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Low-vibration design for shell structure based on structural intensity distribution

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ABSTRACT

Reducing structure-borne sound is an important issue for mechanical industrial products. This paper focuses on countermeasures at the vibration-energy transmission path rather than at the sound source as a potentially better alternative for controlling structure-borne sound. The propagation path can be determined by either measuring or calculating the structural intensity (SI), which is defined as the instantaneous rate of energy transfer per unit area in a structure. Although there have been many reports concerning SI, none can be found that implemented structural design and modification based on the SI distribution. This paper presents a method for implementing structural design by using the SI distribution. First, the ability to control vibration by means of the SI is discussed by comparing the kinetic energy and SI in wave solutions. A shell structure is then designed using the proposed method. The results show that the SI can be used to identify the location to be modified and changing the structure at that location facilitates low vibration. Also presented are the results of an experimental application using a sheet sensor developed specially for visualizing the flow of structural vibration energy. It is shown that this sheet sensor makes it easy to locate the countermeasure areas on a shell structure.

Keywords: Transmission, Structural intensity, Power flow

1. INTRODUCTION

Reducing structure-borne sound is an important issue for mechanical industrial products. Structure-borne sound in manufactured products can be controlled at three locations, namely, the source, the transmission path, and the receiver, and it is often easiest and most effective to control it at the source as the upstream origin of noise and vibration. However, there are many cases in which the source properties cannot be changed without impacting the product performance, and control at the receiver can also be difficult because noise and vibration spread out, making that approach inefficient. This leaves the transmission path as potentially the best approach to controlling structure-borne sound. The vibration transmission path can be determined by either measuring or calculating the structural intensity (SI), which is defined as the instantaneous rate of energy transfer per unit area in a structure (1). There have been many reports concerning SI, but to the best of our knowledge none have implemented structural design and modification based on the SI distribution (4–6).

Against this background, we have conducted a study aimed at establishing a method for low-noise and low-vibration structural design based on the SI (i.e., the flow of vibration energy). In our previous research on SI (7–9), we derived an SI mode expansion equation and showed that SI can be classified roughly as being of either translational or rotational flow type. These flow types can be used to promote transmitted power via translational flow and reduce transmitted power via rotational flow. We also developed a simple and approximate technique for measuring the propagation of vibration energy (10).

The present paper presents a method for specifying the countermeasure location for low-vibration design by using the SI distribution. First, we discuss the ability to control vibration by means of SI by comparing the kinetic energy and SI for wave solutions on a beam. We show that the vibration energy and SI are highly correlated when the progressive wave is dominant, which corresponds to large structural damping, whereas

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the kinetic energy is small when the progressive wave is small. Therefore, under large structural damping, the SI can give important information about the behavior of the progressive wave. We then show that the SI distribution can be used to identify the location to be modified and changing the structure at that location facilitates low vibration. Experimental results suggest that an SI-based countermeasure is useful for reducing the vibration to the same extent over a wide range of frequency. We also present the results of an experimental application in which we use a measurement sheet developed by us to visualize the flow of structural vibration energy. We show that our measurement sheet makes it easy to find the countermeasure location on a shell structure.

2. IDENTIFICATION OF COUNTERMEASURE LOCATION BASED ON STRUCTURAL INTENSITY DISTRIBUTION

We have previously investigated structural design methods to reduce vibration and radiated noise of mechanical structures using the SI distribution. From this, we clarified that the vibration can be reduced by the vibration energy flow to the place is blocking or flowing to other places. Being similar to controlling water flow, this idea is easily understood. The main energy flow for reducing vibration is that represented by the progressive wave. If the reflected wave also becomes influential, then it can be difficult to determine the flow of the progressive wave, but it remains possible to identify the countermeasure location from the energy flow including the reflected wave. Therefore, we describe a method for identifying the countermeasure location based on the SI distribution.

2.1 Correlation between Kinetic Energy and Structural Intensity

First, consider the bending vibration in the far field on a uniform beam along the x axis. The vibration displacement $\zeta(x)$ is expressed as a progressive wave with complex amplitude A and a backward wave with complex amplitude B, that is,

$$\zeta(x) = Ae^{-jkx} + Be^{jkx} \tag{1}$$

and the kinetic energy $K_E(x)$ and the SI $I(x)$ are evaluated as

$$K_E(x) = m|j\omega\zeta|^2 = m\omega^2\left(|A|^2 + |B|^2 + 2\,\mathrm{Re}\left[AB^* e^{-j2kx}\right]\right) \tag{2}$$

$$I(x) = j\omega EIk^2\left(\zeta\frac{\partial\zeta^*}{\partial x} - \zeta^*\frac{\partial\zeta}{\partial x}\right) = 2\omega EIk^3\left(|A|^2 - |B|^2\right) \tag{3}$$

where k is the bending wavenumber, m is the structural mass density, ω is the angular frequency, EI is the bending stiffness, j is the imaginary unit, and Re[] represents the real part.

The kinetic energy is the squared sum of the amplitudes of the progressive wave (A) and backward wave (B) as shown in Eq. (2), whereas the SI is the difference between them as shown in Eq. (3). In the case of a standing wave, the amplitudes of both waves are the same and the SI is zero because $A = B$. In the absence of a backward wave, only the progressive wave is obtained, and the kinetic energy and SI are each proportional to A^2. In other words, the correlation between kinetic energy and SI increases as the progressive wave becomes more dominant. It is therefore important to focus on the progressive wave of SI. In numerical analysis such as the finite-element method (FEM), if the attenuation of the object is increased, then the effect of the progressive wave can be intensified.

2.2 Test Structure

In this section, a steel-panel structure comprising eight flat plates as shown in Fig. 1 is used to describe the advantages of focusing on the progressive wave. Excitation is applied to subsystems 1 and 2, and the vibrations of subsystems 3 and 4 are to be reduced. Consider the problem in which the vibration energy of subsystems 3 and 4 is reduced to be less than the power input into subsystems 1 and 2. Consider also changing the energy propagation paths through subsystems 5–8. The initial thickness of each subsystem is set as follows: 2 mm (subsystems 1 and 2), 4 mm (subsystems 3 and 4), and 1 mm (subsystems 5–8).

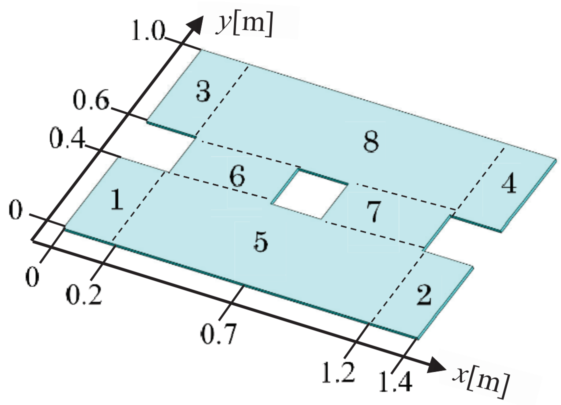


Figure 1 – Test panel comprising eight steel-plate subsystems [thickness of subsystems: 2 mm (1 and 2), 4 mm (3 and 4), and 1 mm (5–8)]

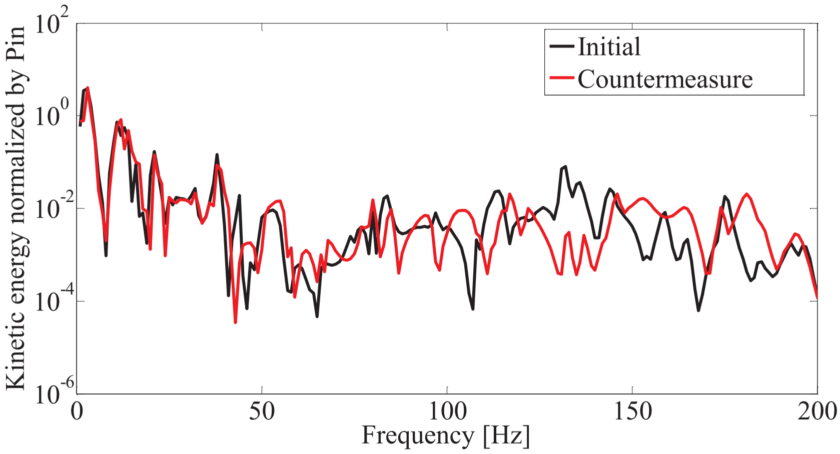
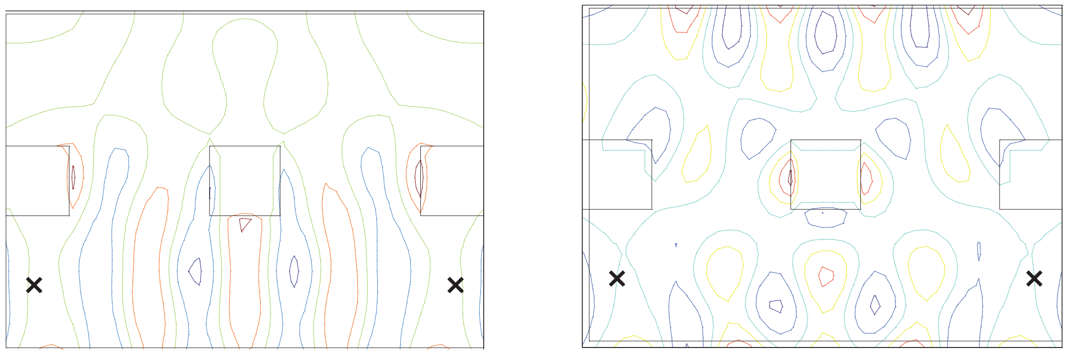


Figure 2 – Vibration energy of subsystem 3 in test structure shown in Fig. 3

The black line (labeled "Initial") in Fig. 2 shows the frequency distribution of the kinetic energy of subsystem 3 normalized by the power input to subsystems 1 and 2 under an external force of 1 N obtained using FEM calculation. This result is for the lowest loss factor of 0.01. The energy is calculated from the spatial average throughout the system. The response is larger around 130 Hz, so we focus on this frequency range.

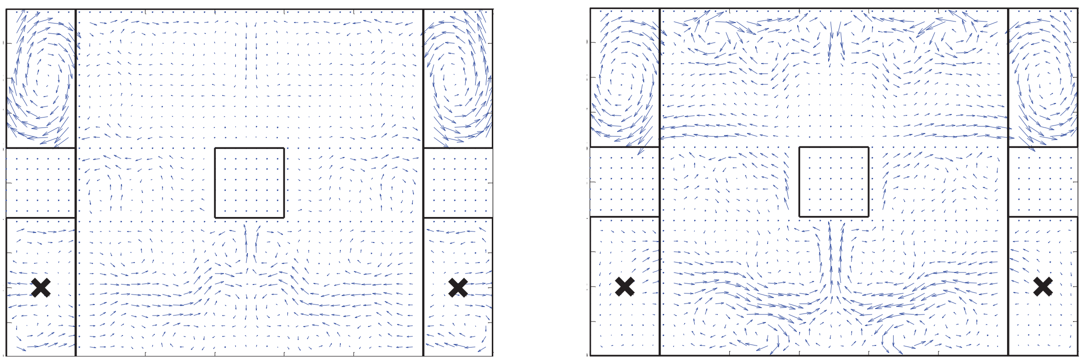
2.3 Advantages of Focusing on Structural Intensity

In this section, we explain the advantages of focusing on the progressive wave. Consider the response around 130 Hz as shown in Fig. 2 with the black line (Initial). In the frequency range around 130 Hz, Fig. 3 shows typical examples of the forced vibration shapes at 131 Hz and 135 Hz. It can be seen that the vibration shapes differ drastically despite the frequency difference of only 4 Hz. Also, it is difficult to identify appropriate countermeasures from the vibrational displacement distribution. Fig. 4 shows the SI distributions at these frequencies with the lowest loss factor (0.01). It is immediately clear that these SI distributions are dissimilar, as for the vibration shape. This is because the backward wave due to reflection at the boundary edge is strong. Comparing the SI distributions shown in Fig. 4 in more detail reveals certain



(a) 131 Hz (b) 135 Hz

Figure 3 – Vibration displacement distributions close to 130 Hz



(a) 131 Hz (b) 135 Hz

Figure 4 – Calculated structural intensity (SI) distributions with lowest loss factor ($\eta_n = 0.01$)

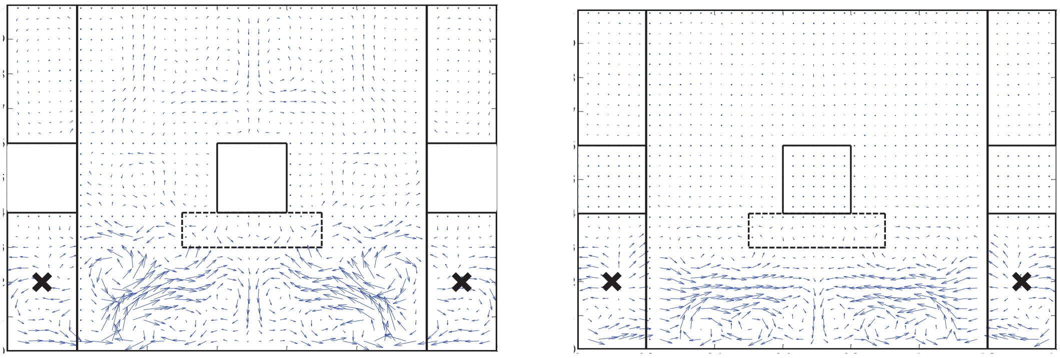
similarities between them, such as a vortex flow distribution on subsystems 3 and 4 and a translational flow on subsystem 5. Adopting countermeasures for these similar flows would reduce the vibration over a wide frequency range because the progressive wave does not change over a wide frequency range (11).

2.4 Structural Change Based on Structural Intensity

In this section, SI-based design is applied in the vicinity of 130 Hz as shown in Fig. 2. As shown in Fig. 4, the SI distribution near 130 Hz is distributed across subsystem 5. Energy is transmitted along the main flow to subsystems 3 and 4, therefore suppressing the energy flow to subsystems 3 and 4 is considered by changing the structure to inhibit the main flow. In this case, the energy transferred from subsystems 1 and 2 to subsystem 5 propagates to subsystems 3 and 4 so as to traverse the center of the structure. Therefore, the countermeasure is to increase the plate thickness for the purpose of suppressing both the flow from subsystem 5 to subsystems 3 and 4 and the flow in the central part of subsystem 5.

The reduction in the vibration of subsystems 3 and 4 is confirmed by FEM (loss factor: 0.01). The red line in Fig. 4 shows the frequency distribution of the summed kinetic energies of subsystem 3 and 4.

Fig. 5 shows the post-countermeasure SI distribution at 135 Hz. The prominent flow across the bottom of subsystem 5 is believed to be due to vibration suppression. Propagation within the region in which the



(a) 131 Hz (b) 135 Hz

Figure 5 – Structural intensity distributions after countermeasure with loss factor of $\eta_n = 0.01$

plate thickness of the upper part of subsystem 5 is increased, with propagation being promoted to the lower part instead. In other words, when the structure is changed based on propagation, focusing not only the part to be interrupted but also the part promoted by the structural change can greatly affect the vibration level of the receiver.

In this paper, we discuss partial structural change based on the SI distribution, but we do not identify the most efficient place to implement structural change for an arbitrary frequency. In future work, we will clarify how much structural change is necessary, which range of frequency to target, and whether vibration reduction is possible over a full order of magnitude of frequency.

3. IDENTIFICATION OF COUNTERMEASURE LOCATION BASED ON STRUCTURAL INTENSITY MEASUREMENT

We aim to develop a system that can plan vibration-reduction measures from a measured SI distribution. In Section 2, we discussed how to identify the vibration-reduction countermeasure location from the SI distribution. In this section, we use a specially developed sheet sensor to measure the SI distribution. By doing so, we identify the vibration-reduction countermeasure location and confirm vibration reduction and change of the SI distribution.

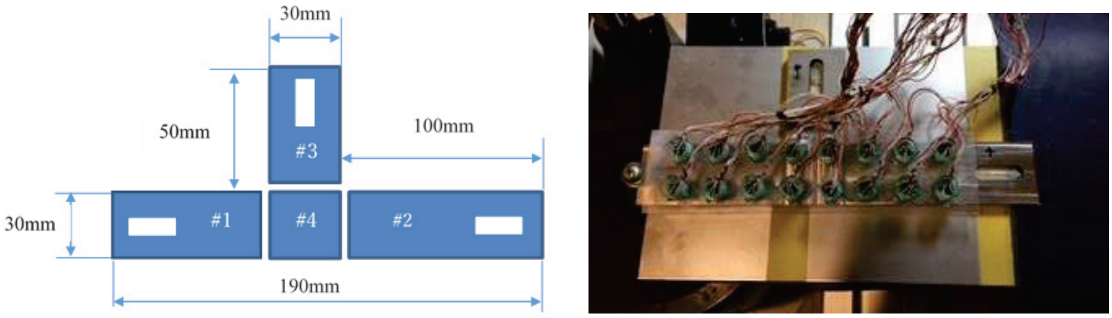
3.1 Test Structure and Method

The target structure used for this experimental measurement is shown in Fig. 8(a), where the numbers labeled "#" are the plate numbers. Consider reducing the vibration of plate 3 when the power input is to plate 1. The ideal energy flow for low vibration is transmitted to plate 2 without being transmitted to plate 3.

As an initial structure, each flat plate is made of steel and is 2 mm thick. Fig. 8(b) shows the state in which the visualization sheet is placed on the test plate. The sheet measures the SI distribution at seven points on a straight line using 16 microelectromechanical sensors. The test structure is bolted at one point on plate 1, and the end of plate 2 is placed on the damping material as shown in Fig. 9; all other places are free. When the edge of plate 1 is excited with an impulse hammer, the accelerance of one point on plate 3 is measured.

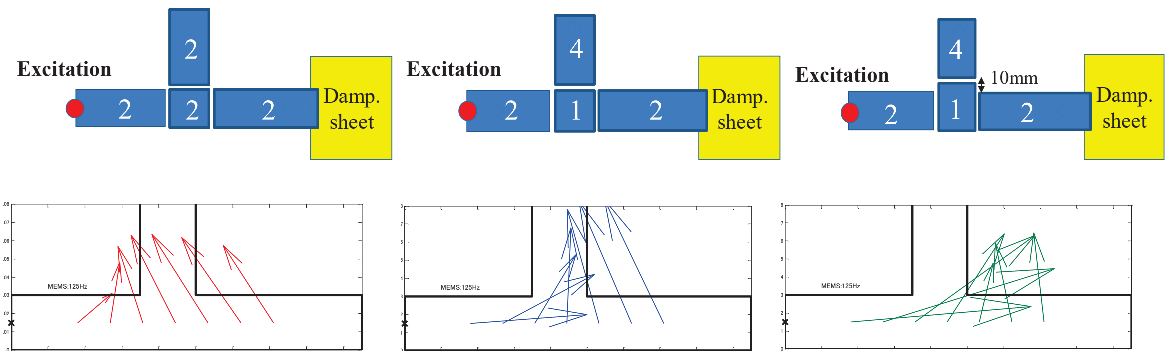
3.2 Identification of Countermeasure Location

The red line in Fig. 10 shows the results of measuring the accelerance in the initial state (when each flat plate is 2 mm thick). The vibration is clearly large around 100 Hz, therefore the results of measuring the SI in that state are shown in the lower part of Fig. 9(a). The SI distribution is toward plate 3, from which we conclude that the vibration of plate 3 is large. It is therefore possible to identify the vicinity of the attachment point of plate 3 as the countermeasure point so as to inhibit the flow to plate 3.



(a) Test T-shaped panel structure (b) SI measurement sheet on test structure

Figure 8 – Test T-shaped structure and apparatus for measuring SI



(a) Initial (b) Countermeasure 1 (CM1) (c) Countermeasure 2 (CM2)

Figure 9 – Measurement conditions and SI results for T-shaped structures with initial configuration and two types of countermeasure (the numbers on the upper figures show the panel thicknesses in millimeters)

3.3 Countermeasures and Their Effects

Of the various possible countermeasures, we consider the two shown in Fig. 9(b) and (c). In the first plan, plate 4 is 1 mm thick and plate 3 is 4 mm thick. In the second plan (termed CM2), the 1-mm-thick portion of plate 4 is extended by 10 mm in the direction of plate 3.

The SI distribution with CM1 is shown in the bottom part of Fig. 9(b), and the results of measuring the accelerance are shown by the blue line (labeled CM1) in Fig. 10. The energy flow to plate 3 is suppressed, and the vibration of plate 3 is reduced. Similarly, the SI distribution with CM2 is shown in the bottom part of Fig. 9(b), and the results of measuring the accelerance are shown by the green line (labeled CM2) in Fig. 10. The energy flow to plate 3 is further reduced, as is the acceleration of plate 3.

Although the countermeasure location is clearly identifiable in this case, we have shown that it can be found from the SI distribution. Also, as in Section 2, Fig. 10 confirms that the vibration is reduced over a wide frequency range.

The purpose of this research is to identify the countermeasure location, and various countermeasures can be considered. In addition, because the SI distribution differs depending on the frequency, the countermeasures using SI are different from those in other frequency ranges. In other words, it cannot be avoided that specific countermeasures bring about to a trade-off between frequency ranges.

From the above discussion, we have confirmed that it is possible to identify the countermeasure location using the SI measurement sheet. In future work, we will assess the validity of using measurements of the SI distribution to identify the countermeasure location for structures that are not uniform flat plates.

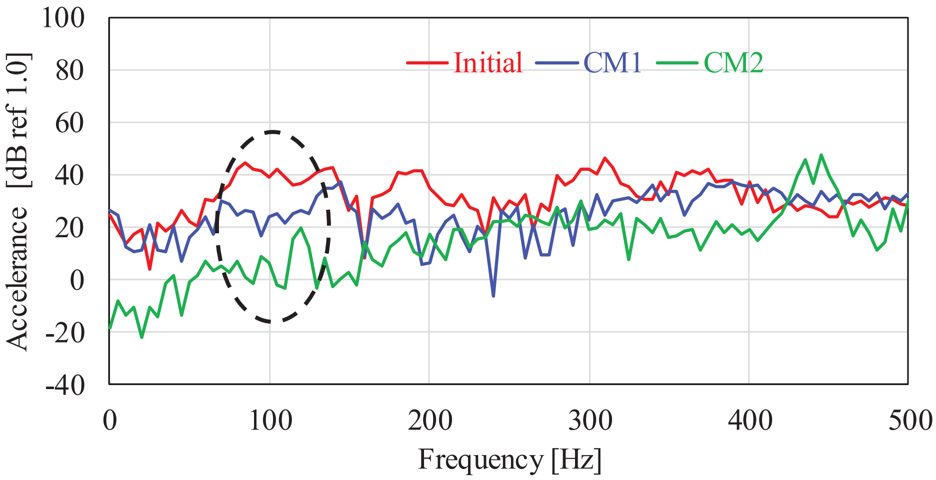


Figure 10 – Comparison of measure targeted for reduction, namely accelerance of plate 3 of T-shaped structure

4. CONCLUSIONS

In this paper, we discussed how to identify countermeasure locations based on SI distributions and presented numerical examples. We also confirmed the feasibility of the method by means of experiments using an SI measurement sheet that is under development. We summarize our findings as follows.

1) SI is highly correlated with kinetic energy for structures that are either heavily damped or away from resonance. Even when lightly damping or at resonance, reducing the progressive wave lowers both the kinetic energy and the SI.
2) There are some advantages in SI-based design, which can work well to reduce vibration over a wide frequency range, including the frequency of interest.
3) The countermeasure location for reducing vibration can be identified using the developed SI measurement sheet, and the reduction of vibration at the target location and the change of the SI distribution have been confirmed

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