eq. (3) can be rewritten as

$$\begin{vmatrix} i & j & k \\ I_x & I_y & I_z \\ \mathrm{d}x & \mathrm{d}y & \mathrm{d}z \end{vmatrix} = 0 \tag{4}$$

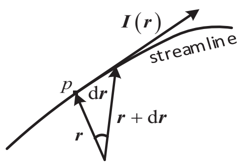

Fig. 1. The SI vector at a point p of one streamline.