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PRACTICAL APPROACH OF STRUCTURAL INTENSITY MEASUREMENT APPLIED FOR BOX-LIKE STRUCTURE

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This paper discribes a structural intensity measurement method and the wave decomposition method using five accelerometers. These methods is used to measure the intensity on structures, to detect the location of source and to estimate propagating power based on measurement at several points on structures. They are experimentally applied to box-like structures composed of flat plates. The 5 transducer array method gave the measurement of power flow in detail. We could identify the location of excitation clearly by the evanescence wave group of displacement, the propagating power could be estimated in high precious easily.

1. INTRODUCTION

The definition of structural intensity was proposed in 1970 by Noiseux[1]. Its measurement is effective to know the transmission path of vibration energy, to detect the source of excitation and to estimate the propagating power. If the structure is a beam or a plate, the theory for measuring the intensity has been established and some methods have been proposed[2]. We have studied on the intensity measurement in 2 dimensional field using the finite difference approximation. We concluded that the method using small number of transducers is actually effective because it is not sensitive to the phase mismatch between transducers. The intensity measurement in near field is almost impossible because the error of finite difference approximation is large in the field. In our previous work[3], we proposed the method for measuring power flow in a flat plate which requires five accelerometers (5 transducer array method). Using this method, it is possible to measure the intensity in far field, but it is impossible to do it in near field in principle. We also presented two methods for detection of sources based on the wave decomposition using 5 transducer array and for estimating the propagating power using the wave decomposition at several points. In this report, these methods are applied to box-like structures composed of flat plates.

Moreover, the power flow on vehicle body is measured using 5 transducer array method.

2. MEASUREMENT PROCEDURE[3]

2.1 Power flow measurement

The x-component of the intensity vector in x-y plane is expressed in frequency domain as

$$I_x(x,y,\omega) = j\omega B\left[\varsigma\left(\frac{\partial^3\varsigma^*}{\partial x^3}+\frac{\partial^3\varsigma^*}{\partial x\partial y^2}\right)-\frac{\partial\varsigma}{\partial x}\left(\frac{\partial^2\varsigma^*}{\partial x^2}+\nu\frac{\partial^2\varsigma^*}{\partial y^2}\right)-(1-\nu)\frac{\partial\varsigma}{\partial y}\frac{\partial^2\varsigma^*}{\partial x\partial y}\right] \qquad (1)$$

where ς :flexural displacement, B :bending stiffness, ν :poisson's ratio, $j:\sqrt{-1}$ and *:complex conjugate. The high order derivatives in Eq.(1) are estimated using 8 transducers[2]. If the vibration field is satisfied with the assumption of the far field, Eq.(1) is simplified to Eq.(2) and the order of derivatives is reduced.

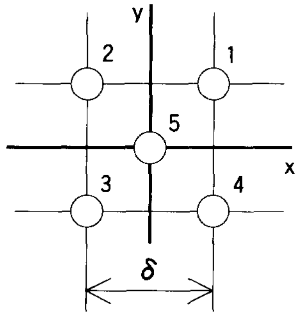


Fig.1 Arrangement of transducers for 5 transducer array method

$$I_x(x,y,\omega) = j\omega B\left[-k^2\varsigma\frac{\partial\varsigma^*}{\partial x}+\left(k_x^2+\nu k_y^2\right)\frac{\partial\varsigma}{\partial x}\varsigma^*-(1-\nu)\frac{\partial\varsigma}{\partial y}\frac{\partial^2\varsigma^*}{\partial x\partial y}\right] \qquad (2)$$

The derivatives in Eq.(2) are determined from the difference equation (3) based on the arrangement of transducers shown in Fig.1.

$$\varsigma=\varsigma_5,\ \frac{\partial\varsigma}{\partial x}=\frac{\varsigma_1-\varsigma_2-\varsigma_3+\varsigma_4}{2\delta},\ \frac{\partial\varsigma}{\partial y}=\frac{\varsigma_1+\varsigma_2-\varsigma_3-\varsigma_4}{2\delta},\ \frac{\partial^2\varsigma}{\partial x\partial y}=\frac{\varsigma_1-\varsigma_2+\varsigma_3-\varsigma_4}{\delta^2} \qquad (3)$$

Here, the x and y components of wave number k_x , k_y are determined from Eq.(4) by rotating the transducer array by 45 degree.

$$\frac{\partial^2\varsigma}{\partial x^2}=\frac{2(\varsigma_1+\varsigma_3-2\varsigma_5)}{\delta^2}=-k_x^2\varsigma,\ \frac{\partial^2\varsigma}{\partial y^2}=\frac{2(\varsigma_2+\varsigma_4-2\varsigma_5)}{\delta^2}=-k_y^2\varsigma \qquad (4)$$

And, the y-component of the intensity vector is also obtained by interchanging x and y in Eq.(1) and (2). Then, the total intensity vector at the point can be determined by adding both components.

2.2 Detection of source

It is actually difficult to identify the location of sources and sinks from the intensity measured even by the 16 transducer array method, which theoretically enables to measure the intensity in near field. It is because the error of finite difference approximation is particularly large in estimating the high order derivatives and the arrangement of many transducers is cumbersome. Then, we have proposed the wave decomposition method using the 5 transducer array.

The vibration field of a plate is expressed by 8 wave solutions as shown in Eq.(5).

$$\varsigma(x,y)=Ae^{-j(k_xx+k_yy)}+Be^{j(k_xx+k_yy)}+Ce^{-j(k_xx-k_yy)}+De^{j(k_xx-k_yy)}$$
$$+Ee^{-(k_xx+k_yy)}+Fe^{k_xx+k_yy}+Ge^{-(k_xx-k_yy)}+He^{k_xx-k_yy} \qquad (5)$$

The displacement is separated into two wave groups as following equations.

Propagating wave group

$$Ae^{-j(k_x x+k_y y)}+Be^{j(k_x x+k_y y)}+Ce^{-j(k_x x-k_y y)}+De^{j(k_x x-k_y y)}=\frac{1}{2}\left(\varsigma-\frac{1}{k_x{}^2}\frac{\partial^2\varsigma}{\partial x^2}\right)\equiv\alpha \tag{6}$$

Evanescence wave group

$$Ee^{-(k_x x+k_y y)}+Fe^{k_x x+k_y y}+Ge^{-(k_x x-k_y y)}+He^{k_x x-k_y y}=\frac{1}{2}\left(\varsigma+\frac{1}{k_x{}^2}\frac{\partial^2\varsigma}{\partial x^2}\right)\equiv\beta \tag{7}$$

Then, the component of evanescence wave group informs us of the location of sources and sinks. The separation is done at arbitrary points on plate. The values of alpha and beta in Eqs.(6) and (7) can be measured using the 5 transducer array.

2.3 Estimation of propagating power based on measurements at 4 points

To know the power flow in detail, many points for measurement are required. The vibrational displacement in two-dimensional filed is expressed using the wave solutions. Then, we can get the mean power flow by the measurements at 4 points.

Each propagating wave amplitude is determined from Eq.(6) obtained at arbitrary four points as shown in Eq.(8).

$$\begin{bmatrix}A\\B\\C\\D\end{bmatrix}=\begin{bmatrix}e^{-j(k_x x_1+k_y y_1)} & e^{j(k_x x_1+k_y y_1)} & e^{-j(k_x x_1-k_y y_1)} & e^{j(k_x x_1-k_y y_1)}\\ e^{-j(k_x x_2+k_y y_2)} & e^{j(k_x x_2+k_y y_2)} & e^{-j(k_x x_2-k_y y_2)} & e^{j(k_x x_2-k_y y_2)}\\ e^{-j(k_x x_3+k_y y_3)} & e^{j(k_x x_3+k_y y_3)} & e^{-j(k_x x_3-k_y y_3)} & e^{j(k_x x_3-k_y y_3)}\\ e^{-j(k_x x_4+k_y y_4)} & e^{j(k_x x_4+k_y y_4)} & e^{-j(k_x x_4-k_y y_4)} & e^{j(k_x x_4-k_y y_4)}\end{bmatrix}^{-1}\begin{bmatrix}\alpha_1\\\alpha_2\\\alpha_3\\\alpha_4\end{bmatrix} \tag{8}$$

Each evanescence wave amplitude is similarly determined.

On the other hand, the intensity in far field is expressed by propagating waves as follow.

$$\begin{aligned}I_x(x,y,\omega)=&\,2\omega Bk^2k_x\left(|A|^2-|B|^2+|C|^2-|D|^2\right)\\&+4\omega Bk_x\left(k_x{}^2+\nu\,k_y{}^2\right)\left[\mathrm{Re}\left(AC^*e^{-j2k_y y}\right)-\mathrm{Re}\left(BD^*e^{j2k_y y}\right)\right]\end{aligned} \tag{9}$$

To reconstruct the intensity without the effect of evanescence waves, each wave amplitude (A, B, C and D) is substituted into Eq.(9).

3. STRUCTURES COMPOSED OF PLATES

3.1 Experiment setup

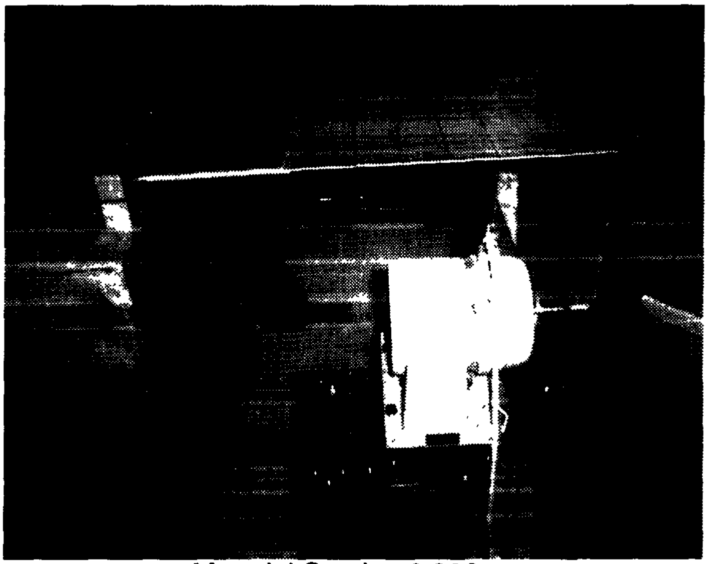
We applied the method described in the previous chapter to two types of structures composed of flat plates. One is an L-shaped structure made by bending a flat steel plate. The two boundary lines parallel to the junction were mounted to rigid steel frame as shown in Fig.2. The other is a box-like structure. This was mounted to bases using rubbers at four points near the corners as shown in Fig.3. The excited signal was 3.2kHz pseudo random and a shaker was used to excite

the structure. The power input to the structure was measured from the driving force and the driving point acceleration using the impedance head. To measure the intensity, accelerations were measured using the 5 transducer array (Fig.4) and the space between accelerometers is 28.3mm. The effect of the base block is negligible up to about 1kHz.
Damping sheets were pasted to some parts of these structures as shown in dark areas of Fig.2 and 3.

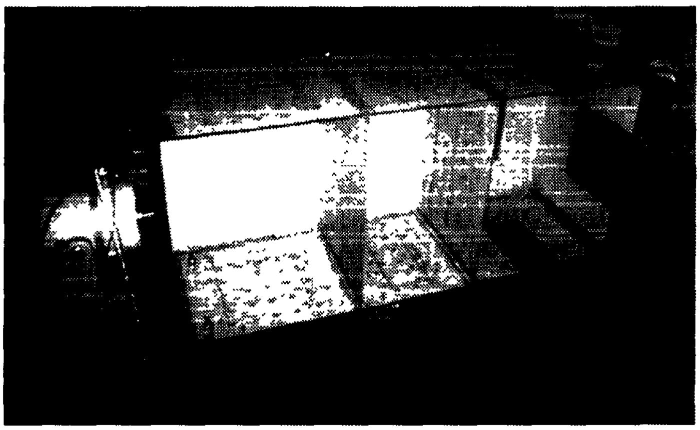
3.2 Power flow measurement

The intensity was measured at 159 points in the L-shaped and at 302 points in the box-like structure. Figures 5 and 6 present the measured intensity of 125Hz one-octave band. They evidently indicate the transmission path of vibration energy but it is difficult to identify the location of excited point.

To verify the measured intensity quantitatively, we estimated the propagating power from plate 2 to 1 of the L-shaped and through the Line A, B and C of the box-like structure. And the propagating powers were also evaluated using Statistical Energy Analysis (SEA) in which internal loss factors were determined from the reverberation time, and coupling loss factors were theoretically estimated. Table 1 indicates that the powers estimated by the measured intensity are in good agreement with those predicted by SEA. Some parts of the power injected by the shaker dissipated in plate 2, and the rest of it propagated to plate 1. In the box-like structure, the intensity measurement



Material:Steel, t=0.002m
plate 1:0.5 × 0.35m, plate 2:0.4 × 0.35m
Fig.2 Setup of L-shaped structure



Material:Steel, t=0.002m
Height:0.5m, Width:0.4+0.3+0.4m, Depth:0.35m
Fig.3 Setup of Box-like structure

Fig.4 5 transducer array

indicates that the propagating power was decreasing as going away from the excited plate.

These investigations show that the 5 transducer array method provides the power flow measured in practical precision.

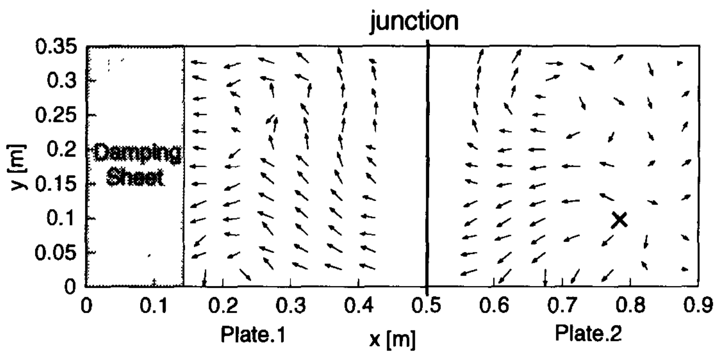


Fig.5 Result of structural intensity measurement at 125Hz octave band in L-shaped structure

3.3 Detection of Source

We can not recognize the location of excited position from the measured intensity by the 5 transducer array method. We applied the separation of displacement to the excited plate of structures. In the L-shaped structure, we evaluated the values of beta in Eq.(7) at 85 points. In the plate 1 of the box-like structure, the values were estimated at 35 points. The evanescence wave group in the plate 2 of the L-shaped is presented in Fig.7. The effect of evanescence wave clearly appeared at the excited position of (0.785, 0.12). And in the box-like structure, the effect was also appeared at the excited position.

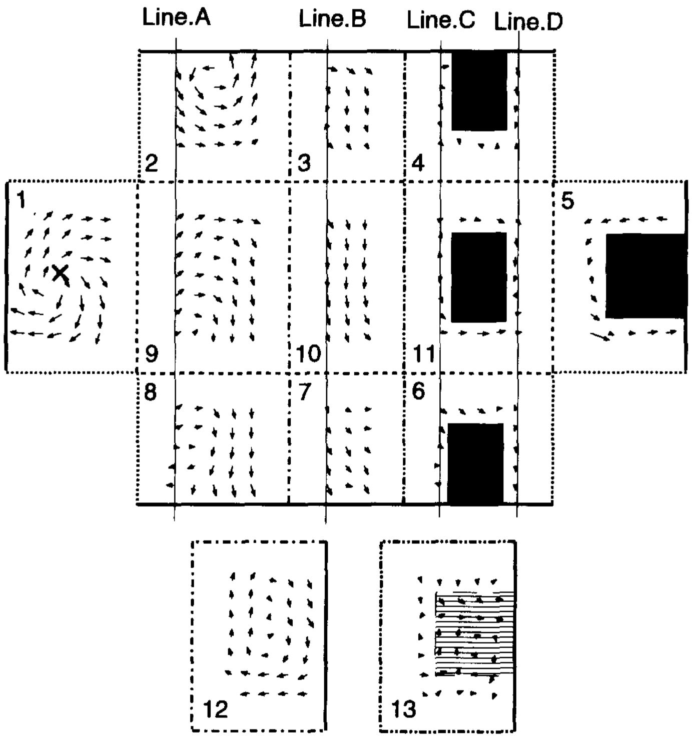


Fig.6 Results of structural intensity measurement at 125Hz octave band in box-like structure

Table.1 Estimation of propagating power in L-shaped structure

	125Hz band	250Hz band	500Hz band	1000Hz band
Intensity	0.77	0.73	0.80	0.80
SEA	0.90	0.89	0.88	0.86
Input Power [W]	1.53E-6	3.57E-6	3.62E-6	2.55E-6

Table.2 Estimation of propagating power in box-like structure

	125Hz band	250	500	1000
	Intensity / SEA	Intensity / SEA	Intensity / SEA	Intensity / SEA
Line.A	0.88 / 0.90	1.08 / 0.88	0.97 / 0.86	0.80 / 0.82
Line.B	0.62 / 0.68	0.64 / 0.61	0.99 / 0.54	0.46 / 0.46
Line.C	0.34 / 0.49	0.46 / 0.41	0.42 / 0.34	0.30 / 0.26
Input Power [W]	1.03E-5	6.12E-6	6.12E-6	1.68E-6

3.4 Estimation of propagating power based on measurements at 4 points

Many measurements by the 5 transducer array method offer the detailed power flow on structures. However, it takes many hours to measure the power flow. To verify the estimation of propagating power based

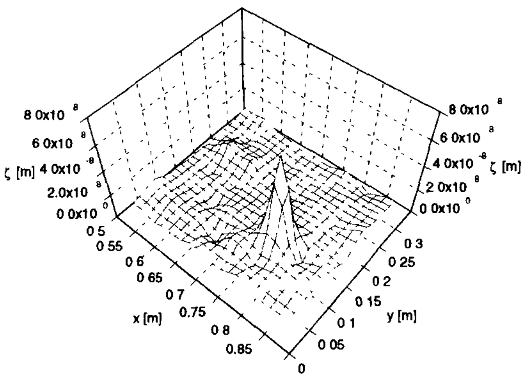


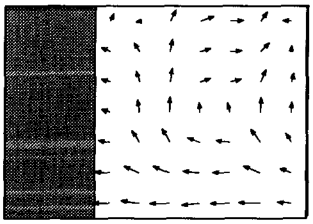
Fig.7 Results of evanescence wave group of displacement in L-shaped structure

on measurements at 4 points, we particularly paid attention to the plate 1 in the L-shaped and the plates 2, 8 and 9 in the box-like structure in this paper.

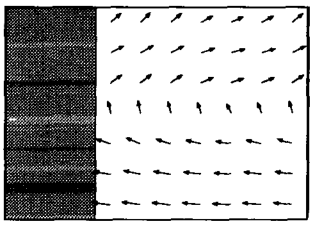
The values of alpha were evaluated at four points using the 5 transducer array on each plate. The intensities were reconstructed using Eq.(8). Figures 8 and 9 present the reconstructed intensity with measured one. The measured intensity is similar to the reconstructed one as shown in these figure (a) and (b). And, the propagating power between plates from these intensities are estimated. In the L-shaped, the measured, the reconstructed and the mean intensity give the values of 0.70, 0.90 and 0.95 as the normalized by input power respectively. In the box-like structure, these estimations are shown in Table 3. These results indicate we can estimate the propagating power by the measurements at only 4 points on a plate in high precious if we have only to know the propagating power.

Table.3 Estimation of propagating power in box-like structure at 190Hz

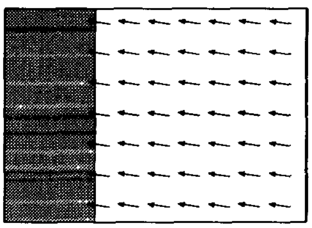
	Line.A	Plate.9 to 2	Plate.9 to 8
Measured	0.97	0.08	0.54
Reconstructed	0.93	0.07	0.53
Mean intensity	0.90	0.09	0.56



(a) Measured

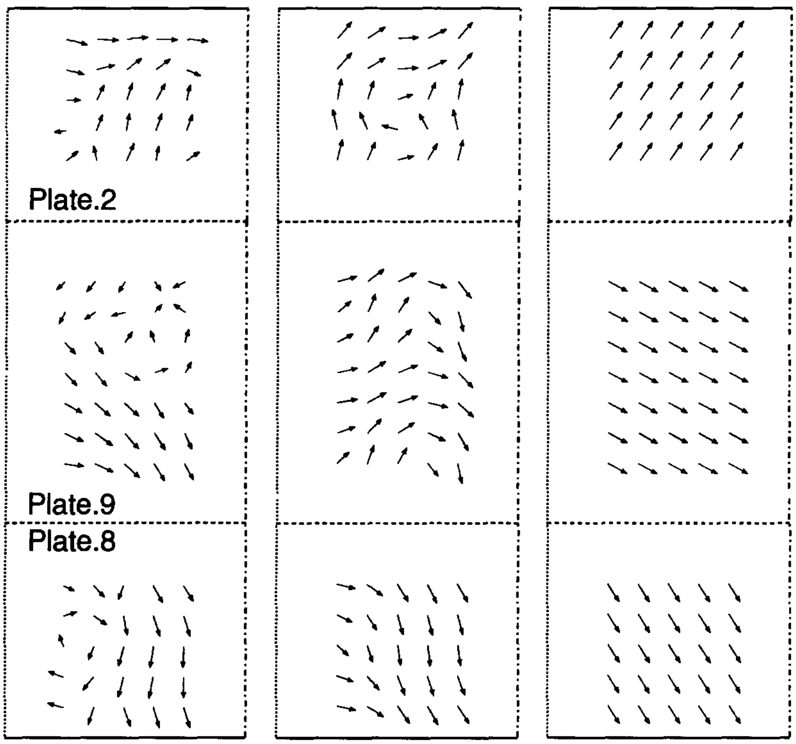


(b) Reconstructed



(c) Mean intensity

Fig.8 Reconstruction of intensity in L-shaped structure at 190Hz



(a) Measured (b) Reconstructed (c) Mean intensity

Fig.9 Reconstruction of intensity in box-like structure at 120Hz

4. VEHICLE BODY

We applied the 5 transducer array method to know to measure the power flow of a vehicle body composed of a thin plate. The object is shown in Fig.10. It is a left front door panel of a micro compact car. The panel is composed of an inner and outer panels. A side impact beam is attached on the other side of the inner panel. The power flow of the panel was measured under fully assembled condition.

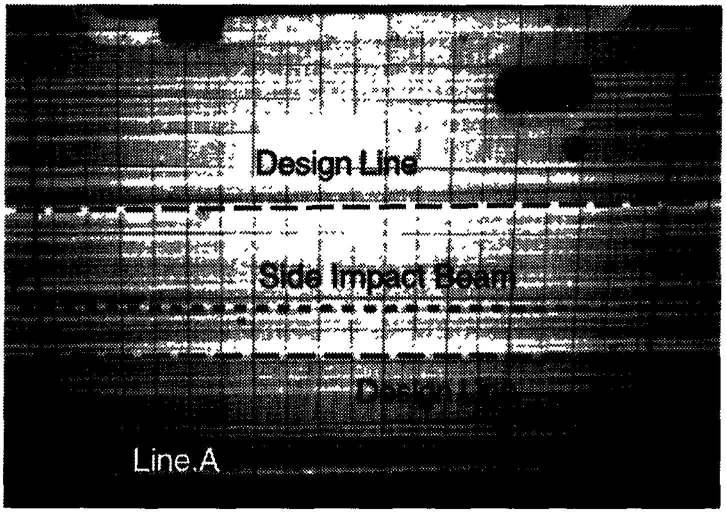


Fig.10 Tested left front door panel of vehicle

4.1 Experiment setup

The automotive was mounted at 4 points by rigid racks and the shaker was set up at front under reinforcing beam as shown in Fig.11. We measured the accelerations on the 5 tranducer array and the input power from the driving force and the driving point acceleration by an impedance head. The intensities were measured at 232 points at the grid of 50mm× 50mm as shown in Fig.10. The thickness of panel is 0.86mm.

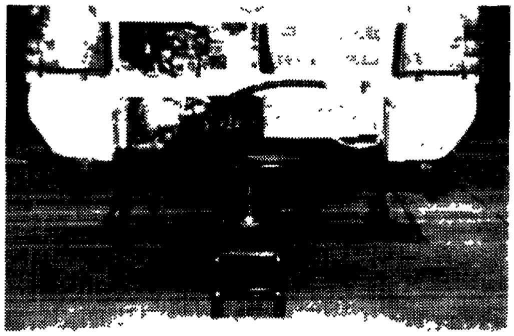


Fig.11 Excitation position on vehicle

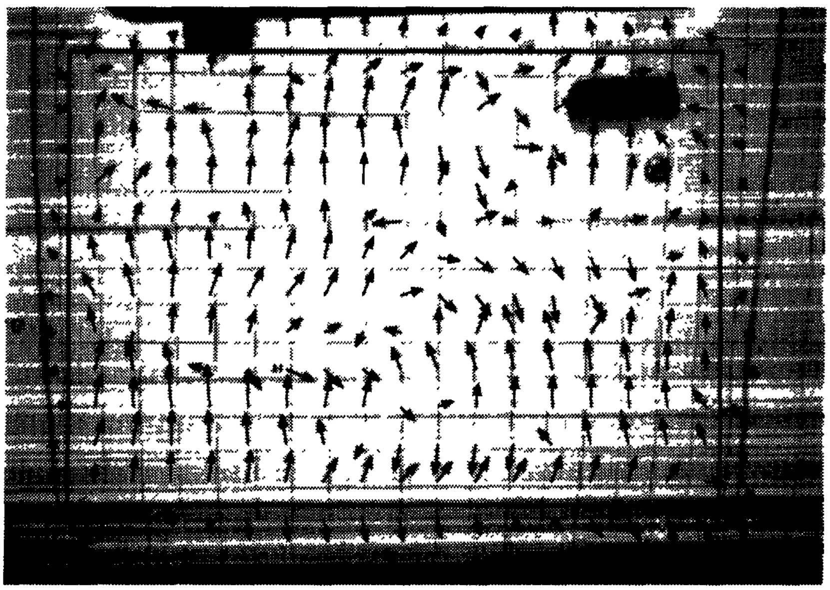


Fig.12 Result of structural intensity measurement on left front door panel at 125 Hz octave band

Table.4 Dissipated and propagating power in door panel

	125Hz band	250Hz band	500Hz band	1000Hz band
Dissipated power	3.99E-6	2.84E-6	4.86E-7	1.08E-7
Propagating power	4.95E-6	1.56E-6	4.43E-7	7.36E-8

4.2 Measurement of power flow

The measured intensity is shown in Fig.12. The power flow indicates that the main path of transmitted power is line A where the inner and the outer panels are attached. And the flow is interrupted by the two design lines and the attached locations of the side impact beam.

In this paper, the propagating power into the square in Fig.12 is compared with the dissipated power in the panel. The dissipated power P_d was evaluated such as SEA from $P_d = \omega\eta E$, here ω:center angular frequency, η:internal loss factor of the panel and E:vibration energy of outer panel. The result is shown in Table.4. It presents that we can measure the intensity even in vehicle door panels using the 5 transducer array method within this practical level.

5. CONCLUDING REMARKS

In this paper, we applied three methods to box-like structures experimentally. We can measure the detailed power flow in far field of structures using the 5 transducer array method. And, the wave decomposition into two groups is effectively applicable to detect the source of excitation. Moreover, the wave decomposition into each wave amplitude enables to reconstruct the intensity without the consideration of evanescence waves. Then, the propagating power can be estimated by the measurements at 4 points. It is also shown as an example of measuring the intensity by the 5 transducer array method that we can measure the intensity even of vehicle door panel.

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