PERFORMANCE PREDICTION 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 the primary means of reducing internal levels of perceptible vibration and re-radiated noise due to sources such as nearby roads and railways. For most applications, the building rests on either steel springs or laminated rubber bearings; the objective being a reduction in vibration transmission of at least 10 dB for frequencies above 10 Hz. However, the performance of base-isolated buildings is difficult both to predict and to verify in practice.

This paper describes a method of predicting the performance of base-isolated buildings based on the mean vibrational power flow through the isolation bearings. Such a measure is insensitive to the spatial distribution of vibration levels within a building and, for many applications, provides a more appropriate means of assessing different isolation designs than the conventional 'insertion loss' approach based on vibration amplitudes.

2. MEASURES OF ISOLATION PERFORMANCE

When considering the benefits of base isolation, one must first be clear about which measure of isolation performance is appropriate. The various possibilities may be categorised as either measures of absolute performance or measures of insertion performance.

Absolute Performance

The future occupants of a new building are interested in the absolute performance of the isolation, i.e. what they will experience in the completed building. Engineers may satisfy this by predicting the vibration levels within the isolated building given vibration data measured on the 'green-field' site prior to any construction work. This prediction requires knowledge of the effects of the building and its foundation on the ground vibration-field, as well as an understanding of the dynamic behaviour of the building itself.

Alternatively, occupants of an existing building may be interested in the vibration levels due to a particular vibration source, such as a new railway. In this case the prediction is particularly difficult to make since a detailed understanding of the entire vibration transmission path is required.

Insertion Performance

The client who pays for the additional cost of base isolation is interested in the insertion performance, i.e. the benefit of inserting isolation bearings beneath a building. This is also of interest to the Engineer who wishes to evaluate alternative types of isolation bearing.

This paper is not concerned with absolute measures of performance but with the prediction of insertion performance. A common measure of insertion performance is Insertion Gain (IG); sometimes referred to as 'insertion loss'. This is based on vibration amplitudes alone and there are problems in using it as a single measure of performance. An alternative to IG is Power Flow Insertion Gain (PFIG) which, for many applications, is considered to be more appropriate.

3. PREDICTION OF INSERTION PERFORMANCE

The simplest model of a base-isolated building, and one of the most commonly used, is the single-degree-of freedom (SDOF) oscillator. This represents the isolated building as a rigid mass supported on a spring. The model was originally used by Waller [1] when describing the design of the UK's first base-isolated building, the Albany Court block of flats erected in London in 1965. This, together with its inherent simplicity, has probably resulted in the model's popularity. However, it is of very limited value 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.

Alternatives to the SDOF model have since been investigated: flexible columns and two-dimensional finite-element models [2]; and two-dimensional dynamic-stiffness models coupled to three-dimensional piled foundations [3]. These models demonstrate, in particular, the importance of modelling a building's flexibility and its foundation. However, there is still no comprehensive model available which accounts for all of the essential characteristics of a base-isolated building. The model discussed below builds on previous work and goes some way to achieving this while remaining relatively simple and requiring little computational effort.

3.1 Overview of Model

The model shown in Figure 1, and discussed in detail by Talbot [4], considers a building founded on piles.

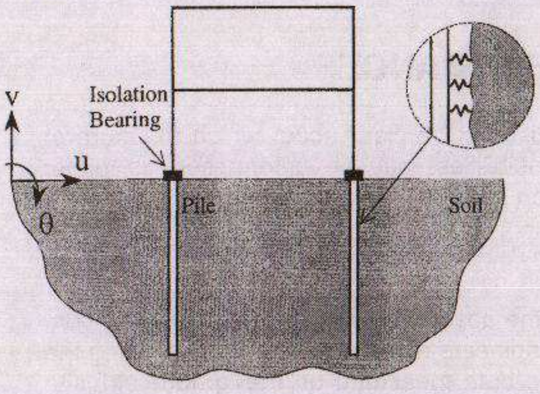

Figure 1: Model of a base-isolated building. The building is represented by a two-dimensional portal frame and the piled foundation is based on a three-dimensional representation due to Gazetas and Makris. The pile-soil interface is represented by distributed springs and dashpots. For clarity, only the 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 [5], 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 [6], [7]. 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 [8] and result in soil-particle motion which describes a retrograde ellipse. Thus the building piles are subject to both vertical and horizontal motion.

3.2 Predictions of Insertion Gain

As mentioned in Section 2, a common measure of insertion performance is the associated Insertion Gain. This is the ratio, usually expressed in decibels, of the vibration response of the building with the isolation bearings in position to that with no bearings at all. It is impractical to measure IG because the response of a given building cannot easily be measured both with and without the isolation bearings in position. When IG is calculated, it is usual to take the response of the building at its base, directly above the isolation bearings themselves:

$$IG = 20\log_{10}\left(\frac{x_{isol}}{x_{unisol}}\right) \qquad 3.1$$

Where x_{isol} and x_{unisol} are the responses of the building in the isolated and unisolated cases respectively. The procedure for calculating IG using the model of Figure 1 may be found in [4].

Although IG is commonly used, it fails to provide a single measure of insertion performance since it (a) does not account for vibration occurring in more than one direction and (b) varies with position in the building. The results presented here correspond to the case of a concrete-framed building mounted on rubber isolation bearings. The bearings are specified in terms of their *isolation frequency*: for example, a set of bearings with an isolation frequency of 10 Hz have a combined vertical stiffness such that an equivalent SDOF model of the building would have an undamped natural frequency of 10 Hz. The corresponding horizontal and rotational stiffnesses are estimated based on the behaviour of a rubber block. Additional physical properties used in the model are given in the Appendix.

(a) Multidirectional Vibration

The horizontal component of ground-borne vibration is rarely considered in assessing the isolation of buildings; it is generally assumed that 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 can lead to various forms of vibration within the building structure. The Rayleigh wave excitation considered here results in both vertical, horizontal and rotational motion of the pile caps. As a result, values of IG may be calculated for all three degrees of freedom of the model (u, v and θ).

Figure 2 shows the variation with frequency in the vertical and horizontal IG based on the displacements of the base of the 'upstream' building column, i.e. the column first met by the Rayleigh wave. As expected, there is an initial peak in the vertical IG corresponding to amplification of the ground vibration due to the essentially rigid-body 'bounce' mode 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. Above this initial peak the bearings are effective although their performance is considerably poorer than a SDOF model would suggest. This is due to the flexibility of the building and piles reducing the efficiency of the isolation. Note that several of the smaller peaks are due to the phase difference in the motions of the piles.

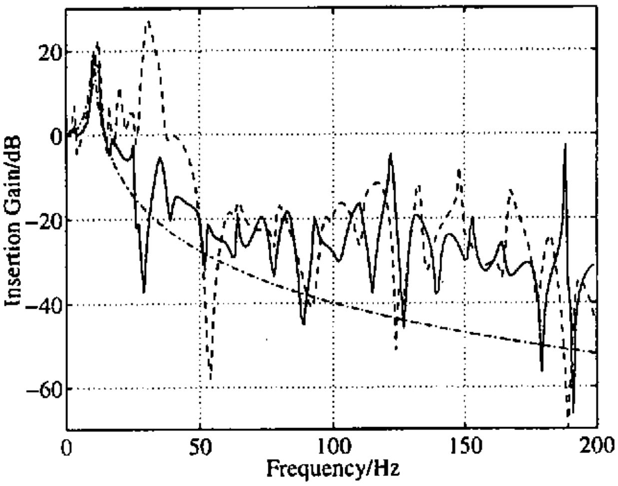

Figure 2: Variation with frequency in the vertical (solid) and horizontal (dashed) Insertion Gain of a '10 Hz' base-isolated building based on the displacements of the 'upstream' building column when excited by Rayleigh waves. The response of an equivalent SDOF model is shown for comparison (chained).

The horizontal (and in fact the rotational) IG shows a similar variation with frequency to that in the vertical direction. Coupling between the global horizontal and rocking modes of the building, due to the offset of its centre of gravity above the bearings, results in two initial peaks after which the isolation is effective. Although such predictions of IG are possible when dealing with multidirectional vibration, it is not clear how these should be combined into one overall measure of insertion performance.

(b) Spatial Variation in Insertion Gain

It was noted that the results in Figure 2 are based on the displacements of the base of the 'upstream' building column. Figure 3 illustrates that consideration of the 'downstream' column leads to different values of IG due to the fact that, although the structure itself is symmetrical, the piles are responding to the passage of a wave.

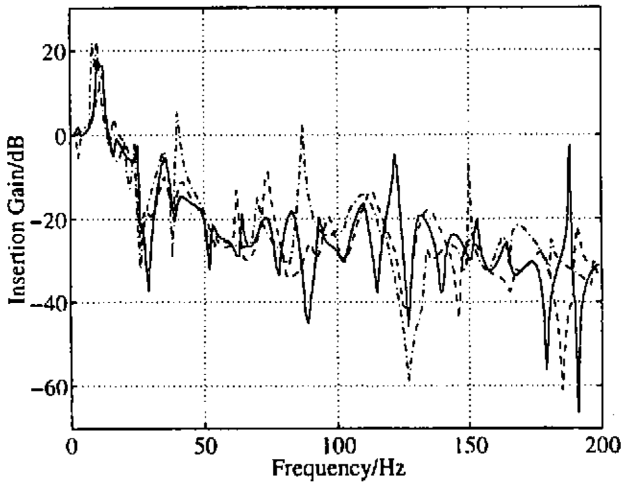

Figure 3: Variation with frequency in the vertical Insertion Gain of a '10 Hz' base-isolated building based on the displacements of the 'upstream' column (solid), the 'downstream' column (dashed) and the point mid-span on the first floor (chained) when excited by Rayleigh waves.

This effect is part of a wider problem relating to the spatial variation in IG around the whole building. Figure 3 also shows the IG based on the displacements of the point mid-span on the first floor; this curve is different again. Since, in general, we are dealing with the response of a complex multi-modal structure, there is no guarantee that the response at any point in the building will be representative of the whole; indeed some points may lie close to a significant vibration node of the structure and exhibit deceptively low vibration levels.

Clearly, while the concept of IG may be useful for systems consisting of just one input and one output, an improved performance measure is required for the assessment of base-isolated buildings.

3.3 Predictions of Power Flow Insertion Gain

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. This enables a *single* measure of insertion performance to be defined, described henceforth as the Power Flow Insertion Gain (PFIG):

$$PFIG = 10\log_{10}\left(\frac{\overline{P}_{isol}}{\overline{P}_{unisol}}\right) \qquad 3.2$$

Where $\overline{P}_{isol}$ and $\overline{P}_{unisol}$ are the total mean power flows entering the building in the isolated and unisolated cases respectively. Calculation of PFIG follows a similar method to the one given in [4] for IG but with the additional step of calculating mean vibrational power flows once the displacements of the portal frame have been computed [9].

PFIG has clear advantages over conventional IG by providing a measure which:

(a) accounts for multidirectional vibration - 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;

(b) is insensitive to the spatial distribution of vibration levels within a building - vibrational power enters a building at various places but the total power flow can be computed as a straightforward sum.

Since the variation with frequency in the PFIG may be represented by a single curve, it is more useful than conventional IG in the design process. For example, when optimising the isolation bearings for a given building, one would be concerned with minimising the PFIG in the knowledge that a reduction is guaranteed to reduce the average levels of structure-borne vibration and re-radiated noise. 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. When a particular room requires consideration, a similar approach may be taken but this time power flow into the room should be considered rather than the building as a whole.

It is worth noting in passing that the measurement of PFIG is just as difficult as conventional IG because, again, we require the response of a given building both with and without the isolation bearings in position. However, 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 particular type of building.

As mentioned above, the minimisation of PFIG enables the design of isolation bearings to be optimised for a given building. Two parameters which are of particular interest are the isolation frequency and the internal damping of the bearings. Figure 4 shows the variation with frequency in the PFIG predicted by the model using the same parameters as in Section 3.2.

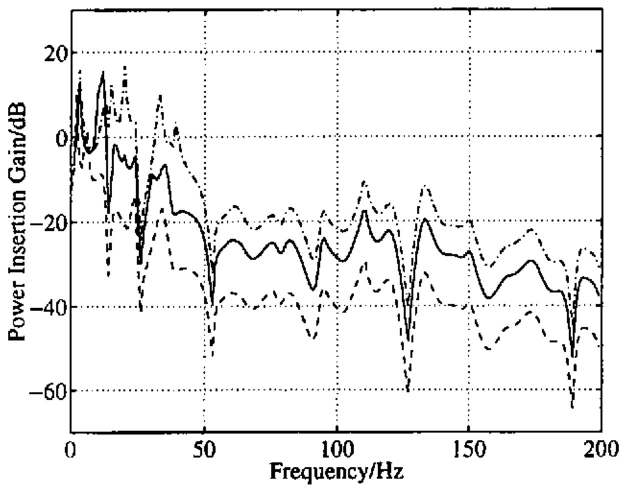

Figure 4: Variation with frequency in the Power Flow Insertion Gain for a base-isolated building with isolation frequencies of 15 Hz (chained), 10 Hz (solid) and 5 Hz (dashed) when excited by Rayleigh waves. The bearing loss factor is 0.1.

The 'baseline' case again concerns bearings with an isolation frequency of 10 Hz; the other two curves are obtained by varying the bearing stiffnesses to achieve isolation frequencies of 5 and 15 Hz. The general form of the curves is broadly as expected given that the PFIG conveniently combines the responses of the building due vertical, horizontal and rotational motion of the pile caps. At low frequencies, we again see peaks corresponding to the global modes of the building. Above these the isolation is effective with subsequent peaks and troughs in the PFIG corresponding 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 trend in Figure 4 due to a change in bearing stiffness: a low isolation frequency clearly improves the insertion performance of the bearings.

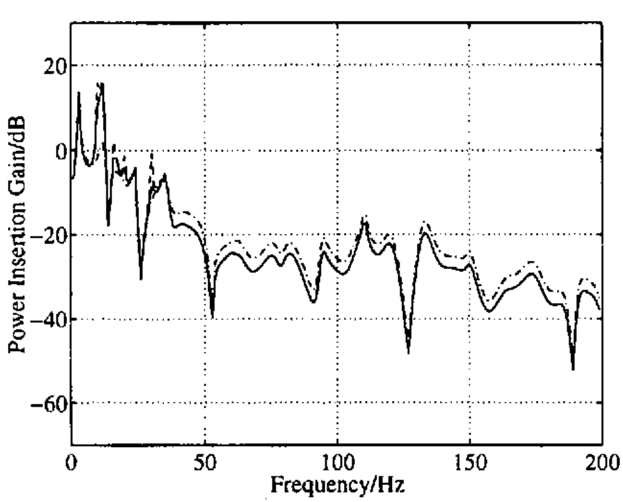

Figure 5: Variation with frequency in the Power Flow Insertion Gain for a '10 Hz' base-isolated building with bearing loss factors of 1.0 (chained), 0.1 (solid) and 0.01 (dashed) when excited by Rayleigh waves.

The results shown in Figure 5 imply that the insertion performance at medium to high frequencies is virtually independent of the internal damping of the bearings: the curves corresponding to damping loss factors of 0.1 and 0.01, typical of rubber and steel respectively, 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.

The trends evident in Figures 4 and 5 due to changes in the bearing parameters are potentially significant since a considerable amount of effort is spent designing isolation systems with the 'correct' isolation frequency and internal damping.

4. POWER FLOW ANALYSIS

In the calculation of PFIG, attention is focussed on the parts of the building directly above the isolation bearings. Power flows may also be calculated around the whole of the building model and this enables greater insight to be gained into the overall behaviour of base-isolated buildings.

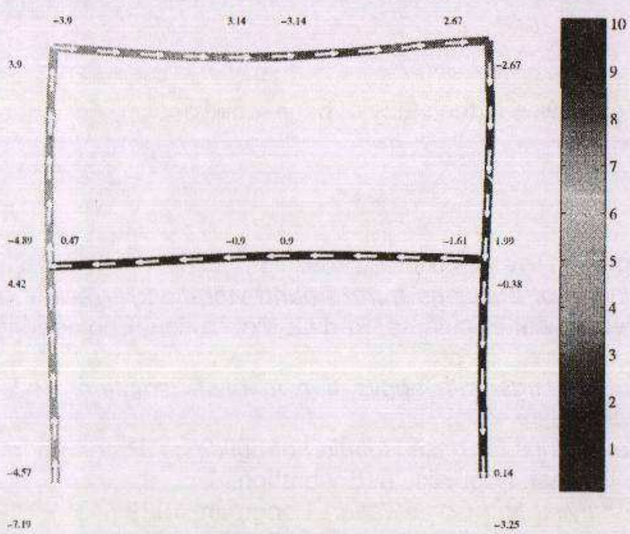

Figure 6: Total mean power flow distribution around a '10 Hz' base-isolated building excited by 20 Hz 'unit amplitude' Rayleigh waves; the shading indicates the magnitude (full scale = 10×10^7 W) and the arrows the direction of the power flow. Numbers represent power flows (in units of 10^7 W) *into* a node of the model. (Piles not shown).

Figure 6 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.

The building considered here is relatively simple. One may imagine more complex structures, such as a partially isolated building, where power flow analysis would provide valuable information on the vibration transmission paths involved.

5. CONCLUSIONS

This paper has considered the prediction of insertion performance for base-isolated buildings. Insertion performance is the measure which is of interest to the client who pays for the base isolation and the Engineer who wishes to evaluate alternative types of bearing.

A model of a base-isolated building has been presented which illustrates fundamental problems with a common measure of insertion performance based on vibration amplitudes alone. As a result, the concept of Power Flow Insertion Gain, based on the total mean vibrational power flow entering a building, has been introduced.

PFIG has been shown to offer clear benefits by providing a *single* measure of insertion performance which accounts for multidirectional vibration at multiple inputs and which is insensitive to the spatial distribution of vibration levels within a building. As a design principle, one would be concerned with minimising the PFIG in the knowledge that a reduction is guaranteed to reduce the average internal noise and vibration levels within a building.

Predictions of the PFIG for a building founded on piles and subject to surface Rayleigh wave excitation have shown that a low isolation frequency significantly improves the insertion performance of the bearings but that this is virtually independent of their internal damping. 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 addition, the potential of power flow analysis to provide insight into the behaviour of base-isolated buildings has been illustrated.

ACKNOWLEDGEMENT

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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.