DYNAMIC STIFFNESS AND DESIGN OF RUBBER-STEEL LAMINATED ISOLATORS

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The efficacy of an antivibration mount system for mitigating the effects of groundborne vibration – typically that induced by underground railways – depends on the dynamic stiffness of the mounts. In turn, the dynamic stiffness depends on amplitude and frequency of the dynamic relative displacement between the foundation and the base diaphragm of the isolated superstructure, as well as on the details of the bearing, namely of the type of rubber, the number and dimensions of the steel reinforcing plates, geometrical design and static load. The purpose of this paper is to build on the basic guidance already available in the literature for design of bearings and estimation of their dynamic stiffness, to identify limitations in this literature and to seek to meet these through development of theory and provision of new insight from experiment. The paper seeks to address the issues faced by all parties to the successful implementation of a vibration isolation system based on rubber-steel laminated bearings: those of the structural engineers and of the bearing designers and manufacturers. The authors welcome feedback from the IACSV community on the issues raised, with a view to this work being fed into the drafting of a replacement for the former Standard BS 6177:1982 Guide to Selection and Use of Elastomeric Bearings for Vibration Isolation of Buildings. This Standard was withdrawn, on the basis of some inconsistency and lack of cross-referencing to other Standards regulating elastomeric structural bearings. However, the authors take the viewpoint that vibration isolation is a significant and distinctive application for structural bearings, meriting application-specific Guidelines.
Keywords: VIBRATION ISOLATION OF BUILDINGS, DYNAMIC STIFFNESS, RUBBER-STEEL LAMINATED BEARINGS, GROUNDBORNE VIBRATION

1. Introduction

The isolation of structures from ground borne vibration seems to have developed in the UK and Germany around the same time, in the 1960s, but using very different types of isolator. In Germany, it was discovered that helical metal springs, which had been developed for protection of structures from subsidence associated with mining, could provide a practical isolation from vibration. In the UK, it was discovered that rubber-steel laminated bearings, developed to accommodate thermally-induced length changes of bridge decks, could be designed to provide also a low enough vertical stiffness to serve as effective antivibration mounts for buildings (Waller[1]). A Guide, DD47:1975, subsequently to be largely adopted as BS6177: 1982 Selection and Use of Elastomeric Bearings for Vibration Isolation of Buildings, was written to ensure good practice in the UK, and the technology is now widely applied throughout the world. The uptake is particularly significant in cities with underground rail systems, enabling the use of land, otherwise blighted by rail-induced vibration, to be used for high quality building purposes.

Although an intention arose to promote BS6177:1982 to CEN with a view to bringing out an equivalent EN Standard, this failed to happen, although CEN did produce EN1337 part 3 on Elastomeric Structural bearings, which is also referenced by EN15129:2009 Antiseismic Devices, which covers the use of elastomeric structural bearings for seismic isolation. The BS committee with responsibility for BS6177:1982 realised that some inconsistencies had arisen with these CEN Standards, but did not have the capacity to undertake the task of revising BS6177:1982, instead deciding to change its status to obsolete in 2013, pending time to revise it. However, many in the industry appreciate that BS6177:1982 primarily complements rather than duplicates the EN structural bearing coverage, since it focuses on safe achievement of the goal of isolating from groundborne vibration, rather than detailed design of the bearings. To this background, a new dimension has also been added: advances in appreciation of the complexities of predicting and evaluating the performance of vibration isolation systems has developed, along with a growing uptake of the approach.

In 2016 an interest group, called the Groundborne Vibration Group, was formed in the UK, to stimulate research in the area and provide guidance to the industry, and it has been suggested that update and relaunch of a Standard, built on BS6177:1982, is one of its goals. This paper explores some issues relating to elastomeric bearings that are likely to be relevant to their performance, and thus merit coverage in the proposed new Guidelines. The authors also invite all suggestions on such matters from practitioners and researchers in the field.

2. Properties of vibration isolation bearings that control their performance

2.1 The overall system

According to Waller [1], generally "people require that the vibration should not be perceptible within the context of their general environmental conditions". In the range 10 to 60Hz would imply that the peak velocity of vibration should not be more than about 0.25mms^{-1}. Regarding noise, vibration of the floors will generate sound waves, and, at frequencies greater than about 60Hz, this will be more perceptible by ear than by the feet as vibration. The threshold for an acceptable level of noise depends on the time of day (or night) and, again, the general environmental conditions. As the latter are subject to change – e.g., a switch from internal combustion engines to electric drives for road vehicles would have a big impact - and understanding of environmental effects on people advances, the acceptable noise level may be a moving target.

Waller [1] pointed out that the minimum complexity of the dynamic system needed to capture the essence of the behaviour involves knowledge not only of the building mass and the dynamic stiffness of the springs between it and the ground, but also of the effective mass and stiffness of the ground that lies between the building and the vibration source. He illustrated this with a 2DOF uniaxial system above a source of vertical vibration, and highlighted the important issue that the effective mass and stiffness of the ground are unknowns.

While it is clear that the function of the springs is to provide a low dynamic stiffness such that the groundborne vibration tends to deflect them rather than to vibrate the building, it is less clear how to optimise this stiffness. Moreover, the industry has tended to think in terms of a uniaxial SDOF model, emphasising a target vertical natural frequency of the building on the springs, as if the foundation were fixed, and the dynamic stiffness of the springs were independent of dynamic amplitude or frequency. Spring suppliers come under pressure to meet a specified noise and vibration level in the building, without adequate tools in place to provide a quantitative spring specification that will ensure this is met.

Waller chose to illustrate vibration isolation in the vertical direction. It is more difficult to achieve a low stiffness in the direction that the springs must also be designed to bear the gravity load safely. Perhaps in consequence, there has been a lack of attention to the lateral ground vibration levels and to treating the lateral stiffness of mounting systems as a design quantity. In fact, current thinking is that both lateral and vertical vibration excitations should be considered and their mitigation by the isolators should be subject to performance-based design optimisation [2].

Although there is little doubt that isolation from groundborne vibration can be effective, there has long been a concern that methodologies for, and examples of, quantitative assessment of performance of a system are lacking. For example, because the presence of the building will perturb the ground vibration level, the Transmissibility, i.e. the ratio of amplitude above the isolators to that below, is inadequate as a measure of efficacy. A better measure would be the Response ratio, i.e.

the ratio of the vibration amplitudes above the isolators to that that would prevail were the building mounted directly on the ground; the Insertion loss, the ratio of the squares of the amplitudes, is a similar measure. In principle, this could be measured, by temporarily transferring the loads on the isolators to rigid blocks. Even though some buildings are designed to enable such a procedure in principle – if designed with the possibility of replacement of the springs in mind – the authors are not aware of any base isolated building that on which such a test has been carried out.

Talbot [2] has argued the case for using Power-flow insertion gain as a more useful measure of overall performance, since, being based on mean vibrational power flowing into the building, it accounts for multidirectional vibration, at multiple inputs, and is insensitive to the special distribution of the vibration levels.

2.2 Scope of BS6177: 1982 Selection and use of elastomeric bearings for vibration isolation of buildings

The title of the withdrawn Standard does not reflect the current practice. When it was written, only elastomeric bearings were used in the UK for isolating buildings from groundborne vibration; now there are some examples of buildings mounted on metal springs, as in other countries. The first decision regarding revision, then, is should the scope address more than systems with elastomeric isolators?

The Standard consists of three Sections, the first of which is a short general introduction regarding scope and definitions. Section 2, Design, includes some information specific to elastomeric bearings, but is mainly about overall issues common to any isolation system.

Section 3 addresses only elastomeric bearings, being of two types: natural rubber without cellular filler, normally reinforced by steel plates, and “elastomeric composite” which includes a cellular filler, and can be reinforced with fabric. The presence of cellular filler radically alters the detailed design of the bearings to meet specified load capacity and stiffnesses, but detailed bearing design equations are not given for either type of bearing.

Three appendices are included: A gives a list of references, B discusses the issue of shape factor, relevant only to bearings based on rubber without cellular filler. Appendix C gives a useful checklist of factors that should be met by the overall design and realisation of the isolation system. Only part C3, about 20% of Appendix C, is focussed on the bearings.

It is evident that on many issues that it already attempts to address, the Standard could be improved, as well as the need to make it consistent with the CEN Standards addressing structural elastomeric bearings. It is our contention that in some cases the knowledge needed to do this exists, while in other cases it is emerging, not least through the activities and expertise of the GVG in the UK. The formation of this Group also indicates that there is sufficient interest and activity among structural engineers in the isolation of buildings from groundborne vibration to justify the effort of amending the Standard, and hopefully the resources to do the work.

Some of the literature regarding isolators that could be useful in this effort is referred to in the remainder of this paper.

2.3 Dynamic stiffness for rubber isolators

Many papers have been published on aspects of rubber isolators in the last 25years, since the publication of BS6177. The dynamic modulus of rubber materials depends on the amplitude and frequency of the dynamic strain. Ahmadi and Muhr [3], for example, gave data on the effects of dynamic amplitude and frequency for a set of illustrative rubber materials. They also discussed mathematical aspects of the dynamic characteristics of isolators, such as the number of parameters needed to describe these characteristics, and calculate them for series combinations of compliant elements. The latter becomes non-trivial when frequencies are high enough to invoke effects of the internal mass of the springs. Wave effects occur, and the force is not equal at each end of the isolator. The theoretical framework had earlier been well developed by Snowdon [4], but has no place in the simplistic SDOF design most often used for isolators.

Picken et al [5] analysed the influence of internal mass on the axial dynamic behaviour of laminated rubber isolation bearings. Having validated an FEA model, which included the mass of both rubber and reinforcing plates, with respect to experiments on a scaled bearing up to a frequency of 500Hz, it was used to quantify the transmissibility of a full sized 9-layer bearing up to 10 kHz. The compressive load on the bearing was consistent with a system first mode vertical frequency of about 3Hz. This showed equivalent behaviour to the SDOF model for transmissibility up to about 100Hz, after which the performance became worse up to 300Hz due to effects of the internal mass. For a level of damping typical of NR, the model showed better performance than anticipated by the SDOF model between 300 and 1000Hz, although this was not the case for a model with zero damping. Above 2000Hz, there were many internal modes, little advantage of damping, and little further reduction in transmissibility.

2.4 Comparison between metal and rubber isolators

Competition has developed between systems based on metal springs and elastomeric springs. As mentioned above, both systems have so far been designed along the lines of choosing a low first mode vertical frequency for the isolated building, with metal springs being expected to enable a lower frequency and hence, it is thought, better isolation.

Coja and Kari [6] compared rubber and steel isolation mounts, intended to reduce the generation of noise induced by structural vibration driven by marine engines. Three types of mount were included: a natural rubber-steel laminated conical mount, a parallel assembly of helical metal springs with foamed steel inserts to provide some frictional damping, and a parallel assembly of a helical metal spring with a rubber noise-stop pad inside a set of inclined natural rubber blocks. They considered the “blocked dynamic stiffness” to be a good measure of its efficacy. This is the complex ratio of the force between the mount and an inertial mass attached to the top of it, and the dynamic displacement applied to its base. Their measurements spanned the frequency range 200 to 1100 Hz for the rubber mount, and 100 to 1000Hz for the other mounts. Plots for the three mounts show that for the natural rubber mount the dynamic stiffness rises smoothly over the full range, while for the other mounts the dynamic stiffness has numerous peaks and troughs (from lightly damped wave effects) above 300Hz. They concluded that the comparisons “clearly expose the superior performances of the rubber conical mounting in terms of mean stiffness and impedance over the examined audible domain, making it the technically most suitable.”

Muhr [7] demonstrated that according to the design methodology of Derham and Thomas [8] it should be possible to design natural rubber-steel laminated bearings for a nominal SDOF natural frequency of 3Hz, matching that typical of helical metal spring isolation systems. However, because of the fact that for rubber the dynamic stiffness is around 50% higher than the static stiffness, the actual natural frequency for the isolator was predicted to be 3.7Hz. However, this is not necessarily the lower limit of what is achievable. A theoretical analysis was also included, showing that low damping will result in the internal resonance issues responsible for impaired isolation at higher frequencies as discussed in the previous two sections. The damping level of natural rubber provides a good mitigation for this, compared to the steel springs. Furthermore, introduction of a “noise-stop pad” of rubber with high damping at the end of a helical metal spring is much less effective as a mitigation strategy, because the damping is not continuously distributed throughout the spring length.

2.5 Developments in rubber isolator design and understanding

An issue for all isolators is to achieve a usefully low axial stiffness while at the same time having an adequate margin of safety against lateral mechanical instability. BS6177 raises this issue, but does not provide design equations. Several authors have pointed out that the equations used in other Standards for structural bearings, from the same theory as that discussed by Derham and Thomas [8], is not the full story [9-11]. This is currently being pursued in our research, and is hoped to deliver more reliable design equations.

Since 1983, much data has also been gathered on the condition of bearings after prolonged service, putting judgements of long-term capability of laminated rubber bearings on a firmer footing.

3. Conclusions

We conclude that elastomeric bearings remain a good choice for antivibration mounts for buildings, but that there is a need and opportunity for refinement of the design of isolation systems to achieve the desired performance. It is clearly desirable that such refinement is made available to the industry in the form of comprehensive Guidelines. The Groundborne Vibration Group is open to suggestions of what the scope of such Guidelines should be.

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