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Journal of Sound and Vibration 286 (2005) 1048–1056

JOURNAL OF
SOUND AND
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Short Communication

Vibrational energy transmission through wall junctions in buildings

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Received 26 November 2004; accepted 13 January 2005
Available online 16 March 2005

1. Introduction

Structure-borne noise level prediction is important in a heavily serviced building as many of these pieces of services equipment are sources of vibration. The statistical energy analysis (SEA) is developed basing on an energy balance concept and it provides a simple framework for the prediction of energy flow within complicated structures. This method requires knowledge on the total loss factors of building elements and the coupling loss factors between building elements [1]. Many researches into the theory and practical use of SEA have been conducted in the past few decades (for instance, Craik [2]). Theories on the vibrational power transfer between coupled plates were also developed [3,4]. While transmission loss for right-angled wall junctions appear to be relatively well understood [1,2], those related to non-right-angled junctions in existing buildings are not available, at least to the knowledge of the authors. Such information is of exceptional importance for a congested high-rise city like Hong Kong where building forms and internal floor layouts are dictated by the limited land availability.

In the present study, the total loss factors and vibrational power transmission losses were measured in-situ in real buildings having non-right-angled wall junctions. The dependence of the vibration power transmission loss with junction angles was discussed. It is hoped that the present

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doi:10.1016/j.jsv.2005.01.012

findings can provide useful information for the further development of the structure-borne noise prediction scheme for use in real buildings.

2. Brief theory of SEA

In this SEA, the walls, ceilings, floors, cavities and other building elements are modeled as subsystems, each of which carries an amount of energy. If Subsystems 1 and 2 are directly connected to each other and vibrational power is injected directly into Subsystem 1 only, the energy balance equation for the Subsystem 2 can be written as

$$E_1\eta_{12} + E_3\eta_{32} + E_4\eta_{42} + E_5\eta_{52} + \cdots = E_2\eta_2, \tag{1}$$

where E is the energy contained in a subsystem, η_{ij} the coupling loss factor from Subsystem i to Subsystem j and η_2 is the total loss factor of Subsystem 2. Since E_1 is much higher than the other energy contents as Subsystem 1 is the only subsystem receiving power input, it has been discussed in [1,2] that the approximation

$$E_1\eta_{12} \approx E_2\eta_2 \Rightarrow \eta_{12} \approx \frac{E_2}{E_1}\eta_2 \tag{2}$$

will introduce an error small enough not to affect the general trends and thus a check on the theories can be done. Since the building structures in the present study are not so different from those of Craik [2], it is assumed that the approximation of Eq. (2) is valid here. The total loss factor of a subsystem at the frequency f can be estimated from the reverberation time T [1].

The consistency relationship of the coupling loss factor between the two subsystems requires that $n_1\eta_{12} = n_2\eta_{21}$, where n is the modal density. However, $\eta_{12} \neq \eta_{21}$ in general as $n_1 \neq n_2$ so that the coupling loss factor is not appropriate for describing the effects of wall junction angle on energy transmission between the walls inside a building.

Suppose two walls are directly coupled inside a building and the vibration fields inside them are diffuse, the power transmission coefficient from the first to the second walls, τ_{12}, is related to η_{12} by [2,5]:

$$\eta_{12} = \frac{c_{g1}L_{12}}{2\pi^2 f A_1}\tau_{12}, \tag{3}$$

where c_{g1}, A_1 and L_{12} are the group velocity, surface area and height of the first wall (same as the length of the junction). Observing in the present study that the each pair of coupled walls were made of the same material and were of the same thickness and height ($L_{12} = L_{21}$), the consistency relationship and the relationship between the modal density n and the group velocity [1] suggest that $\tau_{12} = \tau_{21}$. The power transmission loss $R_{12} = R_{21} = -10\log_{10}(\tau_{12})$. Combining Eqs. (2) and (3), one finds, following the assumptions made in the present study,

$$\tau_{12} = \frac{2\pi^2 f A_1}{c_{g1}L_{12}}\frac{E_2}{E_1}\eta_2. \tag{4}$$

The group velocity can be obtained by using the formulae depicted in [1]. It should be noted that Eq. (4) is an approximation and is expected to lead to the errors described in [2].

3. Site measurements

The site measurements were performed within the general teaching wings of the Hong Kong Polytechnic University, which was erected in the 80 s and inside a newly built high-rise residential building in Hong Kong. The core walls are made of concrete (density 2400 kg/m^3) and the thicknesses are either 125 mm or 300 mm. For the classrooms in the university, the walls are made of brick (density 2000 kg/m^3) and are 100 mm thick. The Poisson's ratios of all the materials are assumed to be 0.2 as suggested in [1]. The heights of the walls involved are roughly 2.6 m.

The reverberation times T were determined using wall acceleration signal decay (impulse method) together with the backward integration technique [6]. These decay signals were obtained by striking a wall once with an impact hammer.

The measurements of the vibrational power transmission losses were carried out using the power injection method with an impact hammer with a hard tip head. Power was injected by continuous hammering at random positions on one of the coupled walls (away from edges) so as to minimize the influence of excitation point on energy transmission measurement [7]. The energy content of a wall, E, was calculated from signals obtained from accelerometers. These vibrational acceleration signals on each wall were measured using four well-separated accelerometers randomly mounted on the wall, but far enough from the wall edges. A total of eight simultaneous acceleration signals, four from the source wall and four from the receiver wall, were involved in each measurement. They were recorded simultaneously by a data acquisition system having a through put rate of 96 000 samples per second. Every spatially averaged squared acceleration $\langle a^2 \rangle$ at the frequency f was calculated from the power spectral densities of the acceleration signals with a constant bandwidth of $\sim$3 Hz. The vibrational energy of a wall, E, is related to $\langle a^2 \rangle$ as [1]:

$$E = \frac{M\langle a^2 \rangle}{(2\pi f)^2}, \tag{5}$$

where M is the mass of the wall. The foregoing analysis was done in the one-third octave frequency band and f hereinafter denotes the centre frequency of a one-third octave band. Since each pair of coupled walls in the present study were made of the same material and thickness, Eq. (4) can be re-written as, for direct vibrational power transmitting from wall 1 to wall 2,

$$\tau_{12} = \frac{2\pi^2 f A_1 \eta_2}{c_{g1} L_{12}} \frac{A_2 \langle a^2 \rangle_2}{A_1 \langle a^2 \rangle_1} = \frac{2\pi^2 f A_2 \eta_2}{c_{g1} L_{12}} \frac{\langle a^2 \rangle_2}{\langle a^2 \rangle_1}. \tag{6}$$

The required number of measurement points on a wall for a reliable estimation of E is controversial and varies widely in existing literature (for instance, Boisson et al. [7], Furukawa et al. [8] and is not given in [2]). A test was carried out on a 3 m by 2.6 m wall using seven well-separated accelerometers away from wall edges. The excitation was obtained by hammering an adjacent wall. The results tend to suggest that four accelerometers would be satisfactory (not shown here).

4. Results and discussions

In the foregoing discussions, those data in the frequency range with modal overlapping factor, m, less than unity are omitted as SEA procedure requires that $m>1$ [9]. The associated junction angles discussed later are defined in Fig. 1. All the walls involved in the present study were coupled with concrete ceilings and floors.

4.1. Two-wall junctions

The included angle θ is defined as shown in Fig. 1a. Fig. 2 illustrates the vibrational power transmission loss for $\theta = 90^\circ$ and 135°. No data is available for $\theta < 90^\circ$ as it is difficult and uncommon to find such an angle in Hong Kong buildings. A total of two 90° and four 135° junctions were involved and all the walls surveyed are either 125 mm thick concrete façade walls

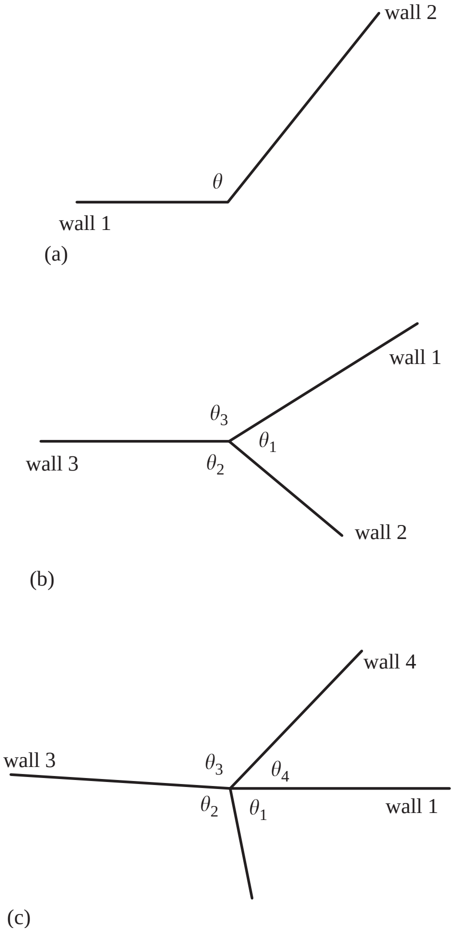

Fig. 1. Types of wall junctions and definition of junction angles. (a) Two-wall junction; (b) three-wall junction; and (c) four-wall junction.

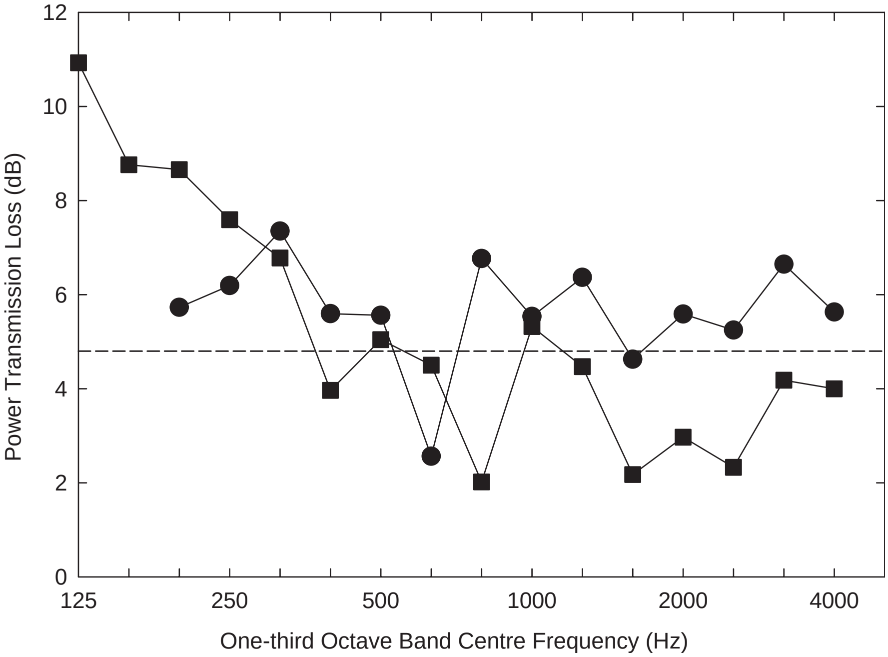

Fig. 2. Vibrational power transmission loss for two-wall junctions. ●: $\theta = 90°$; ■: $\theta = 135°$; ————: right-angled junction [1].

or 300 mm thick core walls. These concrete junctions are continuous as in normal Hong Kong practice. Data for the 90° junctions at frequency lower than 200 Hz are not presented as the corresponding modal overlapping factors are less than unity. Data presented for the 135° junction at frequencies lower than 200 Hz are averages over the results from two junctions only because of the same reason.

One can observe from Fig. 2 that for $\theta = 90°$, the average power transmission loss at frequency higher than 250 Hz is close to the theoretical value for the right-angled corner junction, which is 4.8 dB [1]. For $\theta = 135°$, the power transmission loss decreases with frequency initially, but fluctuates about 3 dB at frequency greater than 500 Hz. This appears consistent with the theoretical computation of Farag and Pan [3] at higher frequency where the effects of individual vibration modes are insignificant. At high frequency, the results of Farag and Pan [3] also indicate higher transmission of energy across junction as θ approaches towards 180° from 90°. All these features agree with the present experimental results obtained in buildings. One thus expects better vibrational power transmission at frequency higher than 500 Hz as $\theta \to 180°$. However at low frequencies where damping is not high enough, the transmission may then depend on mode coupling which complicates the issue. The present results tend to suggest higher vibration power transmission loss at low frequency for $\theta > 90°$.

4.2. Three-wall junctions

These junctions are usually found in the interior of a building. They are of the flush-joint type. In the present study, all of them are brick walls of thickness 100 mm. Fig. 1b defines the angles associated with this kind of junction. θ_1 denotes the included angle between the source wall and the receiver wall. Similar vibrational power transmission loss is resulted when θ_2 and θ_3 are interchanged at fixed θ_1 as the power transmission is non-directional (as shown in Section 2).

The variations of vibrational power transmission loss with frequency are shown in Fig. 3. The results of in-line transmission ($\theta_1 = 180^\circ$, $\theta_2 = \theta_3 = 90^\circ$) appears to fluctuate about 7 dB over the frequency range concerned, but the corresponding transmission loss within 300 Hz–3kHz is fairly constant at ~6 dB. These values of transmission losses appear to be considerably below 8.3 dB depicted in [1] for random incidence. Three Tee-junctions with $\theta_2 = 180^\circ$, $\theta_1 = \theta_3 = 90^\circ$ were included in the present study, the corresponding average vibrational power transmission loss at higher frequency is ~2 dB which is well below the 8.3 dB transmission loss [1].

For the case with $\theta_2 = \theta_3 = 135^\circ$, $\theta_1 = 90^\circ$, one observes that vibrational power transmission loss, which are the average results from two junctions, increases with frequency and fluctuates about the 8.3 dB line only at a narrow frequency band centred at 1.25 kHz. Compared with the case of Tee-junction with $\theta_1 = 90^\circ$, such change in θ_2 and thus θ_3 results in higher transmission loss over the whole frequency spectrum. It tends to suggest that either there has been more power reflected back to the source wall or allowed to propagate into the third wall, or both. Inferring from the results of the two-wall junctions and those of Farag and Pan [3], the portion of vibrational power transmission into the third wall might become higher and higher as $\theta_2 \to 180^\circ$.

An increase in θ_1 with θ_2 remains roughly constant ($\theta_1 = \theta_2 = 113^\circ$, $\theta_3 = 134^\circ$) results in vibrational power transmission loss fluctuates about the 9 dB line as shown in Fig. 3. The

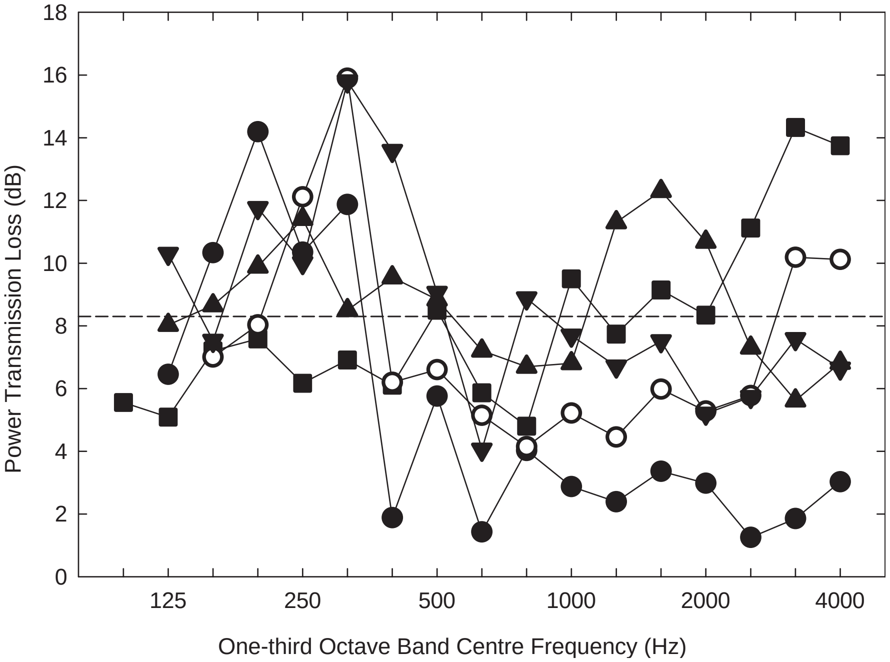

Fig. 3. Vibrational power transmission loss for three-wall junctions. ●: Tee junction right-angled transmission ($\theta_1 = \theta_3 = 90^\circ$, $\theta_2 = 180^\circ$); ○: Tee junction in-line transmission ($\theta_1 = 180^\circ$, $\theta_2 = \theta_3 = 90^\circ$); ■: $\theta_1 = 90$, $\theta_2 = \theta_3 = 135^\circ$; ▲: $\theta_1 = \theta_2 = 113^\circ$, $\theta_3 = 134^\circ$; ▼: $\theta_1 = 134^\circ$, $\theta_2 = \theta_3 = 113^\circ$; ——————: theoretical result for Tee-junction [1].

arrangement of the angles in this case allows a more even transmission of energy from the source wall to the other two walls.

The results obtained with $\theta_1 = 134^\circ$, $\theta_2 = \theta_3 = 113^\circ$ show decreasing power transmission loss as frequency increases beyond 300 Hz. The corresponding power transmission loss is a bit higher than those of the in-line transmission of the Tee-junction ($\theta_1 = 180^\circ$, $\theta_2 = \theta_3 = 90^\circ$) except at very high frequency. A comparison with the results of $\theta_1 = 90^\circ$, $\theta_2 = \theta_3 = 135^\circ$ tends to suggest again the agreement with the above preliminary conclusion that an increase in the included angle between two walls reduces the power transmission loss at higher frequency.

4.3. *Four-wall junctions*

These junctions are found in the interior of a building and are of the flush-joint type. The associated angles are defined in Fig. 1c. In this subsection, any wall can be a source wall or a receiver wall. For Cross-junction ($\theta_1 = \theta_2 = \theta_3 = \theta_4 = 90^\circ$), the vibrational power loss for right-angled transmission fluctuates about 11 dB at lower frequency, but drops to around 5 dB for frequency higher than 500 Hz (Fig. 4). This discrepancy of ~6 dB is consistent with that observed from the right-angled transmission of the Tee-junction. The exact reason is unknown, but the better coupling between the bending and longitudinal waves in the walls at 90° junction, which is implied by Cuschieri and McCollum [4], could be a possible explanation. Allowing for non-uniformity of the walls and experimental uncertainty, the corresponding results for the Cross-junction are about 12 dB which appear to agree with the theoretical prediction of 10.8 dB [1].

The second junction investigated is of $\theta_1 = \theta_2 = 67^\circ$ and $\theta_3 = \theta_4 = 113^\circ$, and is symmetrical about the line formed by wall 2 and wall 4. Therefore, one expects $R_{12} = R_{21} = R_{23} = R_{32}$ and $R_{14} = R_{41} = R_{34} = R_{43}$. Two junctions of this kind were involved. For in-line vibration transmission across these junctions, where power transfer between walls 1 and 3 (R_{13} or R_{31}) and between wall 2 and wall 4 (R_{24} or R_{42}) is concerned, the power transmission loss does not show obvious trend (Fig. 4). However, its overall average across the frequency bands is also well compared with the theoretical value of 10.8 dB.

For power transmission between adjacent walls, the average transmission losses for the coupled walls with included angles less than or equal to 90° generally show a decreasing trend with frequency, but become less dependent on the included angle at frequency higher than 1.6 kHz (Fig. 4). The transmission losses with included angle of 90° and 67° are very similar with the latter slightly lower except at low frequency and within the frequency bands from 630–1.25 kHz. The corresponding results with an included angle of 113° suggest higher transmission loss at frequency higher than 300 Hz. This appears inconsistent with the trend observed in the two-wall and three-wall junction cases. More detailed investigation is required. The vibrational power transmission losses in these cases are again far less than the predicted value of 10.8 dB [1] at higher frequencies.

5. Conclusions

Site investigations on the vibrational energy transmission across wall junctions, where several walls were coupled together inside real buildings were carried out in the present study.

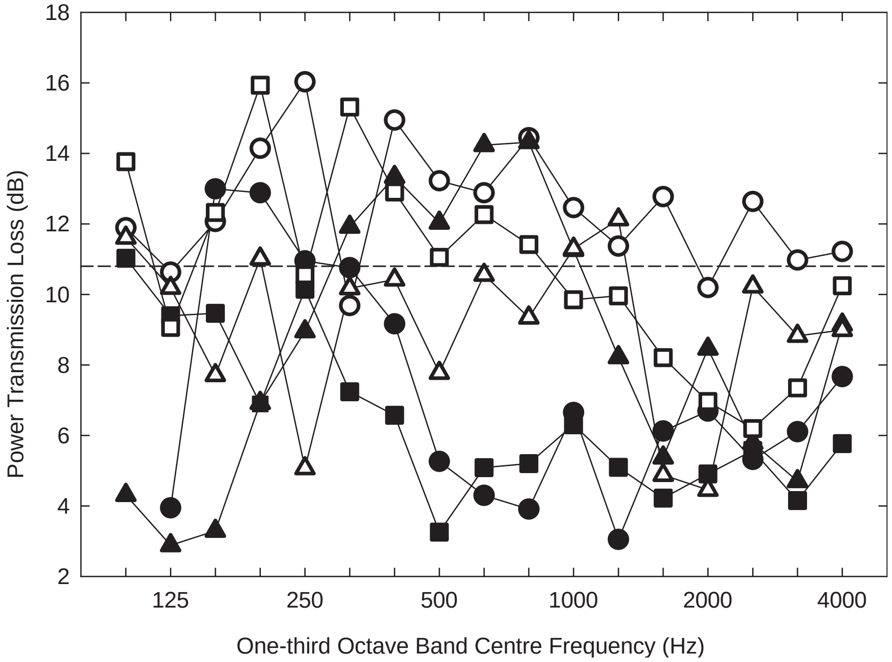

Fig. 4. Vibrational power transmission loss for four-wall junctions. ●: included angle 90° (cross-junction $\theta_1 = \theta_2 = \theta_3 = \theta_4 = 90°$); ○: cross-junction in-line transmission; ■: included angle 67° ($\theta_1 = \theta_2 = 67°$, $\theta_3 = \theta_4 = 113°$); ▲: included angle 113° ($\theta_1 = \theta_2 = 67°$, $\theta_3 = \theta_4 = 113°$); □: in-line transmission from wall 2 to wall 4 ($\theta_1 = \theta_2 = 67°$, $\theta_3 = \theta_4 = 113°$); △: cross transmission from wall 1 to wall 3 ($\theta_1 = \theta_2 = 67°$, $\theta_3 = \theta_4 = 113°$); ——————: theoretical result for cross-junction [1].

For the two-wall junctions, the results tend to suggest that the power transmission loss decreases as frequency increases for included angle greater than 90°, which agree with the theoretical prediction using plate structure in existing literature at frequencies away for any eigenfreqeuncy. The increase in the included angle between two walls beyond 90° reduces the power transmission loss at higher frequency. For the three-wall junctions, the power transmission loss from the source wall to the receiver wall increases as the angle between the source wall and the third wall increases unless the source and receiver walls together form a straight wall (for example, the Tee-junction). Again, an increase in the included angle between the source and receiver walls beyond 90° with the third wall roughly fixed in position relative to the source wall reduces the power transmission loss. The right-angled and in-line power transmissions of a Tee-junction, especially the former, are lower than the theoretical predictions.

The situation for the four-wall junctions is more complicated. For non-right-angled transmission between two adjacent walls, it is found that the reduction in the included angle below 90° enhances power transmission compared to that of the Cross-junction. However, the transmission loss increases as the included angle increases beyond 90°. The vibrational power transmission loss is not much affected by the presence of the two side-walls as far as in-line transmission is concerned, but a broadband reduction in the power transmission loss is observed when the power flow is not in a straight-line direction.

Acknowledgment

The financial support from the Hong Kong Polytechnic University (Project no. GT852) is gratefully acknowledged.

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