Journal of Sound and Vibration (1999) **222**(1), 99–113
Article No. jsvi.1998.2047, available online at http://www.idealibrary.com on IDEAL

STRUCTURE-BORNE SOUND TRANSMISSION FROM MACHINES IN BUILDINGS, PART 2: INDIRECT MEASUREMENT OF FORCE AND MOMENT AT THE MACHINE–RECEIVER INTERFACE OF A SINGLE POINT CONNECTED SYSTEM BY A RECIPROCAL METHOD

S. H. Yap and B. M. Gibbs
Acoustics Research Unit, School of Architecture and Building Engineering, The University of Liverpool, Liverpool, L69 3BX, *England*

(*Received* 15 *May* 1998 *and in final form* 2 *November* 1998)

There is increasing evidence that moments are significant contributors in machine induced structure-borne sound. Omission of these components in prediction can therefore lead to an underestimate of total power in some cases, although it is recognised that considering all transmission paths in prediction generally is not a practical approach, due to the complex nature of the problem. A way forward is to establish the installation conditions and the primary transmission paths and components in order that the least important can be neglected for simplification in the prediction. To permit the measurement of force and moment at machine contacts, the indirect method described in a companion paper (Part 1) was employed. Experimental results for a machine attached to a concrete floor and a brick wall demonstrate that the contribution of moment components is sensitive to source location. At low frequencies, moments are less important than vertical forces when the source is away from the structural discontinuities such as floor edges. However, moments are important at low frequencies when sources are in the proximity of structural discontinuities. Moments have an increasing contribution with increased frequency irrespective of excitation location.

1. INTRODUCTION

Machines impart vibrational energy into connected and supporting structures through all contact points and by up to six components of excitation. Previous studies are almost exclusively concerned with vertical translatory motion and excitation components, but there is growing evidence that other components, such as moments, become important at high frequencies [1–3]. In recent years, Petersson has shown that when a structure-borne source is close to a

0022–460X/99/160099 + 15 $30.00/0

discontinuity such as a plate edge, moment excitation also plays an important role at low frequencies [4–7]. In this situation, the neglect of moments will lead to inaccurate prediction and most importantly, to inappropriate recommendations for control.

The objective of the work described in this paper was to confirm the practicalities of the indirect measurement method where moments and forces are considered simultaneously, and then to study the effect of source location on the relative importance of moments and force in power transmission at a single point, 3-degree of freedom system.

2. POWER AT A SINGLE CONTACT

Studies have been reported on measurements of vibrational power transmission from model multi-point or multi-component sources into supporting structures [8–11]. There is, however, relatively little work reported on real machines on thick structures such as concrete floors. The main problem encountered is in registering the forces and moments at the contact points. This is overcome in the present work by registering the general forces indirectly by means of reciprocity methods described in a companion paper [12].

From the general expression (9) in reference [12], the net active power induced by one translational and two rotational components at a single point (vertical z-direction and rotation about x and y axes, as indicated in Figure 1) is given by

$$P = \frac{1}{2}\mathrm{Re}\left(|v_{r_1}|^2 \{\varphi^*(v_{r_1}, v_z)\varphi^*(v_{r_1}, w_x)\varphi^*(v_{r_1}, w_y)\}[Y_r]^{-1} \left\{ \begin{array}{c} 1 \\ \varphi(v_{r_1}, v_{r_2}) \\ \varphi(v_{r_1}, v_{r_3}) \end{array} \right\} \right). \quad (1)$$

The reciprocal method requires the selection of three arbitrary response points (r_1, r_2 and r_3) on the receiving structure and their transfer and cross-transfer mobilities between the excitation point and components to be known. Hence, Y_r is a 3×3 mobility matrix and when reciprocity is invoked

$$[Y_r] = \begin{bmatrix} Y_{v_{r_1}F_z} & Y_{v_{r_1}M_x} & Y_{v_{r_1}M_y} \\ Y_{v_{r_2}F_z} & Y_{v_{r_2}M_x} & Y_{v_{r_2}M_y} \\ Y_{v_{r_3}F_z} & Y_{v_{r_3}M_x} & Y_{v_{r_3}M_y} \end{bmatrix} = \begin{bmatrix} Y_{v_zF_{r_1}} & Y_{w_xF_{r_1}} & Y_{w_yF_{r_1}} \\ Y_{v_zF_{r_2}} & Y_{w_xF_{r_2}} & Y_{w_yF_{r_2}} \\ Y_{v_2F_{r_3}} & Y_{w_xF_{r_3}} & Y_{w_yF_{r_3}} \end{bmatrix}.$$

The remaining terms in expression (1) are the velocity transfer functions on the receiving structure due to all excitation components when the connected machine is set into operation.

In the basic power expression, the powers respectively contributed by the vertical translational force (F_z) and moments (M_x, M_y) now can be written as

$$P_{F_z} = \tfrac{1}{2}\mathrm{Re}[F_z v_{r_1}^* \varphi^*(v_{r_1}, v_z)], \quad (2)$$

$$P_{M_x} = \tfrac{1}{2}\mathrm{Re}[M_x v_{r_1}^* \varphi^*(v_{r_1}, w_x)], \quad (3)$$

$$P_{M_y} = \tfrac{1}{2}\mathrm{Re}[M_y v_{r_1}^* \varphi^*(v_{r_1}, w_y)], \quad (4)$$

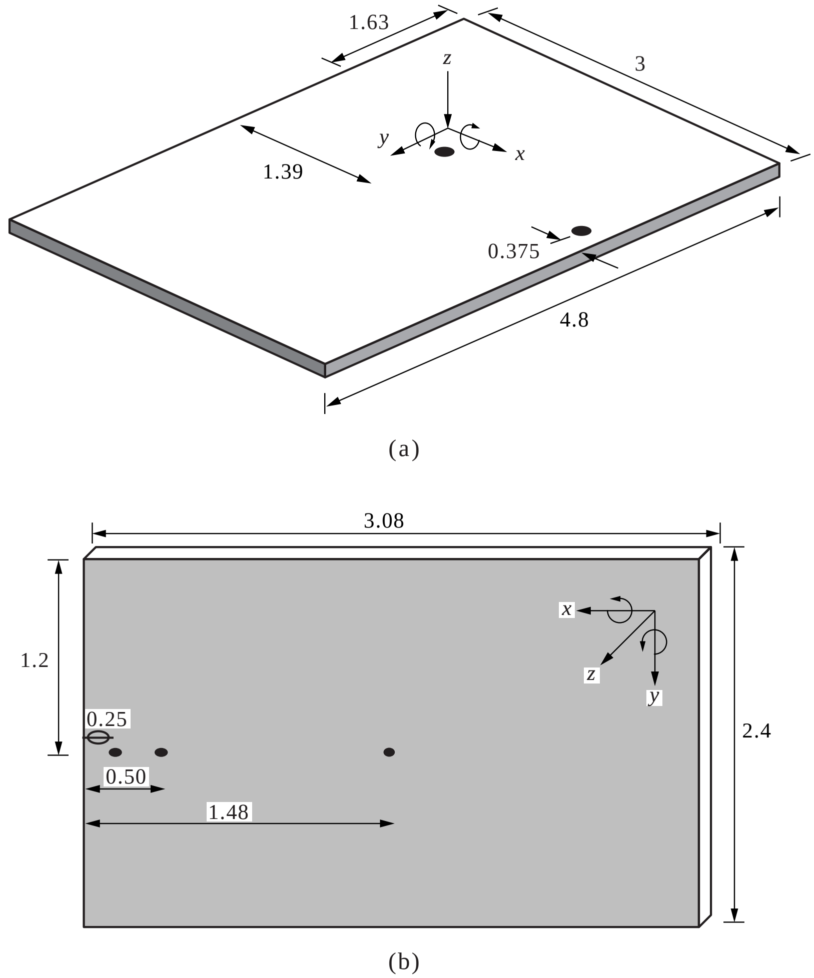

Figure 1 Excitation positions in (a) 120 mm thick concrete floor and (b) 115 mm thick brick wall. Dimensions in m.

where the force and moments are obtained indirectly from inversion of the mobility matrix. In this arrangement, the power from each component can be evaluated individually for their contribution to the net power as force and moment induced powers are dimensionally compatible.

3. EXPERIMENTAL DETERMINATION OF POWER FLOW

There were two components to the experimental work. The first involved measurement of vibrational power transmission from a built-up machine source into a concrete floor. In the second part, a brick wall was chosen as the test structure. The investigation was not exhaustive, but rather was aimed to provide engineering insight into power transmission when structures are subject to combined excitation at different locations. Therefore, excitations close to the centre of the supporting plate and in the proximity of a single edge were

Figure 2 Experimental set-up.

examined. For the case of the brick wall, where the measurement was easier, an additional point close to the edge was investigated. Figure 1 shows the dimensions of both structures and the excitation positions.

Results from previous measurements, described in the companion paper [12], showed that using a real machine as a source often gives rise to airborne and flanking transmission. In order to highlight the phenomenon being investigated, a sub-assembly of a machine base, consisting of the frame of a belt-driven centrifugal fan, was employed. A large electrodynamic shaker, mounted within an insulated enclosure to reduce airborne noise, was attached. In order to produce combined force and moments excitation at the contact point, the shaker was mounted eccentrically. A "U" bracket was fabricated and attached to the frame to serve as the machine contact (see Figure 2). The assembly had the advantage of transmitting the vibrational energy efficiently but at the same time, behaved as a poor airborne sound radiator compared with normal machine casings. More importantly, it possessed the dynamic characteristics of real machine bases. In this controlled condition, airborne excitation and other flanking paths were assumed insignificant. Another advantage was that the energy injected into the receiving structure could be controlled by increasing the output of the shaker, should there be insufficient response signal. The signal was further enhanced by using a low-pass filter, set at 2 kHz. Thus, a broadband excitation was achieved, as opposed to the machine tonal source where only conspicuous peaks at the harmonic frequencies were seen. Figure 3 shows the schematic of the instrumentation set-up.

A load washer of diameter 40 mm was inserted between the machine frame and structure to register the force directly. The mechanical compression, which is inevitable when the machine load is imposed, causes a change in the sensitivity of the load washer. The load washer was therefore pre-compressed by a pair of pre-load flanges. The whole assembly was then calibrated with a known mass and accelerometer on an electrodynamic shaker. The installed sensitivity was 3% lower than the original sensitivity, quoted by the manufacturer, since some of the force has been sustained by the pre-load flanges.

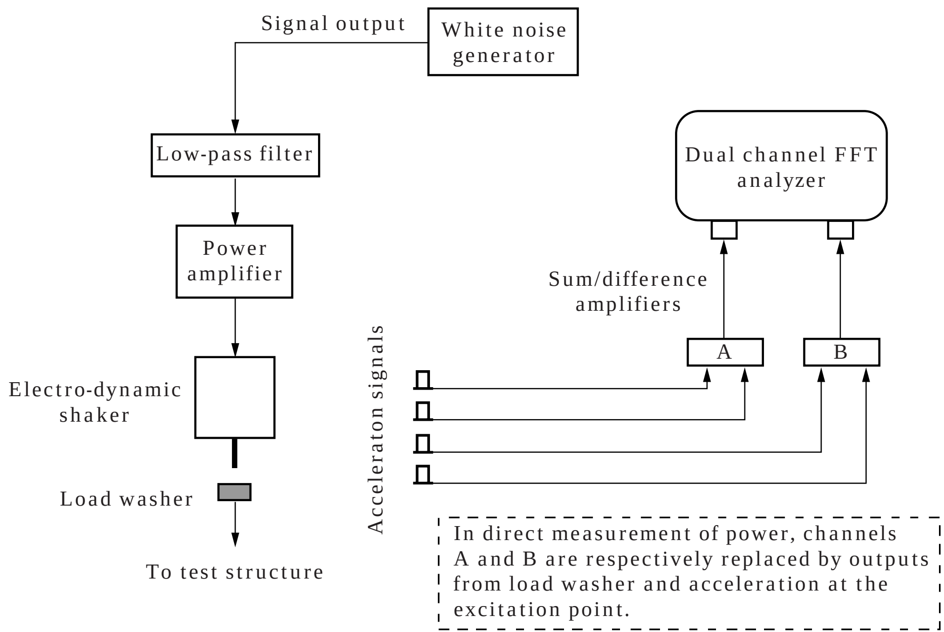

Figure 3 Instrumentation in set-up.

The measurement conditions were similar for both test structures, except that in the case of the brick wall, the assembled source excited the structure in a vertical plane.

4. RESULTS AND DISCUSSIONS

The measured data was transferred to a MATLAB environment where mobility matrices and velocity transfer function vectors were constructed from the measured spectra. Once the matrices and vectors were formed, the force, moments and the associated powers were obtained from matrix inversion and a series of routine calculations.

4.1. MEASURED POWER FLOW ON A CONCRETE FLOOR

Since only the force can be measured directly, its associated power was used to check the power obtained by the indirect method. Figure 4 shows the deviation between the directly and indirectly measured force induced power for excitation at a central location. It is seen that both indirect measured results, calculated by the single element mobility matrix (i.e., vertical translational motion only considered) and the complete inversed mobility matrix, agree with direct measurement within ± 5 dB. The deviation is unbiased and fluctuates about zero up to 1 kHz.

The agreement between the two indirectly acquired powers suggests that the excitation at the contact point was due mainly to the force component. It is also reasonable to assume that the in-plane excitations, which are not considered in this study, were negligible. In Figures 5 and 6 are shown the active powers

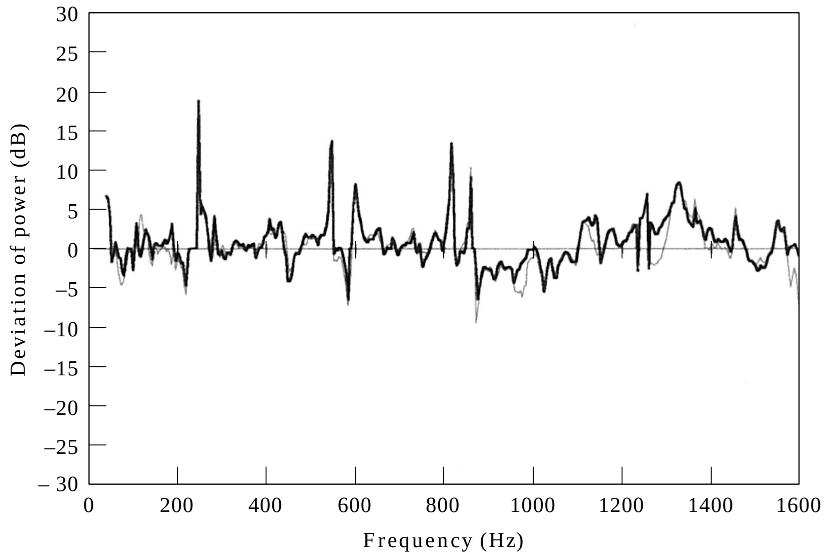

Figure 4 Deviation between directly and indirectly measured force-induced power. —, 1 × 1 matrix; —, 3 × 3 matrix.

generated by the vertical force and by moments perpendicular and parallel to the plate edge of interest. Figure 5 confirms that the force induced power is consistently higher by typically 10 dB than the moment induced powers. For clarity, the spectra also are shown on a log frequency scale in Figure 6, as the significance of moment in relation to force induced power in the low frequency

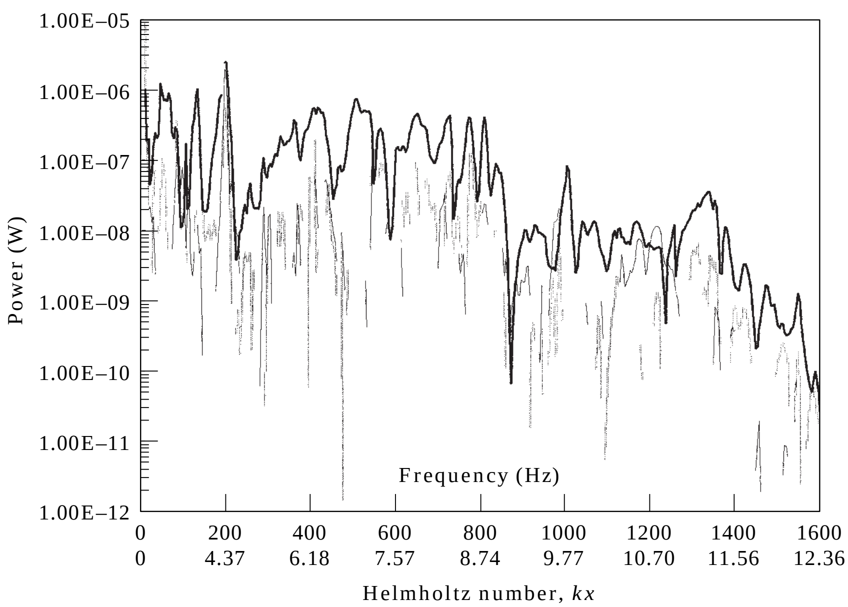

Figure 5 Force- and moment-induced powers near central location on concrete floor. —, M_y; —, M_x; —, F_z.

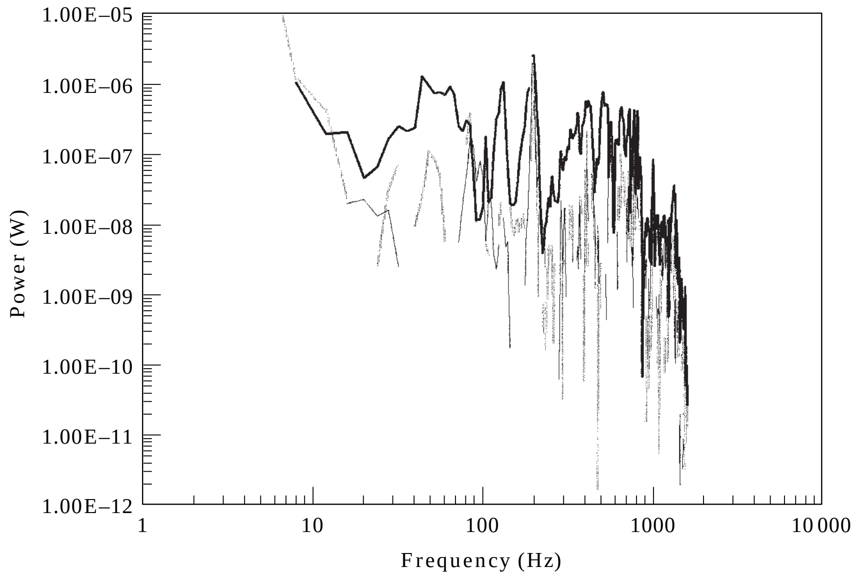

Figure 6 As Figure 5 but plotted *versus* the logarithm of the frequency.

region is of prime interest in this investigation. In Figure 7 are shown the total active power, from three components, and the force induced power, for a central location. Over most of the frequency range, the moments have little influence on the net power transmitted into the floor and the overall power is reasonably approximated by the force induced power alone. At high frequencies, the moment term comes into effect. The "high frequency" transition point cannot be generalised as it depends upon geometric and material properties of source and receiving structures. The discontinuities in the curves in Figures 5 and 6 indicate negative power flows (i.e., in an upward direction), which for a selected excitation component, is the result of the floor being energised by other excitation components. This is allowed provided the net power flow due to all components is positive. The force curves are generally continuous indicating that it predominantly energises the floor. Although in analysing the energy propagated to the remote part of a structure only the real part of power is of main concern, the magnitude spectra in Figure 8 gives a good approximation to the active power transmitted. The magnitude spectra indicate a region where the moment induced powers can be ignored; between Helmholtz number of unity and eight.

For the case of excitation near an edge of the concrete floor, the point selected was along the x-axis of the previous case, 375 mm from the nearest discontinuity (see Figure 1). The results are significantly different from the previous case. In Figure 9 it is shown that the indirectly measured force induced power is within ± 4 dB of the directly measured spectrum. However, close examination reveals that the single element matrix calculated power shows a positive bias whereas the 3×3 matrix produces a deviation fluctuating about the zero line. Although the 4-dB overestimate in the former case seems to be within the margin of

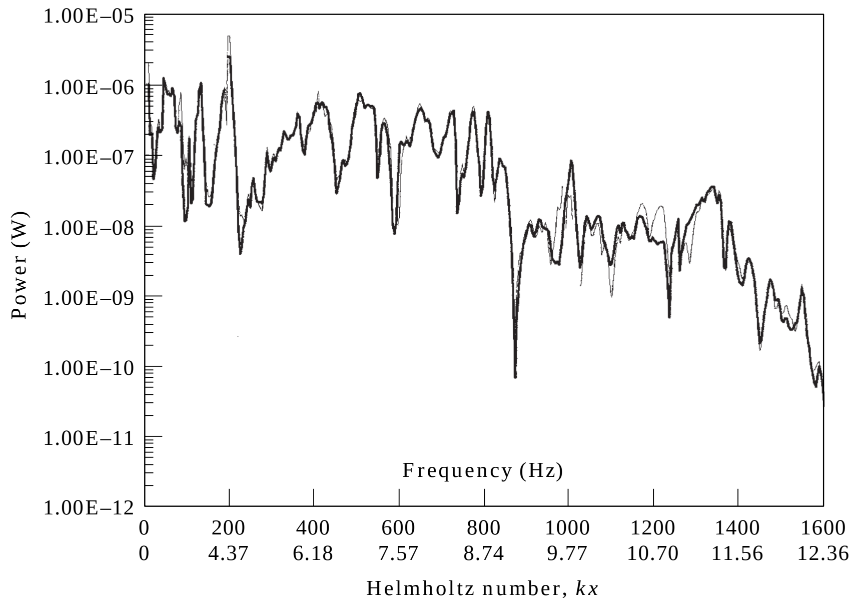

Figure 7 Comparison between net (—) and F_z force-induced (▬) powers near central location on concrete floor.

experimental error, the consistent bias invites speculation that the contribution of moment induced power cannot be ignored. Power generated by bending moments which are equal or marginally higher than the force associated power is sufficient to result in this 4-dB overestimate. The significance of the moment

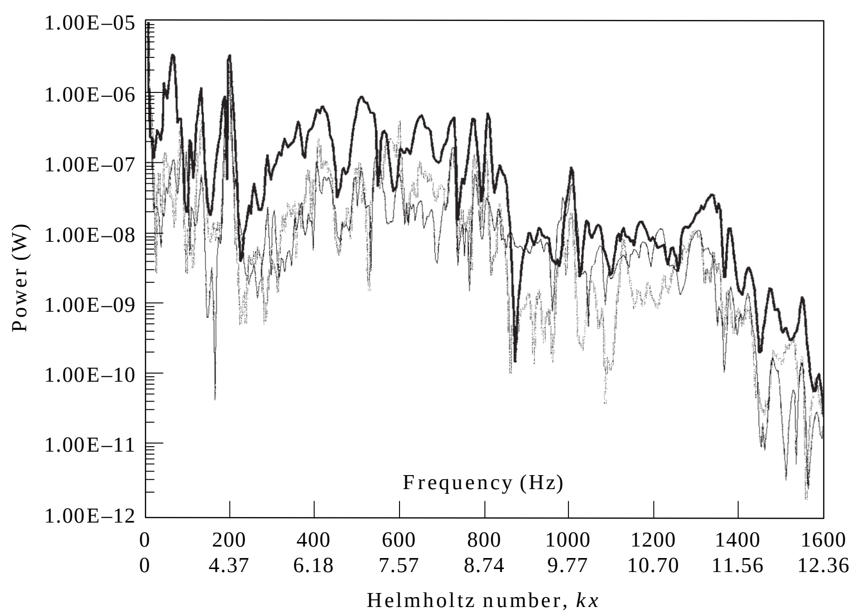

Figure 8 Magnitudes of force- and moment-induced powers near central location on concrete floor. —, M_y; —, M_x; ▬, F_z.

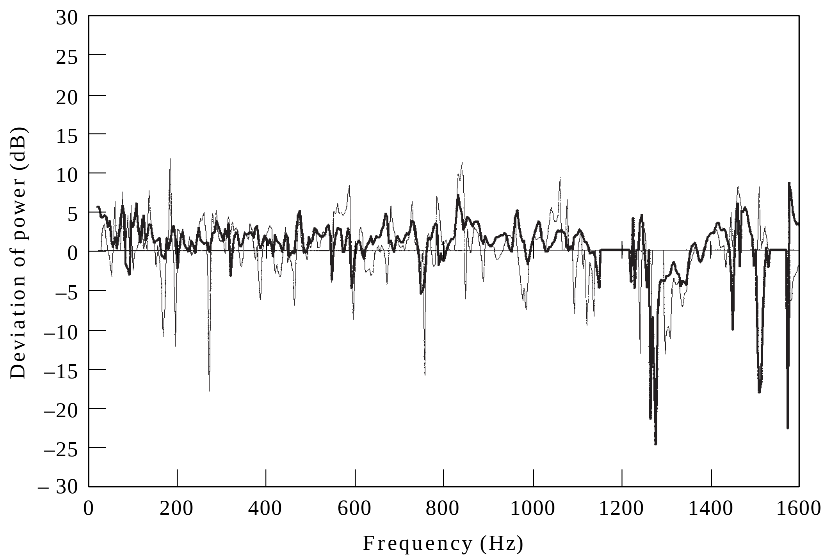

Figure 9 Deviation between directly and indirectly measured force-induced power near an edge on concrete floor. —, 1×1 matrix; —, 3×3 matrix.

components is confirmed in Figure 10, where the dominant effect of force, in the previous case of excitation near a central location (see Figure 8), is no longer apparent. The moment induced power curves are more continuous, indicating less negative power flow, compared with the case of the centrally located source. The floor structure becomes more receptive to moment excitation at low frequencies because of the presence of cross coupling and a high moment mobility in relation to force mobility. This is in addition to the normal trend where the contribution from moments increases in importance relative to the vertical forces with increased frequency. Now, the net power is appreciably greater than the force induced power, as shown in Figure 11 where they are plotted against both frequency and Helmholtz number. It is apparent that moments have energised the floor, along with force. Again, to confirm the overall trend, the magnitudes are presented in Figure 12. The signatures of the magnitudes show a strong resemblance to those of active power, except now the values are marginally higher due to the inclusion of the imaginary component. At high frequencies, moment is seen to surpass the force associated power. The overall increase in net power due to moment may be accompanied by cancellation effects between the components governing the power flow. This effect has been studied in references [3, 4] and most recently in reference [13] where experiments were carried out on scale models in carefully controlled conditions. However, in a full scale installation, it is practically difficult to achieve a desired reduction in power transmission by passive methods and the phenomenon was not observed in the present study.

4.2. MEASURED POWER FLOW ON A BRICK WALL

The force and moment induced power spectra are presented in Figure 13 for a central location, on a brick wall, and the results obtained are consistent with

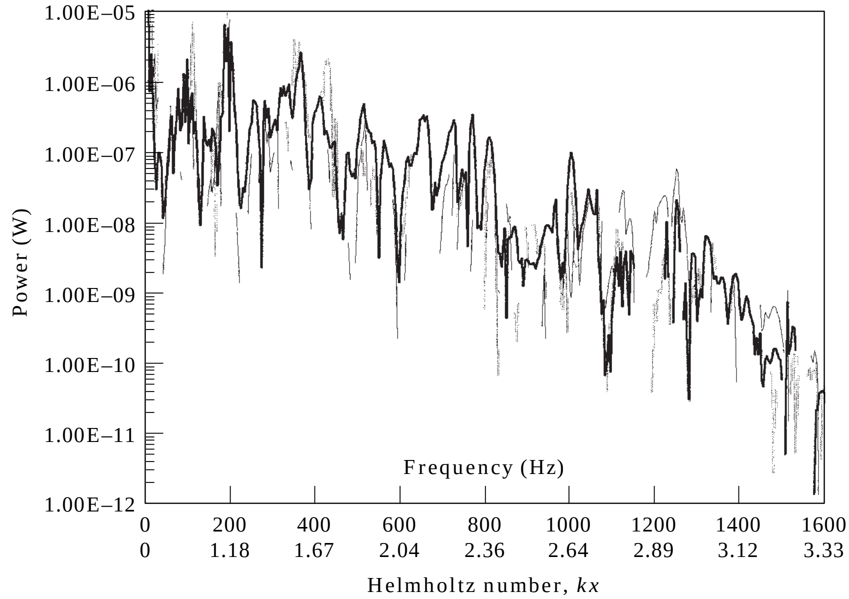

Figure 10 Force- and moment-induced powers near an edge on concrete floor. —, M_y; —, M_x; —, F_z.

those for the concrete floor. The force induced power spectrum now is dominant over the whole frequency range of interest. It is shown in Figure 14 that the net power is reasonably approximated by force induced power.

The active power spectra for excitation at 250 mm from an edge, is shown in Figure 15. Cursory inspection indicates that the domination of force induced

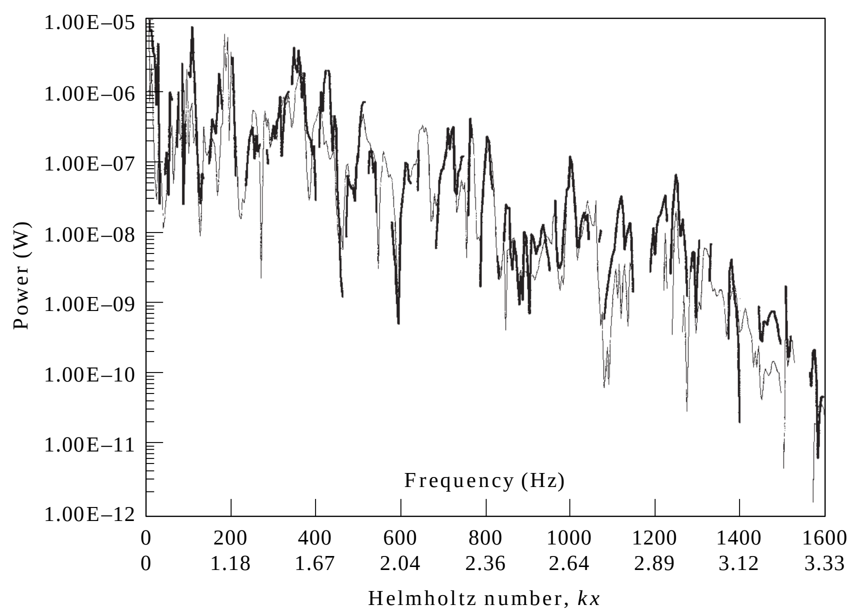

Figure 11 Comparison between net (—) and F_z force-induced (—) powers near an edge on concrete floor.

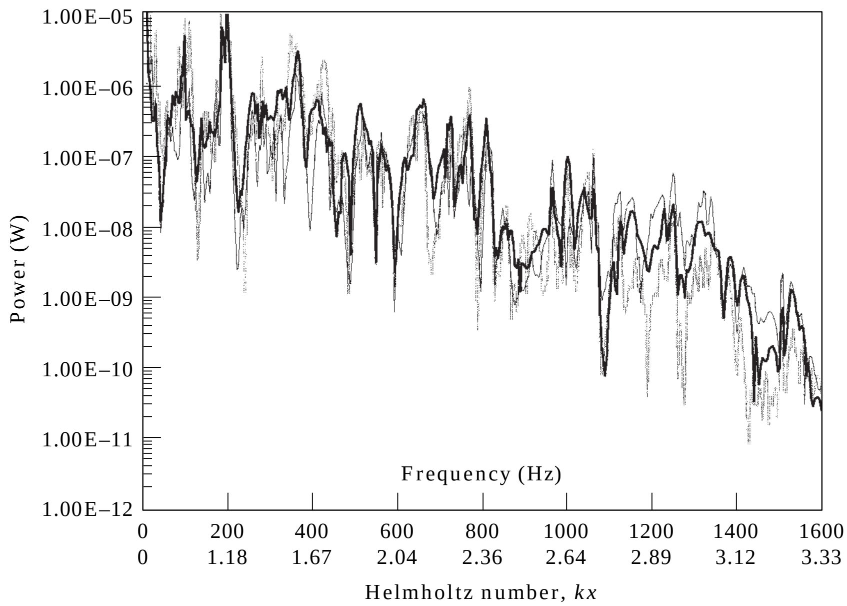

Figure 12 Magnitude of force- and moment-induced powers near an edge on concrete floor. Key as Figure 10.

power is not apparent. In most frequencies, mainly about the *y*-axis, the moment induced powers are relatively close to or higher than the force induced power.

The net and force induced power are compared in Figure 16. The consistently higher net power flow implies that moments are influential. Figure 17 shows the

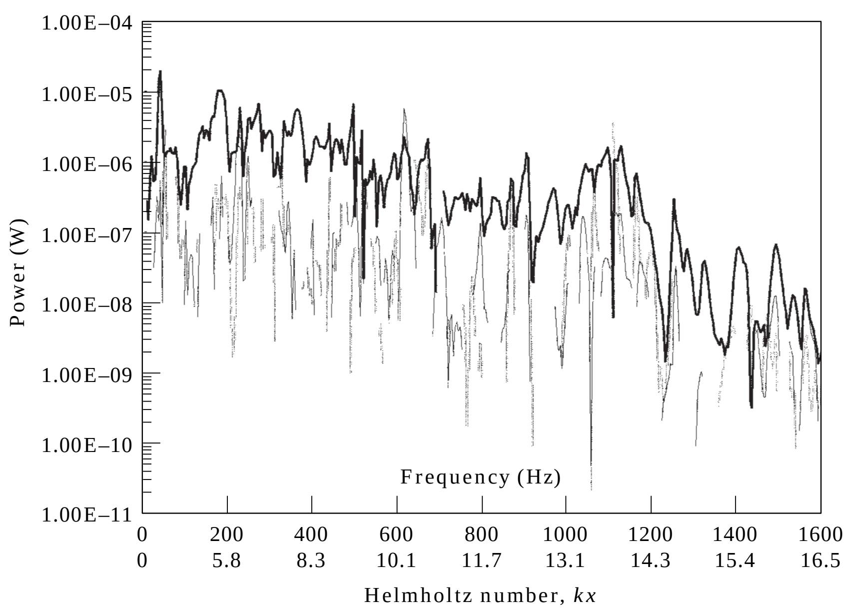

Figure 13 Force- and moment-induced powers near central location on brick wall. Key as Figure 10.

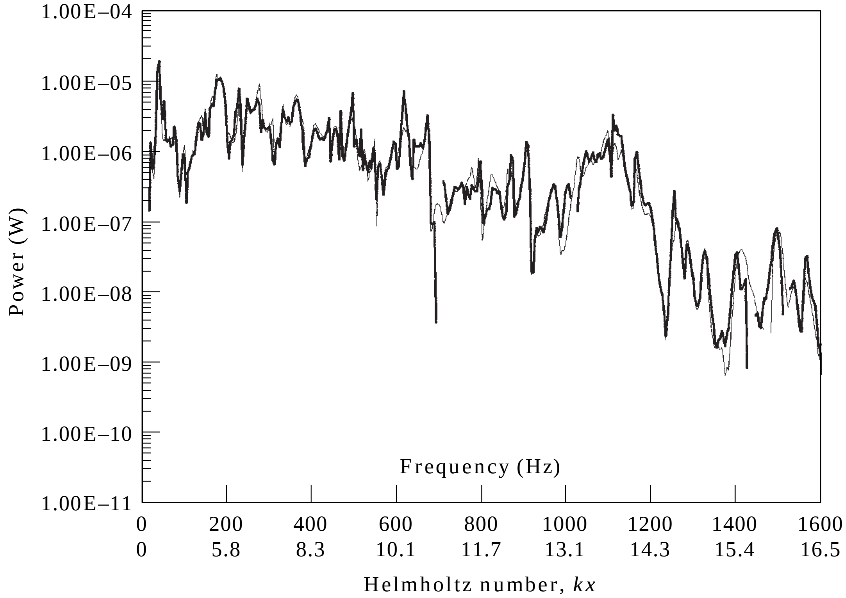

Figure 14 Comparison between net (—) and F_z (▬) force-induced powers near central location on brick wall.

magnitudes of the moment induced powers, normalised by that of the force induced power. Generally, the moment about the x-axis (i.e., perpendicular to the edge of interest) is not influential. The level consistently falls below the other two spectra up to about 800 Hz. The moment about the y-axis is higher overall.

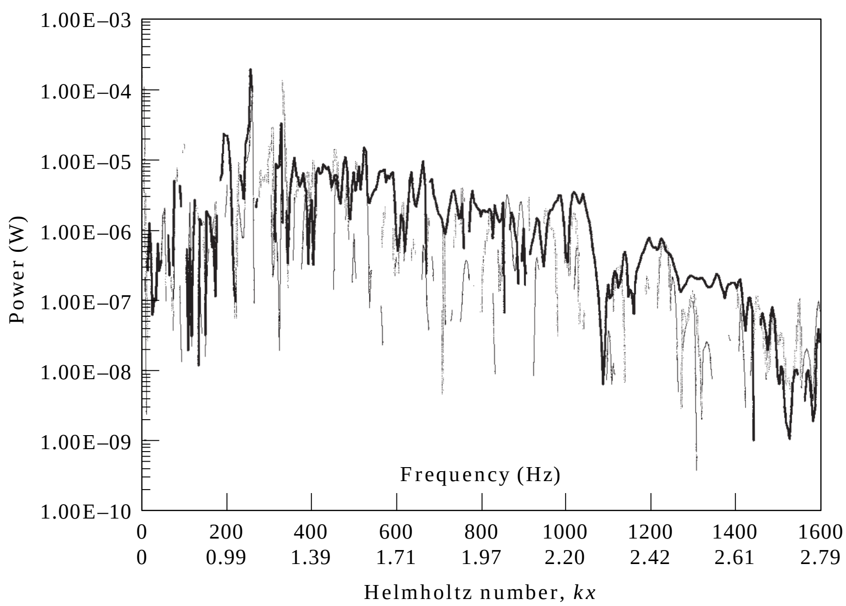

Figure 15 Force- and moment-induced powers at 0·25 m from an edge of the brick wall. —, M_x; —, M_y; ▬, F_z.

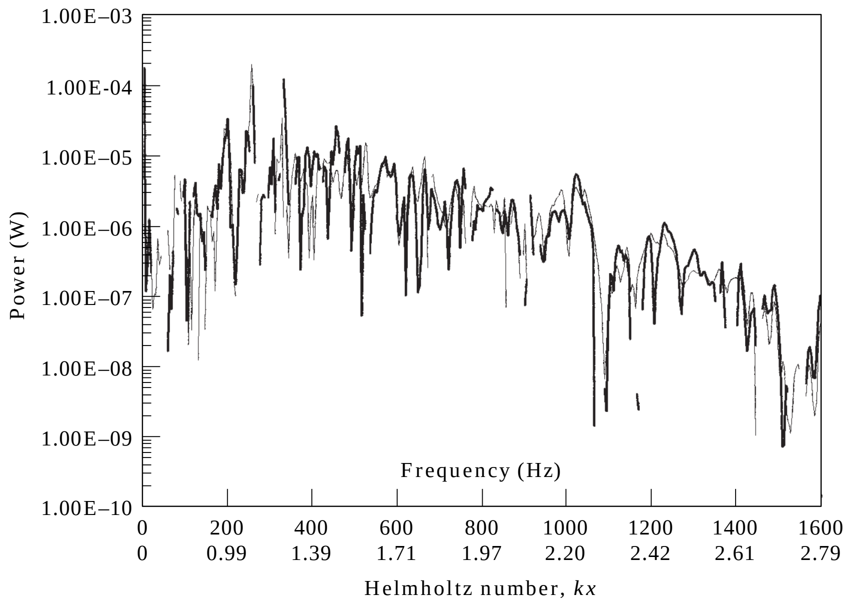

Figure 16 Comparison between net (—) and F_z (▬) force-induced powers at 0·25 m from an edge of the brick wall.

It might be expected that the net power into the receiving structure in all measurements should be positive (downward) since there was only one excitation point. In addition to the airborne and flanking paths described earlier, the negative power flow might result from matrix inversion when some of the matrix elements were corrupted. Such situations occurred at frequencies when the difference in acceleration signals was small, or where one of the selected points

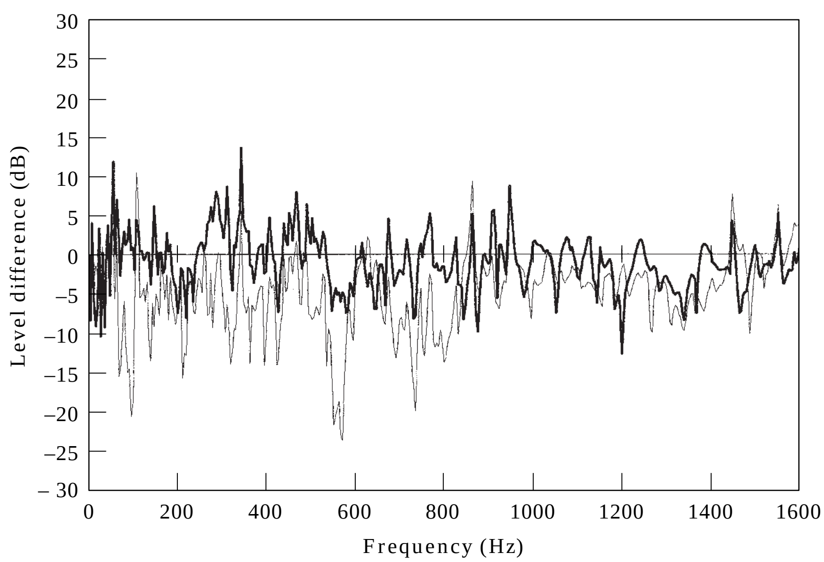

Figure 17 Normalized magnitudes of power. —, M_y; ▬, M_x.

was on a node. However, this problem was thought not significant, judging from the net power spectra for both the concrete floor and brick wall, at the central locations. The respective power components were obtained by matrix inversion but there was little negative net power flow in these cases, as seen in Figures 7 and 14. In addition, Figure 4 shows that the force induced power calculated by a single mobility element and the 3×3 matrix involving inversion are in good agreement.

5. CONCLUDING REMARKS

Measurements of force and moment induced power flow from a built-up machine base to masonry structures have been performed by means of a reciprocal method. For the cases studied, results show that when the excitation point is near the centre of a floor, the power flow is dominated by vertical force and net power is well approximated by the force induced power alone. In the regions above $kx = 10$, moments assume importance and result in a higher net power flow. The findings for a brick wall were consistent with the concrete floor. In this case, moments became effective where $kx \geqslant 12$.

When the same machine base assembly was installed near an edge, the results for both the concrete floor and brick wall demonstrated the significance of moments at low frequencies. This was in addition to the normal trend where the contribution from moments is increasingly important relative to force with increased frequency. Consequently the net power is appreciably higher than the force induced power over the entire bandwidth. In both cases, the contribution was attributed to the moment with rotational vector parallel to the nearest edge.

It is confirmed that in building structures, the contribution from moments, in the low frequency region, is sensitive to excitation location with respect to an edge. When the excitation is away from an edge, moments are less important than vertical force at low frequency. When sources are near structural discontinuities such as floor edges, the contribution from moments is important at low frequencies. In addition, moments assume increased importance with increased frequency, irrespective of source location and therefore, should be included in the prediction of structure-borne power.

REFERENCES

1. L. Cremer, M. Heckl and E. E. Ungar 1973 *Structure-borne Sound*. Berlin: Springer-Verlag.
2. B. M. Gibbs, B. A. T. Petersson and Qiu Shuye 1991 *Noise Control Engineering Journal* **37**, 53–61. The characterisation of structure-borne emission of services machinery using the source descriptor concept.
3. Y. K. Koh 1992 *PhD Thesis*, *University of Southampton*. Prediction and control of vibrational-power transmission between coupled structural systems.
4. B. A. T. Petersson 1990 *TNO Institute of Applied Physics*, *Delft*, *The Netherlands*. Moment excitation and structural acoustic power transmission between machinery and foundations; Part 1: combined moment and force excitation of beam and frame-like structures at or close to discontinuities.

5. B. A. T. Petersson 1990 *TNO Institute of Applied Physics*, *Delft*, *The Netherlands*. Moment excitation and structural acoustic power transmission between machinery and foundations; Part 2: combined moment and force excitation of beam and frame-like structures at or close to discontinuities.
6. B. A. T. Petersson 1990 *TNO Institute of Applied Physics*, *Delft*, *The Netherlands*. Moment excitation and structural acoustic power transmission between machinery and foundations; Part 3: combined moment and force excitation of beam and frame-like structures at or close to discontinuities.
7. B. A. T. Petersson and B. M. Gibbs 1990 *International Congress on Intensity Techniques*, *Senlis*, *France*, 449–456. The influence of source location with respect to vibrational energy transmission.
8. R. J. Pinnington and R. G. White 1981 *Journal of Sound and Vibration* **75**, 179–197. Power flow through machine isolators to resonant and non-resonant beams.
9. R. J. Pinnington 1987 *Journal of Sound and Vibration* **118**, 515–530. Vibrational power transmission to a seating of a vibration isolated motor.
10. Y. K. Koh and R. G. White 1996 *Journal of Sound and Vibration* **196**, 495–508. Analysis and control of vibrational power transmission to machinery supporting structures subjected to a multi-excitation system, Part II: Vibrational power analysis and control schemes.
11. Y. K. Koh and R. G. White 1996 *Journal of Sound and Vibration* **196**, 508–522. Analysis and control of vibrational power transmission to machinery supporting structures subjected to a multi-excitation system, Part III: vibrational power cancellation and control experiments.
12. S. H. Yap and B. M. Gibbs 1999 *Journal of Sound and Vibration*. **222**, 85–98. Structure-borne sound transmission from machines in buildings, Part 1: indirect measurement of force at the machine-receiver interface of a single and multi-point connected system by a reciprocal method.
13. O. Bardou, P. Gardonio, S. J. Elliott and R. J. Pinnington 1997 *Journal of Sound and Vibration* **208**, 111–115. Active power minimization and power absorption in a plate with force and moment excitation.