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DAMPING PATCH PLACEMENT ON OUTDOOR UNIT OF AIR-CONDITIONER BY USING STRUCTURAL INTENSITY TECHNIQUE

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ABSTRACT

In this paper, reactive shearing structural intensity method is extended to damping patches placement on outer panels of outdoor unit of air-conditioner to reduce its structural borne noise. After the structural intensity is calculated for simple structures such as plate, corrugated plate and outdoor unit panel, damping patches are placed over areas of high reactive shearing structural intensity. The structural intensity is calculated from the normal velocities of each panel of an outdoor unit that is measured by using a laser scanning vibrometer, and *k*-space signal processing is used to obtain the spatial derivatives in formulation of structural intensity. Then this method is also applied to the outdoor unit of air-conditioner during operating mode. Finally, experimental results show the largest reduction of sound pressure level of an outdoor unit by applying small damping patches to optimized position.

1. INTRODUCTION

The existing researches on the structural intensity mostly have been focused on measurement techniques and their equations that are applied on beams and flat plates. Zhang (1985) compared the steps and the results of the structural intensity calculation methods of Pavic's and Romano's formulation. Zhang also performed study of the energy flow and its effect on ribs, by placing the ribs on flat plates. Morikawa and Ueha (1996) demonstrated the errors that occur while processing the spatial *k*-space(wave number domain) signal in the structural intensity calculation, taking a step closer to providing better-suited filter width. Nejade and Singh (2002) computed the structural intensities, based on the configuration and arbitrary boundary conditions of the flat plates. Furthermore, the energy flow of the structural intensity and the magnitude of the sound intensity were studied by comparing the structural and the sound intensity maps of the upper gearbox.

Spalding and Mann (1995) showed that, after applying the damping patches, using the reactive shearing structural intensity could change in the local or the global surface velocity of the flat plates. This study ignited the idea of applying the reactive shearing structural intensity technique to reduce the radiated noise that occurs in structures. Kruger *et al.* (1997) computed the reactive shearing structural intensity in first and third modes of a side of cubic structure and reduced the noise by changing and applying the numbers, sizes and shapes of the damping patches at the areas with high reactive shearing structural intensity.

In this paper, the structural intensities are measured to verify the flow and source of the vibration energy on the flat and corrugated plates. Furthermore, the structural intensities of the outer panels of outdoor unit of air-conditioner are measured and then the structural borne noise is reduced to applying small damping patches on areas of the high reactive shearing structural intensity locations.

2. STRUCTURAL INTENSITY

2.1 Structural Intensity Theory

Many other papers have been documented the topics of the formulations, signal process methods and filtering methods on the structural intensity, therefore this paper will only refer to the basic Pavic's formulation. The structural intensity formulation of *x* and *y* directions of plate, placed in *x*-*y* plane, is written as follows (Pavic, 1976).

$$I_x = \left\langle D\left[-\left(\frac{\partial^2 \xi}{\partial x^2} + \nu \frac{\partial^2 \xi}{\partial y^2}\right)\left(\frac{\partial}{\partial x}\dot{\xi}^*\right) - (1-\nu)\frac{\partial^2 \xi}{\partial x \partial y}\left(\frac{\partial}{\partial y}\dot{\xi}^*\right) + \left(\frac{\partial^3 \xi}{\partial x^3} + \frac{\partial^3 \xi}{\partial y \partial x^2}\right)\dot{\xi}^* \right]\right\rangle_t \tag{1}$$

$$I_y = \left\langle D\left[-\left(\frac{\partial^2 \xi}{\partial y^2} + \nu \frac{\partial^2 \xi}{\partial x^2}\right)\left(\frac{\partial}{\partial y}\dot{\xi}^*\right) - (1-\nu)\frac{\partial^2 \xi}{\partial x \partial y}\left(\frac{\partial}{\partial x}\dot{\xi}^*\right) + \left(\frac{\partial^3 \xi}{\partial x^2 \partial y} + \frac{\partial^3 \xi}{\partial y^3}\right)\dot{\xi}^* \right]\right\rangle_t \tag{2}$$

where ν is Poisson's ratio for the plate, ξ is the normal displacement of the plate surface, $\bullet$ is a time derivative, * is a complex conjugate, $\langle\ \rangle_t$ means time average, and D is the bending stiffness of the plate.

$$D = \frac{Eh^2}{12(1-\nu^2)} \tag{3}$$

where E is the Young's modulus , h is the thickness of the plate.

The structural intensity equations can be divided into three terms that correspond to three wave types, bending, twisting and shearing that are propagating in the plate. Following shows the three parts of the structural intensity of *x* direction.

$$-\left(\frac{\partial^2 \xi}{\partial x^2} + \nu \frac{\partial^2 \xi}{\partial y^2}\right)\left(\frac{\partial}{\partial x}\dot{\xi}^*\right) \tag{4}$$

$$-(1-\nu)\frac{\partial^2 \xi}{\partial x \partial y}\left(\frac{\partial}{\partial y}\dot{\xi}^*\right) \tag{5}$$

$$\left(\frac{\partial^3 \xi}{\partial x^2 \partial y} + \frac{\partial^3 \xi}{\partial y^3}\right)\dot{\xi}^* \tag{6}$$

Equation (4) is corresponded to bending wave, equation (5) is corresponded to twisting wave and equation (6) is corresponded to shearing wave (Zhang and Mann III, 1996).

The structural intensity, like that of sound intensity, is expressed in a complex number. The real part is called the active structural intensity, and the imaginary part is called the reactive structural intensity. Here, the active structural intensity indicates the energy flow in time average power, while the reactive structural intensity carries no distinct meaning (Zhang, 1985). However, the reactive shearing structural intensity in relation with the shearing wave, according to the researches of Kruger (1997), Spalding and Mann (1995), presents the useful method in determining the damping patches location for reducing the radiated noise.

2.2 Structural Intensity Calculation

The structural intensities in equations (1) and (2) are computed on the normal velocity and its spatial differentiation, and the accuracy of the structural intensity is dependant on the spatial differentiation processing. The velocity data, measured for the computation of spatial differentiation, transform into spatial frequency domain through spatial Fourier transform and then executed through algebraic calculation as below.

$$F\left[\frac{\partial^{n+m}\dot{\xi}}{\partial x^n \partial y^m}\right] = (jk_x)^n (jk_y)^m F\left[\dot{\xi}\right] \tag{7}$$

where $F[\ ]$ represents the spatial Fourier transform, k_x and k_y are wave numbers in the x and y directions respectively.

Since the errors included in the measured data are amplified in high frequency domain, *k*-space spatial filter is needed to reduce the data error and also the spatial window function is needed to exponentially decay the measured velocity data. Figure 1 illustrates the structural intensity calculation process based on Pavic's formulation, where the equations (1), (2) and (7) are used.

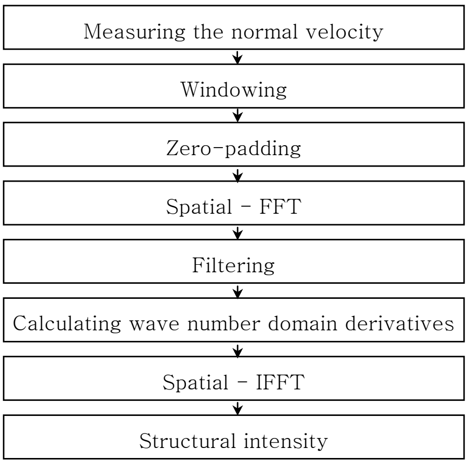


Figure 1: Procedure to calculate structure intensity.

3. EXPERIMENTS

3.1 Flat Plate and Corrugated Plate

Prior to measuring the structural intensity of an air-conditioner outdoor unit, the structural intensities of simple structures such as flat and corrugated plates were measured. The simple structures were hung from the iron frame with piano wire, connected a 20 cm stringer at the same place as the Figure 2 below and then excited by using shaker. Flat and corrugated plate has a thickness 2 mm and is made by steel. The total size of flat plate is 84 cm by 23 cm, and Figure 2 is the configuration of corrugated plate. The laser vibrometer collected the velocity data of flat and corrugated plate on a 31 by 9 point and 45 by 17 point grid over the plate surface respectively.

3.2 Outdoor Unit on Shaker-Exciting Mode

To compute the structural intensity of each panel of the air-conditioner outdoor unit, experimental equipment was structured that measures the normal velocities of the outdoor unit as in Figure 2. The outdoor unit was connected to the iron frame with piano wire, connected a 20cm stringer at the bottom of the unit where the compressor is placed and then excited using MB Modal 50A. The point of excitation was at 230 mm and 150 mm from the left side of the base panel as in Figure 2. The reference signal was received using PCB 208C02 force transducer between the stringer and the panel, and the normal velocities of the outdoor unit's surface were measured by using PSV 300 Polytec's laser scanning vibrometer. B&K 1/2" 4189 microphone was used to measure the sound pressure level, simultaneously with the vibration measurement, before and after placing the damping patches, which was performed

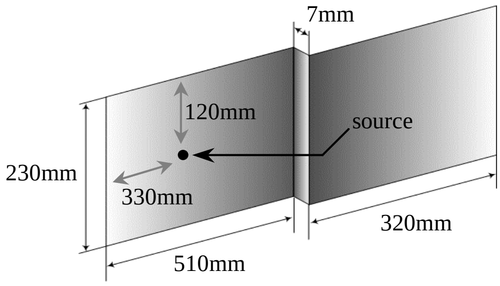


Figure 2: Geometry of the corrugated plate with an excitation point.

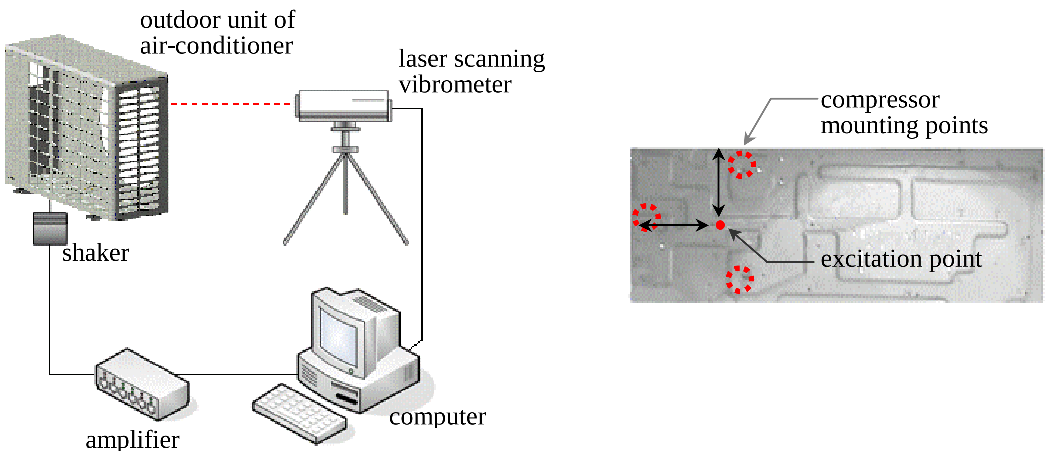


Figure 3: Experimental set-up for outdoor unit and base panel configuration.

in anechoic room. The sound pressure level was measured 1 m away from the front of the outdoor unit, and butyle tape damping patches with 0.06 loss factor were used in all experiments.

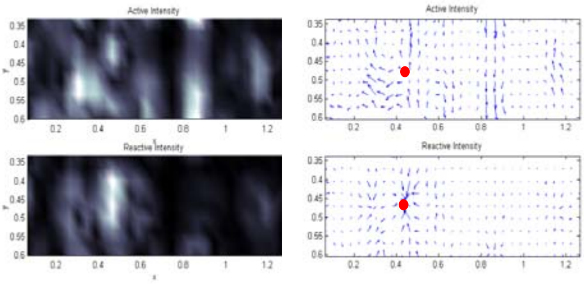
The velocity measurement was performed on five sides, namely the base, top, front, rear and the right side panels, with the measurement points being 555(37×15) points, 855(45×19) points, 555(15×37) points, 429(11×39) points and 243(37×15) points respectively. The spatial resolutions between the measurement points in respect to x and y directions are the base at 22 mm and 20 mm, top at 17.2 mm and 14.5 mm, front at 18 mm and 14 mm, rear at 17 mm and 14 mm and the right side at 20 mm and 16 mm.

3.3 Outdoor Unit on Operating Mode

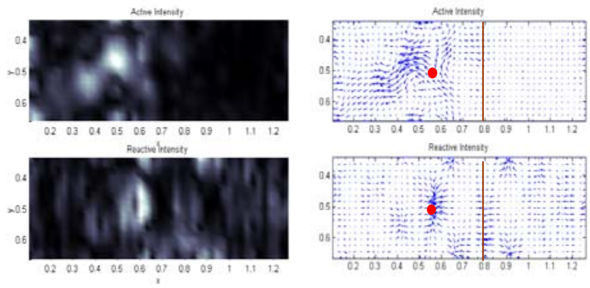
In order to calculate the structural intensity of the outdoor unit on operation mode, the air-conditioner outdoor unit was fixed on aluminum frame in an anechoic room and then the normal velocities of each side panel were measured. Accelerometer was used to receive the reference signal in measuring, while the calculating process and the methods for measuring the radiated noise and the structural intensity were same as the experiment on outdoor unit of air-conditioner on shaker-exciting mode.

4. RESULTS AND DISCUSSION

It was possible to verify that the energy does flow outward from the source location on the simple flat and corrugated plates, by using the active and reactive structural intensity vector diagrams as Figure 4. This in turn showed the source of the vibration. It was also showed that the value was the highest at the source through reactive shearing intensity vector diagram.



(a) flat plate (252Hz)



(b) corrugated plate (252Hz)

Figure 4: Structural intensity maps and vector diagrams for a flat plate and a corrugated plate(points indicate vibration source and lines represent bent area).

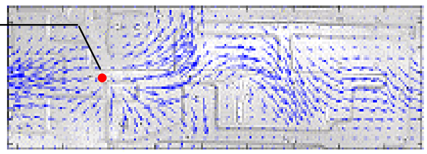
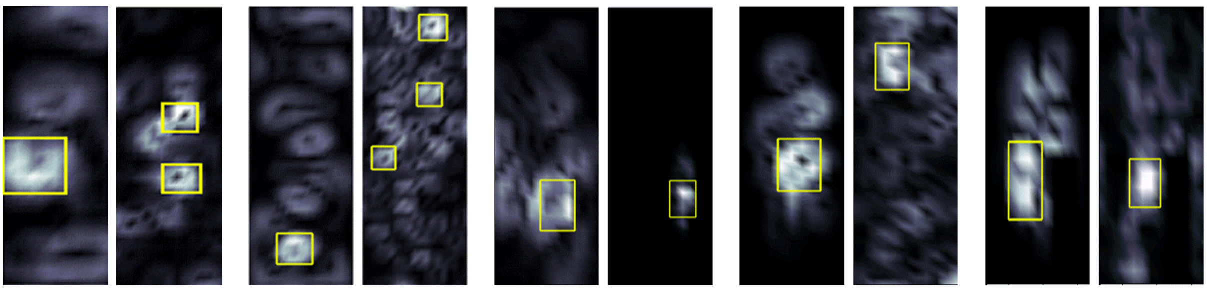


Figure 5: Structural intensity vector diagram of base panel of outdoor unit on shaker-exciting mode at 240 Hz .



(a) base panel (b) top panel (c) front panel (d) rear panel (e) right side panel

Figure 6: Reactive shearing structural intensities of outdoor unit on shaker-exciting mode at 240 Hz and 746 Hz.

Therefore, the structural intensity is a decisive technique in determining the source location and shows the energy flow in the vibrating structure. The shape of the base panel on the unit makes it difficult to apply flat-plate-based structural intensity formulation. Consequently, this paper postulated the irregular base panel surface, Figure 3, as flat in calculating the structural intensity. Examining the structural intensity vector diagram of the base panel at 240 Hz showed that the energy flows from the vibrating source as shown in Figure 5. This result shows that vibrating source in complex base panel surface was very nicely represented by active structural intensity. Therefore postulating the base panel as flat deems to be reliant to some degree.

240 Hz and 746 Hz were selected as the target frequencies, which showed the peak values in vibration and sound pressure level spectrums on the outdoor unit in operation mode disregard to their operational environment and the vibration or sound pressure level measuring locations, and then the structural intensities were calculated. Reactive shearing structural intensity maps are shown as Figures 6, using the surface velocity data of outdoor unit panels through Figure 1 calculation process.

The white boxes mark the highest reactive shearing structural intensity of each panel in Figure 6. The damping patches were placed in these locations and radiated sound pressure levels were measured. When the damping

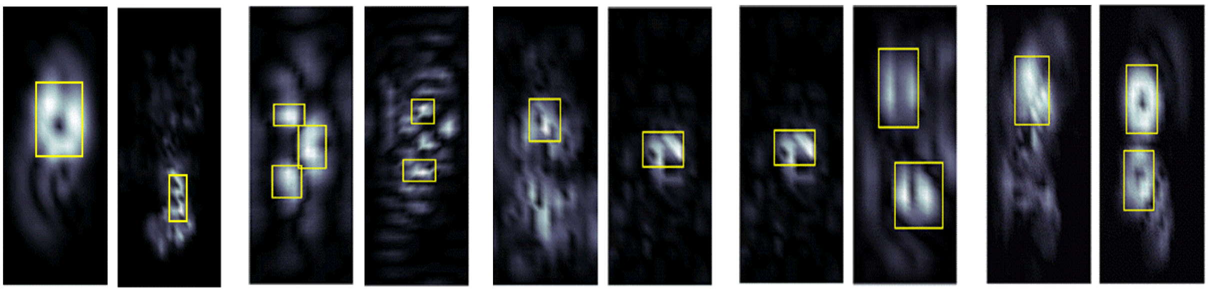


Figure 7: Reactive shearing structural intensity of outdoor unit on operating mode at 240 Hz and 746 Hz.

Table 1: Change of sound pressure level of outdoor unit on shaker-exciting mode

		Radiated Sound Pressure Level (Reduction), [dB]	
		240 Hz	**746 Hz**
No Damping Patches		67.1	58.4
Apply Damping Patches	**Base Panel**	62.8 (–4.3)	42.0 (–16.4)
	Top Panel	53.5 (–13.6)	55.6 (–2.8)
	Front Panel	60.7 (–6.4)	56.9 (–1.5)
	Rear Panel	64.4 (–2.7)	56.5 (–1.9)
	Right Panel	63.2 (–3.9)	56.8 (–1.6)

Table 2: Change of sound pressure level of outdoor unit on operating mode

		Change of Sound Pressure Level, [dB]			
		Measured at Front Side		**Measured at Rear Side**	
		240 Hz	**746 Hz**	**240 Hz**	**746 Hz**
Apply Damping Patches	**Base Panel**	–2.1	+0.6	–0.4	–0.7
	Top Panel	–0.7	+1.0	+0.3	–1.2
	Front Panel	–1.4	–0.6	–0.9	–1.9
	Rear Panel	–0.8	+0.5	–0.2	–1.2
	Right Panel	0	–0.3	+0.1	–1.4
	All Panels	–3.0	–0.8	–1.0	–2.3

patches were applied to the top panel of the outdoor unit, a maximum sound pressure level reduction of 13.6 dB was achieved at 240 Hz. when the damping patches were attached to the base panel of the outdoor unit, a maximum sound pressure level reduction of 16.4 dB was achieved at 746 Hz.

The sound pressure levels and the reduction degrees for each panel before and after applying the damping patches are summarized in Table 1. The spectrums on the changed sound pressure level before and after applying the damping patches are as indicated in Figure 8 and Figure 9. Arbitrary placement of the damping patches confirmed poor reduction effectiveness or increased radiated noise compared to the method of applying the damping patches based on the structural intensity technique.

The results of radiated sound pressure level measurements before and after applying the damping patches while the unit is in operating mode indicate, as the Table 2 shows, the maximum reduction effectiveness of 1.4 dB (front measurement) at 240 Hz and 1.9 dB (rear measurement) at 746 Hz. Furthermore, Table 2 indicates that when the damping patches are applied simultaneously on the locations with high reactive shearing structural intensity on all

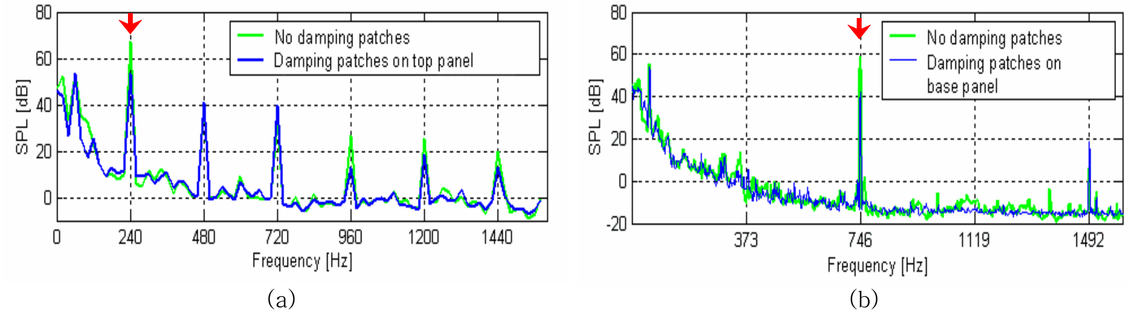


Figure 8: Sound pressure level with and without damping patches on shaker-exciting mode - (a) 240 Hz, (b) 746 Hz.

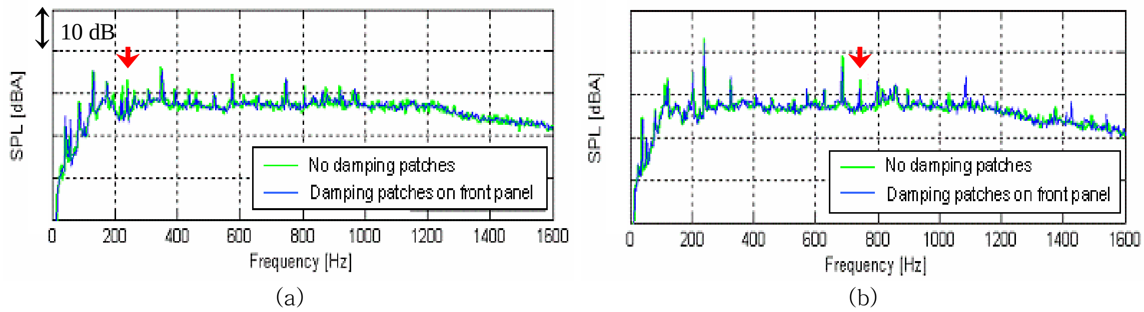


Figure 9: Sound pressure level with and without damping patches on operating mode - (a) 240Hz, (b) 746Hz.

panels, the reduction of sound pressure level increase up to 3 dB (front measurement) and 2.3 dB(rear measurement) at 240 Hz and 746 Hz respectively.

5. CONCLUSIONS

In this study, the normal velocities were measured on the outer panels of outdoor unit of air-conditioner and their structural intensity calculated. Furthermore, the sound pressure level reduction of up to 16.4 dB of structural borne noise was shown by application the damping patch to the location with high reactive shearing structural intensity in exciter experiment. This verifies that utilizing the reactive shearing structural intensity technique is an appropriate method in predicting the proper damping patch applicable location in structures such as outdoor unit of air-conditioner. However, the application on the actual operating unit resulted considerably less effectiveness in reducing sound pressure level compared to the exciter experiment unit. This indication confirms that the air borne noise from the compressor and fan is comparable to the structural borne noise from the outer panels and inner constituents, which lessen the effect of the damping patch used at certain frequencies.

After postulating that the base panel as flat, which was not, the computation of the structural intensity and the application of the damping patch resulted in reduction of radiated sound pressure level. This result suggests that the structural intensity technique can be extended to structure with complex surface. However, more studies and experiments on the magnitudes of structural intensity and the vibration energy flows are needed on the plates with more complex shapes of structure.

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