ATTENUATING LATERAL VIBRATION SOURCES

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1 INTRODUCTION

Vibration is often characterised and detailed in simplistic terms in the vertical axis. Similarly, many isolation calculations continue to be carried out on the assumption that systems operate in a single degree of freedom (SDOF). While this is often the most crucial direction to consider in lightweight structures with responsive floorplates, this ignores vibration generated and carried in lateral axes, for example from ground-borne rail sources where the energy can be significant. This paper is focussed on base-isolated buildings, but similar principles can apply to box-in-box or MEP isolation.

Specifying vibration isolation bearings to control vibration in lateral directions is more complex. Care must be taken when calculating the lateral SDOF natural frequency as the lateral isolation system is not gravity-loaded. Designs should be sympathetic to this and must respect limits on movement required by the project structural engineer.

Treating the vertical and lateral axes independently can easily lead to designs which are overly stiff in the vertical plane. Furthermore, when considering the global building response, coupling between the vertical and lateral axes should be considered.

This paper discusses this in more detail and how to balance the acoustic requirement with the structural. Case studies are discussed which include preventing lateral structural movement of the core under wind loading, safeguarding against lateral forces in blast/seismic scenarios and resiliently supporting facades.

2 WHEN LATERAL ISOLATION IS REQUIRED

If the main bearings supporting the weight of the building are of a helical spring design, correct spring geometry typically results in good levels of lateral stiffness to react lateral loads. If elastomeric, bearings designed to have low and consistent stress distribution necessary to provide a life equal to that of the structure have a low lateral stiffness by default, owing to the relatively low shear stiffness of the elastomer. It is therefore common to require additional bearings to restrain a structure laterally when specifying an elastomeric solution, but these can also be required for helical spring bearings especially during a blast or collapse condition.

Because of the risk of lateral bearings compromising the acoustic performance, it is essential that there is a discussion between the bearing supplier, acoustic consultant and structural engineer about a compromise between two potentially conflicting aims:

- Structurally, it is ideal to have stiff connections with negligible movement to transfer forces consistently around a structure, avoiding undesirable stresses which can add cost to counter with additional reinforcing or local thickening.
- Acoustically, it is ideal to have compliant connections which provide impedance and effective response against structure borne vibration sources, avoiding uncertainty and the potential for additional treatments within the building which would consume space and add cost.

Compromise can be sought by reviewing the nature of the forces. If these forces are an ultimate loading case, a rare condition (such as a 1 in 100 year gust) or a structural collapse condition then it is possible to remove the permanent connection and use limit stops with an agreed clearance. However, there are some conditions which require permanently in-contact bearings to react lateral forces. This can result from the need to avoid a dynamic loading condition where stops come into contact, to control lateral movement with a consistent spring rate, or because the lateral load condition will frequently occur.

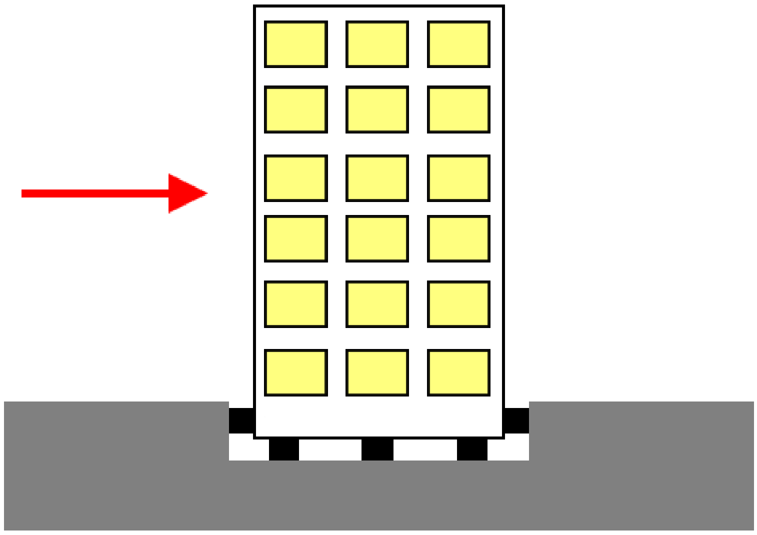

Figure 1: Schematic diagram of building supported by vertical and lateral base isolation bearings

The simplest solution is to avoid laterally mounted bearings wherever possible. However, in the following example bearings are typically aligned in the vertical plane to directly react forces since the main horizontal / gravity loaded bearings have insufficient lateral stiffness by themselves. Typical reasons for requiring lateral bearings are:

- To react wind and gust loading. Forces generated as wind/gust push laterally against a structure. Often reacted at the bottom of the core and shear walls as an overturning moment.
- To react permanent structural loading. Some structures use a geometry which relies on connections which can resist forces with both horizontal and lateral components. Examples would be diagonal trusses and walking columns.
- Stability of key structural elements. It is not possible to have reinforcing continuity across the isolation line and this can potentially destabilise connections, for example when floor plates provide stability to supporting columns. This may necessitate lateral bearings to stabilise, prevent movement and even to make the structure buildable.
- Supporting structure which lacks the ability to support itself, such as facades which sit on the ‘noisy’ side of an isolation line.
- Ultimate load conditions, disproportionate collapse, restraint against blast forces etc. can result in very significant forces but ideally the solution can be engineered away from overly stiff lateral bearings.

3 DESIGNING LATERAL ISOLATION BEARINGS

When designing resilient bearings to control vibration in the horizontal axes, the following points should be considered:

- The required stiffness is often driven by the structural engineer’s requirement for limiting lateral movement rather than the acoustic engineer’s requirement for a prescribed natural frequency or insertion loss.
- The isolators are usually pre-compressed, or wind-loaded rather than gravity-loaded so the natural frequency cannot be calculated based on the static force applied to the bearing or the resultant static deflection.

3.1 Engineering the Dynamic and Static Stiffness

When designing a bearing acting in the vertical axis following the SDOF methodology, the required dynamic stiffness $K_{dyn,z}$ of a bearing can be calculated using equation (1) with the target natural frequency f_0 being the independent variable. The compressive structural load F_z applied to the bearing is assumed to be due to the supported mass acting under gravity g.

$$K_{dyn,z} = (2\pi f_0)^2 \frac{F_z}{g} \tag{1}$$

The bearing manufacturer engineers the bearing to give the required dynamic stiffness via correct material choice and geometry.

The resultant static deflection X_z of the bearing under the structural load can be related to the prescribed dynamic stiffness as given by equation (2), where r is the dynamic to static stiffness ratio of the elastomer.

(Note: For helical spring bearings the dynamic stiffness is virtually identical to the static stiffness so the dynamic to static ratio is assumed to be unity and omitted from calculations).

$$X_z = \frac{F_z r}{K_{dyn,z}} \tag{2}$$

The engineering implication for the full building design is that the static deflection is driven by the acoustic requirement and must be accommodated in the structural engineer's design.

In the case of lateral isolation bearings, it is typical for the structural engineer to specify the maximum allowable deflection of the bearing when subjected to the lateral load F_y. The lateral static stiffness $K_{stat,y}$ is engineered with lateral deflection X_y as the independent variable, as given by equation (3):

$$K_{stat,y} = \frac{F_y}{X_y} \tag{3}$$

The lateral dynamic stiffness is dependent on the lateral static stiffness as given by equation (4):

$$K_{dyn,y} = K_{stat,y} r \tag{4}$$

The engineering implication for the full building design is that the stiffness of lateral isolation bearings is driven by the structural requirements. The effect of the resultant dynamic stiffness on the dynamic response of the building must be accommodated in the acoustic engineer's design.

Dialogue between supplier, acoustic consultant and structural engineer is essential in the early stages of a project to find the optimum compromise.

3.2 Natural Frequency of Lateral Restraint Bearings

It is common within the industry to refer to the 'bearing natural frequency'. This usually means the calculated natural frequency of a hypothetical system consisting of a mass freely supported by the bearing. The natural frequency is determined by the equations of motion relating to the restoring and dissipative forces of the bearing dynamic stiffness and the inertia of the mass under dynamic excitation in an SDOF system.

The common equation for natural frequency can be re-written in terms of deflection X by substituting $K = F/X$ and $F = Mg$ as shown in equation (5).

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{M}} = 15.8\sqrt{\frac{1}{X}} \tag{5}$$

This equation can be useful for the design engineer specifying isolators in terms of static deflection, where the deflection of the isolator is due to mass loading. However, in the case of lateral isolation, the deflection of the isolator is not due to the mass load of the building so equation (5) does not apply when expressed in terms of static deflection, X.

In order to accommodate quasi-static operational loading in the horizontal plane, it is usually preferable to pre-compress isolators in the lateral axis, effectively ‘clamping’ the structure. Figure 2 is a schematic representation of a situation where the mass is isolated from the sidewalls by pre-compressed ideal springs.

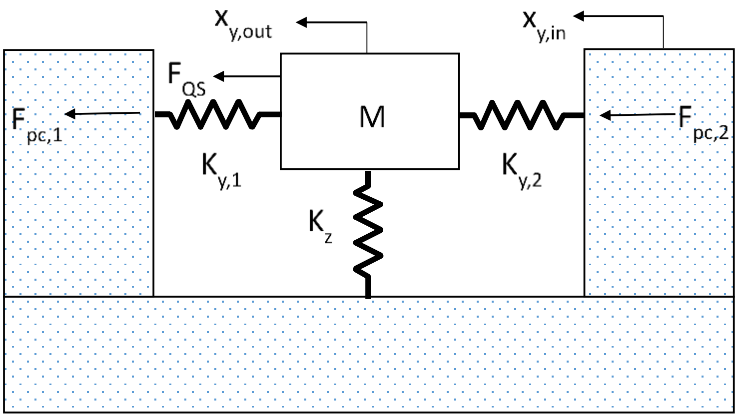

Figure 2: Schematic diagram of isolated mass with pre-compressed lateral restraint bearings.

When the quasi-static structural load F_{QS} is applied positively or negatively in the horizontal plane, lateral supporting forces between the isolated structure and the sidewalls are always maintained through the springs Ky,1 and Ky,2. This is achieved by applying a pre-compressive load to Ky,1 and Ky,2 during installation that is greater than any quasi-static load experienced during operation of the building. This ensures that separation between the structure and the lateral restraint bearings does not occur during operation of the building.

The deflection of the spring with stiffness $K_{y,1}$ is determined by the resultant of the pre-compressive force $F_{pc,1}$ and the quasi-static structural load F_{Qs} at any given time. Similarly, the deflection of the spring with stiffness $K_{y,2}$ is determined by the resultant of the pre-compressive force $F_{pc,2}$ and the quasi-static structural load F_{Qs}.

When excited by a dynamic displacement X_{yin} due to vibration ingress through the side wall, the dynamic displacement X_{yout} would correspond to the response of an SDOF system with natural frequency given by equation (6):

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K_{y,1} + K_{y,2}}{M}} \tag{6}$$

4 LIMITATIONS

Whilst the horizontal natural frequency of the idealised system of figure 2 can be calculated using equation (6), the SDOF assumption is unlikely to be justified for a typical building. Following an elementary analysis in the two-dimensional plane, the designer is confronted with a rigid body having three degrees of freedom.

The centre of mass of the building is usually higher in the vertical plane than the lateral restraint bearings, giving rise to rotational as well as axial movement when excited by lateral vibration at ground level[1]. This results in coupled modes which shift the resonant frequency, hence independently calculated vertical and horizontal natural frequencies no longer correlate with the response of the supported mass. Therefore, insertion loss predictions using bearing natural frequency in an SDOF model are of limited use when specifying bearings for buildings where lateral isolation is required.

In addition, the fact that lateral bearings have themselves a lateral stiffness must be considered, i.e. resistance to motion in the vertical axis. The design must take this into account as, while it is desirable to provide a compact / thin lateral restraint bearing system which is structurally and architecturally beneficial, this can provide a clamping effect, increasing the vertical stiffness of the system. Thus, the lateral spring rate (acting vertically) of the lateral bearings must be minimised.

Prior work by James Talbot[1] provides mathematical models demonstrating that the introduction of lateral bearings can limit the effectiveness of an isolation system.

1. To be confident of achieving a global building natural frequency in the vertical axis, all elements which affect this mode should be quantified.
2. The stiffness in shear of vertically mounted bearings placed to react lateral loads influences the global vertical mode, a contribution to which is due to structural rotation and coupling.
3. Increasing complexity of model showed that the introduction of lateral bearings with high stiffness in the vertical plane (shear) can have a significant effect of the effectiveness of the base isolation system.
4. Therefore, the stiffness of any lateral bearing should be minimised as far as possible.

Efficiency of the vibration system will be limited if the inclusion of lateral bearings increases global vertical stiffness and if there is significant energy carried in the lateral axes.

5 DESIGNING FOR LATERAL RESTRAINT

Whether looking at how the main bearings react to lateral vibration, or how laterally loaded bearings affect the global vertical natural frequency, the bearing shear and dynamic stiffness is the primary driver. Therefore, the following aspects should be observed:

1. For bearings loaded primarily by the gravity weight of the building, their lateral stiffness should be minimised to mitigate as far as practicable transmission of vibration in lateral axes.
2. For bearings loaded primarily by lateral forces and hence orientated vertically, their compressive stiffness should be minimised to mitigate as far as practicable transmission of vibration in lateral axes.
3. For bearings loaded primarily by lateral forces and hence orientated vertically, their shear stiffness should be minimised to mitigate as far as practicable transmission of vibration in the vertical axis.

In the above three cases, expressing as natural frequency and quantifying as a global insertion loss may not be possible. The specification should therefore express these aspects as an expected design principle.

Bearings with a low shape factor (the ratio between loaded and unloaded surfaces) are primarily designed to operate under low stress-strain conditions extending the life span to be equal or beyond that of the structure. Due to the thicker rubber layers associated with low shape factor design, the shear stiffness is also reduced which lends itself to realising this design principle.

The structural requirements will always drive the design and the bearing spring rate but the earlier in a project this issue is raised by the supplier, the softer the connection that can likely be achieved. It is always necessary to understand maximum permissible movement under the various load conditions as these can be used to drive the minimum permissible bearing spring rate in that direction.

It is strongly recommended that an acoustic consultant is contracted throughout the design phase to support these efforts.

6 CASE STUDIES REFLECTING ADVICE

The following examples reflect the practical result of minimising spring rate in the vertical and lateral directions as far as able, while respecting structurally permissible movement under load.

6.1 Core lateral restraint

Figure 3 illustrates a compromise position found by working with the structural engineer and acoustic consultants, whereby the softest viable connection was determined in an architecturally acceptable package. The overall design driver is a permanently engaged bearing with the thickest viable section as to minimise detriment to the system vertical response. Adjustment was incorporated to allow for building tolerances and fitting of temporary rigid supports during the construction phase.

A series of windows were cast into structure to allow bearings to be installed and adjusted to provide the correct clamping force in opposing pairs. This attained the correct pre-compression to be applied irrespective of building tolerances. This ensured that, even under the highest likely loading, bearings would remain in contact with structure to provide a restorative force and prevent a dynamic loading condition. This system also allowed the installation of steel spacers to allow the crane to be supported on the isolated structure and ultimately that there was no intrusion into the rentable space.

Figure 3: Core lateral restraint bearing with hardware to apply a prescribed compression

6.2 Safeguarding against lateral forces in collapse/blast/seismic scenarios

Figure 4 is a one of 58 column capitals, each of which was different owing to extremely limited architectural envelope. The bolt on lateral braces are double-acting, able to accept positive and negative forces in each axis and were applied singularly, in pairs or in fours depending on the load at each column. Bearing assemblies were supplied by the factory pre-compressed for ease of installation. The bearings were designed with the thickest possible section to provide negligible additional stiffness in the vertical axis. A benefit of this system is that zero force is applied to the hardware (unless a lateral force is applied) as the bearing blocks are compressed equally against each other, so that no separation will occur under load and a restorative force is always present.

Figure 4: Column head assembly with bolt-on lateral braces (gravity-loaded bearing not visible)

Figure 5: Uni-directional facade braces designed to a precise spring rate

6.3 Resilient Facade Support

Figure 5 reflects a solution for retained facades. The same principles can be applied; however far more frequent support is typically required, especially for fragile/aged facades. Movement in this case had to be constrained and the original position of the structural and historical team was that only rigid connections should be allowed which would have severely compromised the acoustics. Following review and development of a new design which underwent significant testing to prove the displacement characteristics with negligible tolerance, a permissible spring rate was agreed. For this reason, all supplied braces were factory pre-compressed.

7 CONCLUSIONS

This paper has briefly explored the limitations of considering and specifying lateral isolation for a base-isolated building using a single degree of freedom approach, but the principles can also apply to box-in-box constructions and smaller-scope projects. If lateral restraints are required, it is imperative that a more holistic design approach be taken by the design team as early as possible to consider the effects on the global response of the building.

Each stage of the design should be optimised as far as able in order to produce the most acoustically sympathetic design within the bounds of structural limits. Compromise should be sought between these potentially conflicting aims and the acoustic consultant should be able to inform the design team of the need for good design practices. Whilst it may not always be possible to quantify the insertion loss, the design principle should be to minimise the horizontal stiffness of all bearings and to minimise the vertical stiffness of the lateral isolation bearings.

Case studies have been presented demonstrating how this process can result in a design which is sympathetic to structural and acoustic concerns but also take into account the need to minimise intrusion architecturally.

8 REFERENCES

1. J P Talbot and H E M Hunt., 'The effect of side-restraint bearings on the performance of base-isolated buildings' Mechanical Engineering Science 2003