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A POWER-FLOW APPROACH TO THE ASSESSMENT OF BASE-ISOLATED BUILDINGS

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1. INTRODUCTION

Base isolation is a means of reducing the transmission of ground-borne vibration into buildings. It is often used to reduce internal levels of perceptible vibration and re-radiated noise due to sources such as nearby roads and railways. Examples in London include the Albany Court block of flats over St James' Park Station, Wellington Hospital and, of course, the recently opened IMAX cinema at Waterloo, to name just a few.

A typical objective for base isolation is a reduction in vibration transmission of at least 10 dB for frequencies above 10 Hz. The isolation bearings consist of either steel springs or laminated rubber bearings which are usually located at the base of the building, such as on the pile caps or just above basement level. The bearings are specified in terms of their *isolation frequency*. This is the frequency of vertical oscillation of the building assuming that it behaves as a rigid mass on a spring. Typical isolation frequencies lie in the range from 5 to 15 Hz.

There is little doubt that base isolation does work, but its effectiveness and the benefits of certain design features, such as a low isolation frequency or a particular level of isolator damping, remain uncertain. This paper reports on an ongoing programme of research concerned with the prediction of isolation performance; in particular it introduces a new power-flow approach to the assessment of base-isolated buildings.

2. THE PROBLEM WITH 'INSERTION LOSS'

A common measure of an isolation bearing's performance is its associated *insertion loss*, sometimes referred to more correctly as insertion *gain*. This is the ratio, usually expressed in decibels, of the vibration response of the building with the bearings in position to that with no bearings at all. It is impractical to measure insertion loss because buildings cannot easily be taken off their foundations. When insertion loss is calculated, it is usual to take the response of the building at its base, directly above the isolation bearings themselves. Either the displacement, velocity or acceleration response may be used since it is assumed that the behaviour of the building is linear at the low levels of vibration concerned.

Despite the practical difficulties in measuring insertion loss, it remains a widely used concept. Theoretical predictions of the value of insertion loss may aid the design of an isolation system. However, there is a fundamental problem with insertion loss as a measure of isolation performance. This is due to the fact that it is based on the vibration response of one part of a complex multi-modal structure. There is no guarantee that the response of the 'measurement' point, such as the base of a building column, will be representative of the overall building; indeed the measurement point may lie close to a significant vibration node of the structure and exhibit deceptively low vibration levels.

In order to account for the spatial variation in vibration levels, insertion losses could be determined for a number of different points within the building but it is not then clear how these results should be combined into one overall measure of isolation performance.

An additional consideration is vibration occurring in different directions. It is generally assumed that the horizontal component of ground motion may be neglected since the building's inherent flexibility in this direction provides sufficient isolation. However, there is no evidence to support this assumption and vibration entering a building in any direction may be significant. This could be characterised by 'horizontal' or 'rotational' insertion losses but, again, there is no obvious way to combine these into one measure of isolation performance.

3. THE BENEFITS OF CONSIDERING POWER FLOW

As an alternative and more appropriate means of assessing isolation performance, it is proposed to consider the total mean vibrational power flow entering the building. The underlying principle is that the vibrational energy entering a building drives all internal structural vibration and re-radiated noise. A performance measure based on power flow is not sensitive to the spatial distribution of vibration levels within the building in the same way as insertion loss: vibrational power enters the building at various places but the total power flow can be computed as a straightforward sum. Similarly, power flows associated with vibration occurring in different directions and with different forms of vibration, such as that associated with axial strain or bending of structural elements, can be easily accounted for. Thus the total mean vibrational power flow entering the building enables a single measure of isolation performance to be defined, described henceforth as the *power insertion gain*:

$$PIG = 10\log_{10}\left(\frac{\overline{P}_i}{\overline{P}_{ui}}\right) \qquad 3.1$$

Where $\overline{P}_i$ and $\overline{P}_{ui}$ are the total mean power flows entering the building in the isolated and unisolated cases respectively.

The measurement of power insertion gain is just as difficult as conventional insertion loss, because buildings cannot easily be taken off their foundations. However, it is worth noting that $\overline{P}_i$, the total mean power flow entering the isolated building, may be measured more easily and this may be a perfectly useful parameter in its own right - perhaps we can say that 30 W/m^3 (for example) is an acceptable vibrational power entering a building.

As a design principle, one would be concerned with minimising the power insertion gain in the knowledge that a reduction is guaranteed, at least in the case of a resonant structure such as a building, to reduce the average internal noise and vibration levels. Such an approach is appropriate for many buildings where an improvement in the average environment is required rather than the environment in a particular room.

4. PREDICTION OF ISOLATION PERFORMANCE

Simple mass-spring models are often used to make predictions of isolation performance. The standard single-degree-of freedom (SDOF) model was originally used by Waller [1] when describing the design of Albany Court and is used extensively in the design of isolation bearings for machines. This, together with its inherent simplicity, has probably resulted in the model's popularity. However, performance predictions based on this model are far too optimistic since it fails to describe some of the major features of a building's dynamic behaviour, in particular the flexibility and damping properties of the building and the effects of its foundation [3], [2].

4.1 Overview of Model

The model shown in Figure 1, and discussed in detail by Talbot [2], considers a building founded on piles. The model aims to capture the essential characteristics of a base-isolated building while being relatively simple and requiring little computational effort. Here the model is used to illustrate the use of power flow as a means of assessing isolation performance.

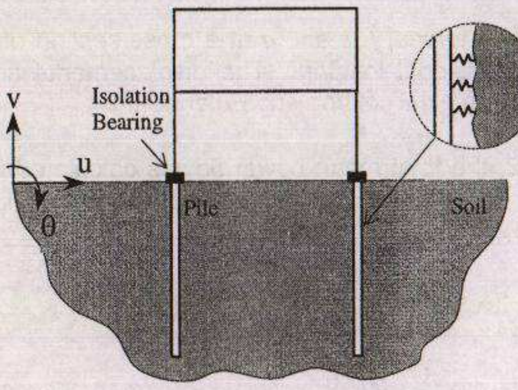


Figure 1: Model of a base-isolated building. The building is represented by a two-dimensional portal frame and the piled foundation is based on a three-dimensional representation due to Gazetas and Makris. The pile-soil interface is represented by distributed springs and dashpots. For clarity, only the horizontal springs are shown.

The building is represented by a two-dimensional portal frame, modelled using the dynamic-stiffness method. The dynamic axial and transverse behaviour of each 'element' of the frame is characterised by the exact linear-elastic solutions for an axial column and Euler beam [4], thereby accounting for the essential dynamic behaviour of the columns and floors, and the coupling between them. The isolation bearings are represented by linear massless springs with hysteretic damping. There are three springs located on each pile cap to represent the vertical, horizontal and rotational stiffness of each bearing.

The piles are modelled using the analytical approach of Gazetas and Makris [5], [6]. This approach uses the solutions for a linear-elastic axial column and Euler beam to model the axial and transverse behaviour of each pile. Wave propagation in the free field is accounted for by modelling the soil as a homogeneous isotropic linear-elastic half-space. In the near field, in both the horizontal and vertical directions, the pile-soil interface is modelled with continuously distributed linear springs and dashpots, the latter to represent radiation and hysteretic material damping within the soil. The model includes a representation of pile-soil-pile interaction, i.e. interaction between the piles through wave propagation in the surrounding soil.

The ground vibration-field consists of surface Rayleigh waves. These are created by surface activity, such as surface vehicles or piling operations, and have been chosen as being representative of a real source of ground-borne vibration. They are well known as one of the three basic wave types supported by an elastic half-space [7] and result in soil-particle motion which describes a retrograde ellipse. Thus the building piles are subject to both vertical and horizontal motion.

4.2 Calculation of Power Flow

An advantage of the dynamic stiffness method is that, once the nodal displacements of the portal frame have been computed, the displaced shape and corresponding force distributions along each element can easily be recovered. This makes the calculation of vibrational power flow straightforward [8].

Figure 2: Displacements, u, v and θ, and corresponding forces, f, s and q at a cross-section of a uniform dynamic stiffness element subject to two-dimensional loading. The displacements and forces are related through the linear-elastic solutions for an axial column and Euler beam.

Considering the cross-section located at x in Figure 2, the total mean power flow is calculated as the mean rate at which the element does work against the elastic forces. Thus, for harmonic motion at angular frequency ω:

$$\overline{P}(x) = \overline{-\operatorname{Re}\left(fe^{i\omega t}\right)\operatorname{Re}\left(i\omega ue^{i\omega t}\right) - \operatorname{Re}\left(se^{i\omega t}\right)\operatorname{Re}\left(i\omega ve^{i\omega t}\right) - \operatorname{Re}\left(qe^{i\omega t}\right)\operatorname{Re}\left(i\omega\theta e^{i\omega t}\right)}$$

$$\overline{P}(x) = -\tfrac{1}{2}\operatorname{Re}\left(i\omega\left(uf^{*} + vs^{*} + \theta q^{*}\right)\right) \qquad 4.1$$

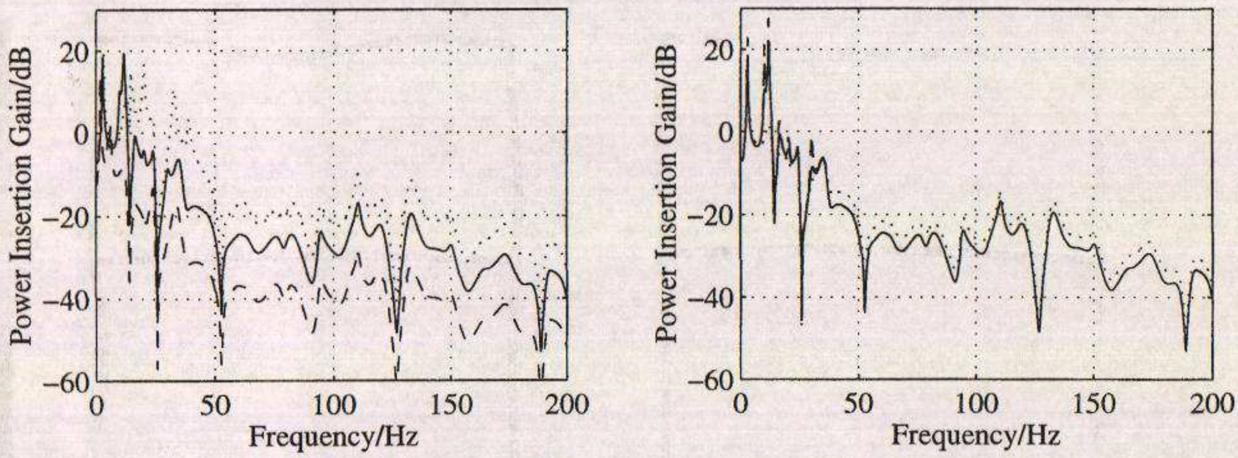
Where $i=\sqrt{-1}$ and $*$ indicates the complex conjugate.

In this way the magnitude and direction of the power flow can be calculated at any point in the portal frame. To determine the power insertion gain, as defined by Equation 3.1, the total mean power flow entering the building is calculated by considering the bases of the building columns directly above the pile caps, in the unisolated case, and directly above the isolation bearings in the isolated case.

4.3 Results for Power Insertion Gain

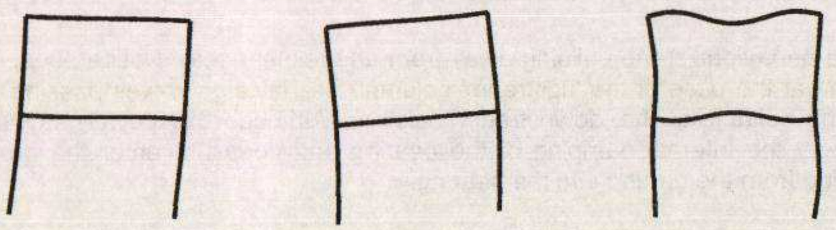
Figure 3 shows the variation with frequency in the power insertion gain for a concrete-framed building mounted on rubber isolation bearings, as predicted by the model of section 4.1. The 'baseline' case (solid curve) concerns bearings with an isolation frequency of 10 Hz and a loss factor of 0.1, i.e. typical properties for rubber bearings; additional physical properties used in the model are given in the Appendix. Three example mode shapes, corresponding to peaks in the curves of Figure 3, are plotted in Figure 4.

The general form of the curves is broadly as expected from simple single-degree-of-freedom models [3], [2], remembering that the power insertion gain conveniently combines the responses of the building due vertical, horizontal and rotational motion of the pile caps. At low frequencies, two peaks are evident in the curves at 2.8 and 11.7 Hz. These correspond to amplification of the ground vibration due to the essentially rigid-body 'bounce' modes of the building. Note that a purely vertical mode at 10 Hz is not evident, as may be expected from the 10 Hz isolation frequency of the bearings, since the Rayleigh wave excitation results in the motions of the pile caps being out of phase. Just above these initial peaks, the curves fall below zero and the isolation is effective.



(a) (b)

Figure 3: Variation with frequency in the power insertion gain for a concrete-framed building mounted on rubber isolation bearings with (a) isolation frequencies of 15 Hz (dotted), 10 Hz (solid) and 5 Hz (dashed), with a bearing loss factor of 0.1, and (b) bearing loss factors of 1.0 (dotted), 0.1 (solid), 0.01 (dashed), with an isolation frequency of 10 Hz.



(a) (b) (c)

Figure 4: Example mode shapes corresponding to peaks in the curves of Figure 3 at (a) 2.8 Hz, (b) 11.7 Hz and (c) 110.5 Hz. (Piles not shown).

Subsequent peaks and troughs in the power insertion gain correspond to vibration modes of the building; whether a peak or tough results from a particular mode depends on the relative significance of that mode in the unisolated and isolated cases.

It is interesting to note the trends in Figure 3 due to changes in the bearing parameters. Figure 3(a) implies that a low isolation frequency significantly improves the effectiveness of the bearings and Figure 3(b) implies that the effectiveness at medium to high frequencies is virtually independent of the internal damping of the bearings: the curves corresponding to loss factors of 0.1 and 0.01 are almost indistinguishable and no further changes are evident if the damping is reduced further. As expected, at the frequencies corresponding to the 'rigid-body' modes of the isolated building, the bearing damping controls the resonant response.

4.4 Power Flow Analysis

As well as enabling a single measure of isolation performance to be defined power flow analysis enables greater insight to be gained into the overall behaviour of base-isolated buildings. Using the method outlined in Section 4.2, the power flow distribution may be calculated around the whole of the building model. This is illustrated in Figure 5.

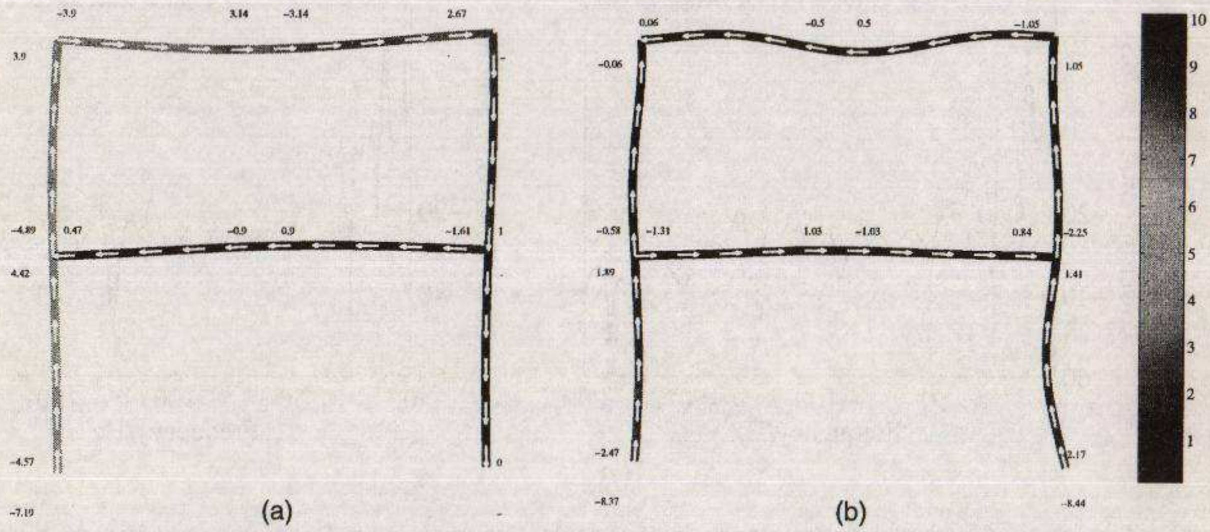


Figure 5: Total mean power flow distributions around a concrete-framed building mounted on '10 Hz' rubber isolation bearings and excited by 'unit amplitude' Rayleigh waves at (a) 20 Hz and (b) 127 Hz; the shading indicates the magnitude (full scale = 10×10^7 W) and the arrows the direction of the power flow. Numbers represent power flows (in units of 10^7 W) *into* a node of the model. (Piles not shown).

Figure 5(a) illustrates the behaviour of the building away from any resonances. Notice how power is flowing into the building at the base of the 'upstream' column (the Rayleigh waves passing from left to right) but out of the building at the 'downstream' column. Although this power leaves the building, it is dissipated by the internal damping of the bearing and does not enter the ground, indeed power is still flowing from the ground into the bearing.

Figure 5(b) illustrates the case when the excitation frequency coincides with a resonance frequency of the top floor. In this case, power enters the building up both columns and the flow distribution is more uniform.

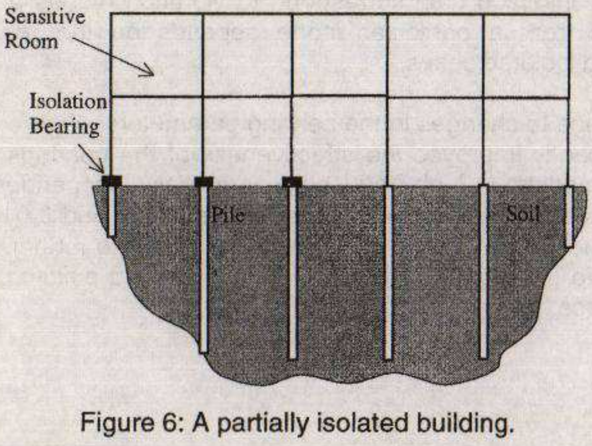


Figure 6: A partially isolated building.

In order to illustrate further the potential for power flow analysis to provide valuable information on the vibration transmission paths of a base-isolated building, consider the more complex structure shown in Figure 6.

This building contains a 'sensitive room', for example it might house an item of vibration sensitive equipment, but due to cost constraints it is only possible to partially isolate the structure. In this case, it is not obvious whether or not base-isolation would be beneficial. It may be that the floors from the unisolated side of the building form the dominant vibration transmission path and that isolating the left-hand side of the building offers little benefit. Indeed, it may be that the isolation helps to contain vibration which would otherwise dissipate into the foundation within the building, thereby resulting in undesirable local resonances. A 'design assessment' is clearly required and this would greatly benefit from an analysis of the power flows involved.

5. CONCLUSIONS

This paper has discussed the advantages of a power-flow approach to the assessment of base-isolated buildings. The concept of a *power insertion gain*, based on the total mean vibrational power flow entering a building, has been introduced as an alternative and more appropriate means of assessing isolation performance. In addition, the potential for power flow analysis to provide valuable insight into the behaviour of base-isolated buildings has been illustrated.

It has been argued that power insertion gain offers clear benefits over the conventional 'insertion loss' based on vibration amplitudes alone. For a given building, power insertion gain provides a single measure of isolation performance, accounting for: multiple vibration inputs; vibration occurring in different directions; and with different forms of vibration, such as that associated with axial strain or bending of structural elements. As a design principle, one would be concerned with minimising the power insertion gain in the knowledge that a reduction is guaranteed to reduce the average internal noise and vibration levels within a building.

Predictions of the power insertion gain for a building founded on piles and subject to surface Rayleigh wave excitation have shown that a low isolation frequency significantly improves the effectiveness of the bearings but that this is virtually independent of the internal damping of the bearings. This is an interesting and potentially significant result. However, the work discussed here is part of an ongoing programme of research and further work is required to confirm such findings. In particular, work is required to develop the foundation model, to include a more realistic representation of dynamic interaction between neighbouring piles, and to study the effects of different ground vibration-fields.

ACKNOWLEDGEMENT

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REFERENCES

1. Waller, R.A., *Building on Springs.* Pergamon Press, Oxford, 1969.

2. Talbot, J.P., *Rubber bearings and steel springs for base isolation of buildings.* Proc. 6th Int. Conf. Sound Vib., Copenhagen, 1999. Int. Inst. Acoustics and Vibration.

3. Newland, D.E. and Hunt, H.E.M., *Isolation of buildings from ground vibration: a review of recent progress.* Proc. Institution of Mechanical Engineers, Part C: Mechanical Engineering Science, 1991. **205(1)**: p. 39-52.

4. Newland, D.E., *Mechanical Vibration Analysis and Computation.* Longman, 1989.

5. Gazetas, G. and Makris, N., *Dynamic pile-soil-pile interaction. Part1: analysis of axial vibration.* Earthquake Engineering and Structural Dynamics, 1991. **20**: p. 115-132.

6. Makris, N. and Gazetas, G., *Dynamic pile-soil-pile interaction. Part 2: Lateral and seismic response.* Earthquake Engineering and Structural Dynamics, 1992. **21**: p. 145-162.

7. Graff, K.F., *Wave Motion in Elastic Solids.* Clarendon Press, Oxford, 1975.

8. Langley, R.S., *Analysis of power flow in beams and frameworks using the direct-dynamic stiffness method.* J. Sound and Vibration, 1990. **136**(3): p. 439-452.

APPENDIX

The approximate physical properties used in the model are as follows:

Building	*Piles*	*Soil (free-field)*
Width = Height = 8m	Length = 15m	Young's modulus = 100 MPa
Bending stiffness = 0.4 GPam^4	Bending stiffness = 0.4 GPam^4	Poisson's ratio = 0.4
Axial stiffness = 5.0 GPam^2	Axial stiffness = 5.0 GPam^2	Density = 2000 kgm^{-3}
Density = 2400 kgm^{-3}	Density = 2400 kgm^{-3}	
Damping loss factor = 0.1	Damping loss factor = 0.1	

Specification of the isolation bearings is based on a '10Hz' bearing (see text), giving stiffnesses for each bearing of: 150 MNm^{-1} vertically, 46 MNm^{-1} horizontally and 1.5 MNm rotationally.