A New Damper System for Walking Induced Floor Vibration Control

T.H. Nguyen, E.F. Gad and J.L. Wilson

Faculty of Engineering and Industrial Sciences
Swinburne University of Technology, VIC 3122, Australia

tuannguyen@swin.edu.au; egad@swin.edu.au; jwilson@swin.edu.au

N. Haritos

Department of Infrastructure Engineering
The University of Melbourne, VIC 3010, Australia

nharitos@unimelb.edu.au

This paper presents analytical and experimental studies on the application of an innovative viscoelastic tuned mass damper system to mitigate disturbing footfall induced vibrations observed on a real office floor. The damper system consists of a number of steel-rubber sandwich beams arranged in a distributed form. Different tuning scenarios were investigated via FE simulations, demonstrating that dampers appropriately tuned to multi frequencies would be more effective than those tuned to a single frequency. The influence of the installation of the dampers on a floor bay on the response of the adjacent bay is also discussed. The custom-made dampers have been successfully installed on the existing floor without requiring any architectural or structural modifications. Results from numerical investigation and field tests show that the dampers can reduce at least 40% of the floor response to an acceptable level for human comfort in an office environment.

1. Introduction

High strength materials, optimised design approaches and advanced construction technology have enabled floor systems to be designed and constructed with longer spans and smaller structural members. The floors, normally in good condition from a strength perspective, can be very vulnerable to vibrations caused by various human activities. Resonance that significantly amplifies the vibration amplitude may occur when the floor frequency is low enough to match one of the harmonic components of the excitation. Current design guides have recommended limits on floor vibration to ensure human comfort and hence floor serviceability (Murray et al., 2003; European Commission, 2006; Smith et al., 2009).

Of several methods to minimise human-induced floor vibrations, the use of viscoelastic materials has been attempted with some degree of success. Nelson (1968) employed a constrained viscoelastic layer on a typical floor panel in a large department store.
A pressure sensitive adhesive produced by the 3M Co. was used as the viscoelastic material. It was applied to the bottom flange of the floor beam and constrained by a steel layer on the top. The treatment increased the floor damping by about 3.5%. Moiseev (1991) added a special concrete layer, formed with viscoelastic damping admixture replacing a certain amount of water, on top of three existing floors. The special concrete, commercially named as Concredamp, increased the damping level of the floors by a factor of approximately two. Experimental works performed by Falati and Williams (1998), however, revealed that Concredamp did not significantly improve the floor damping. When a laboratory floor strip of post-tensioned concrete construction was covered with a screed layer treated with Concredamp, the increase in damping was just 0.2%. When some laboratory beams were cast with Concredamp, i.e. the viscoelastic admixture was used as a component of the structural material rather than of a screed layer, the increase in damping was 1.3%. Ljunggren and Agren (2002) developed a new damper in the form of small pieces of viscoelastic material installed between the ceiling joist and an angle piece fastened to the main floor beam. When the lightweight floor and the flexible ceiling were moving out of phase to each other, the damper could provide an additional damping of 1.3%–9%, as observed on some laboratory floors. Arup and Richard Lees Decking has developed the Resotec damping system for composite floors (Willford et al., 2006). The device, which consists of a thin layer of high damping viscoelastic material constrained between two thin steel plates, can be placed on top of the floor beam before the concrete slab is cast. The Resotec is hence installed during construction rather than being used as a remedial solution for existing floors.

More recently, a new type of tuned mass damper (TMD) using viscoelastic material has been developed and proven effective on some laboratory beams at Swinburne University of Technology, Australia (Saidi et al., 2011). This paper explores the use of an innovative damper system configuration, based on the new TMD type, to suppress annoying vibrations due to humans walking on a real office floor. The presented work includes a numerical investigation of various tuning strategies for the TMD system, followed by an experimental validation of the system’s efficiency.

2. Description of Case Study Floor and Concept of a New Damper System

Fig. 1(a) shows the framing plan of a real office floor of steel-concrete composite construction where disturbing footfall-induced vibrations were reported by the tenants working on a bay located at the north-west corner of the building. This bay, denoted by “A” in Fig. 1(a), has two long perpendicular corridors intersecting at the bay centre which is unfortunately very close to some workstations. The dynamic properties of the floor were determined from a number of physical heel drop tests conducted on the problematic bay. It was estimated that the natural frequency was about 6.2 Hz whilst the damping ratio was within 2.5-3%. Walking tests were also performed in which people walked along the corridors with a normal pacing rate of around 1.9-2.2 Hz. The measured peak floor acceleration was within a range of 0.5-0.7% g. This vibration level exceeds the recommended threshold of 0.5% g for human comfort in an office environment (Murray et al., 2003). Remedial measures were therefore targeted to vibration response. It was decided to design an appropriate TMD system to mitigate the vibration amplitude to a tolerable level.
From the measured peak acceleration of 0.7% g (i.e. 68.7 mm/s²) and frequency of 6.2 Hz, the peak floor displacement can be roughly estimated at 0.05 mm (68.7/(2\times\pi\times6.2)^2 = 0.05). Given that this level of motion is considered too small to excite a conventional TMD with a mechanical spring and dashpot, we have developed a new type of damper which is more sensitive to the floor motion. The damper has the form of a cantilever sandwich beam consisting of a layer of rubber as viscoelastic material constrained between two steel plates, as shown in Fig. 1(b). Tuning of the TMD frequency can be achieved by varying the length of the sandwich beam or the amount of end mass concentrated at the tip of the beam. When the damper undergoes cyclic bending, the constrained viscoelastic material layer is forced to deform in shear and dissipates energy. One challenging design requirement for this case study floor is that the damper system must be installed on top of the concrete floor and enclosed entirely within the limited space of the false floor, hence avoiding access to the ceiling space below. To meet this demand, multiple dampers with a smaller mass arranged in a distributed form can be used instead of a single large damper. The distributed TMD system consists of some closely-spaced four-arm dampers, each of which has four sandwich beams attached to a common base, as shown in Fig. 1(c). The TMD system should be located within the centre area of the problematic bay where maximum modal displacements occur.

![Figure 1](image)

Figure 1: (a) Floor framing plan; (b) Schematic of a damper; (c) Distributed multi TMD system.

3. Numerical Studies of Damper Tuning Strategies

3.1. Modal Analysis

An FE model of the entire floor was created and calibrated to match the measured natural frequency. From a study of the obtained mode shapes, it was found that the 4\textsuperscript{th} mode (rather than the 1\textsuperscript{st} mode as one might assume) was the resonant mode of the problematic bay (i.e. bay A) with antinodes located around the bay centre as shown in Fig. 2(a). The natural frequency and modal mass of this mode, as obtained from FE modal analysis, were 6.22 Hz and 20,600 kg respectively. Another mode that can be
taken into account was mode 5 with a natural frequency of 6.33 Hz and modal mass of 35,000 kg. Although this mode yielded quite large modal displacement on bay A, it is not as critical to bay A as mode 4 because its modal mass was 1.7 times larger than that of mode 4 and its antinodes occurred at the adjacent bay denoted by “B” in Fig. 2(b). Treatment was therefore focused more on mode 4.

3.2. Damper Tuning

A preliminary design assumed the use of 12 TMDs, each with a mass of 23 kg, distributed (on bay A) in three groups as depicted in Fig. 1(c). The damper system would have a total mass of about 280 kg which was 1.3% of the modal mass in accordance with the 4th mode. Tests on a sandwich beam prototype revealed a damping ratio of approx. 5% for the TMD. Three tuning scenarios were numerically investigated as follows:

(a) Tuning based on one mode of the original floor: all 12 dampers were tuned to 6.2 Hz, i.e. close to the natural frequency of mode 4.
(b) Tuning based on two modes of the original floor: 8 dampers of groups 2 and 3 were tuned to 6.2 Hz (mode 4) while 4 dampers of group 1 were tuned to 6.3 Hz which was close to the natural frequency of mode 5.
(c) Step by step frequency-updated tuning: 4 dampers of group 1 were first tuned to mode 4 of the original floor (6.2 Hz). Dampers of group 2 and 3 were then tuned to 6.0 Hz and 6.5 Hz, respectively. These two new frequency values related to the natural frequencies of a combined system consisting of the floor and 4 dampers of group 1.

The concept of frequency-updated tuning suggested above can be best illustrated via the response spectra of the floor subjected to simulated heel drop excitations (Fig. 3). For the original floor without TMDs, the response spectrum of Fig 3(a) shows a sharp peak at 6.25 Hz which was very close to the natural frequency of mode 4 (6.22 Hz) computed from the modal analysis. Four dampers of group 1 were tuned to this frequency and added to the floor model. The heel drop force was then applied to an updated FE model of the floor with 4 dampers included, resulting in a new response spectrum as shown in Fig 3(b). The previous sharp peak of Fig 3(a) was lowered and split into two peaks at frequencies of 6.05 and 6.54 Hz of Fig 3(b). TMDs of group 2 and 3 were then tuned to 6.0 Hz and 6.5 Hz, respectively. The FE model was updated
again with the inclusion of 8 dampers from groups 2 and 3. Consequently, the response spectrum was further flattened with lower peaks as can be seen from Fig 3(c). Although the walking response has not been analysed here, the heel drop response spectra alone can still demonstrate the effectiveness of the dampers in reducing the vibration amplitude.

Figure 3: Floor response to heel drop: illustration of step by step frequency-updated tuning.

3.3. Calculation of Walking Response

Walking forces were applied to four FE models of which one was for the original floor without TMDs and the others were for the floor with dampers associated with the three tuning scenarios (a), (b) and (c) described above. The walking excitation was modelled as a concentrated force $F(t)$ of Eq. (1) applied at the centre of the problematic floor bay:

$$F(t) = P \sum \alpha_i \cos(2\pi f_{p,i} t + \phi_j) u$$

in which $P$ is the walker’s weight taken as 800 N. The Fourier coefficient $\alpha_i$ can be taken as 0.5, 0.2, 0.1 and 0.05 for the first, second, third and fourth harmonic components, respectively, of the walking excitation with a footstep frequency of $f_p$ (Murray et al., 2003). Phase angles $\phi_i$ can be taken as 0 for the first harmonic and $\pi/2$ for the others (Bachmann and Ammann, 1987). To model a person walking from one end of the floor span to the other, the floor mode shape value $u$ corresponding to various footstep locations along the walking path was incorporated into the forcing function (Nguyen et al., 2011). More than 50 time traces of walking force in the form of Eq. (1) with footstep frequencies covering a range of 1.85-2.30 Hz were created as the input for time history analysis of each floor model. This range of pacing rate is common for human walking activities. Moreover, the fine resolution of the input loading spectrum ensures a close match between the forcing frequency $f_p$ and the natural frequencies of the floor with and without dampers. Hence the worst case where resonance occurs was effectively included in the time history analysis.

Fig. 4 shows some acceleration histories for the floor models subject to walking at resonance. Fig. 5(a) illustrates the response spectrum with peak acceleration response of the problematic floor bay to different pacing rates. Each data point of Fig. 5(a) was collected from an appropriate time history analysis case. Without dampers, the floor was predicted to have a maximum acceleration of 0.73% g which exceeds the tolerable threshold of 0.5% g. With dampers, the vibration level can be reduced to 0.38% g, 0.36% g and 0.32% g for the tuning scenarios (a), (b) and (c) mentioned in section 3.2, respectively. All the tuning scenarios investigated can result in vibration
levels being below 0.5% g and hence acceptable. Tuning to modes 4 and 5 was slightly more effective than tuning to mode 4 only. Moreover, the frequency-updated tuning can further reduce the floor response by 18% compared to the single-mode tuning scheme.

![Figure 4](image_url)

**Figure 4:** Floor response to walking at resonance.

![Figure 5](image_url)

**Figure 5:** (a) Response spectrum of bay A, and (b) peak response of bay A and B.

### 3.4. Effect of Dampers on Different Floor Bays

In order to get an idea of the effect of the installation of dampers in the problematic bay (A) on the vibration response of its adjacent bay (B), walking forces were applied to bay B followed by time history analyses. The left column group of Fig. 5(b) shows peak acceleration for bay A when subjected to walking on bay A, as obtained from section 3.3, whilst the right column group is for bay B when subjected to walking on bay B. It was found that bay B satisfied human comfort criteria regardless of whether or not dampers were installed on bay A. The addition of dampers on bay A neither adversely affected nor significantly improved the performance of bay B. Of the tuning strategies investigated, the frequency-updated scheme provided the greatest reduction in floor response, being of 56% for bay A and 18% for bay B.

### 4. Final Design and Experimental Evaluation of the Damper System

The numerical study above reveals that the simplest tuning scheme in which all dampers are tuned to the same frequency can be efficient enough to mitigate the vibration of this particular floor to an acceptable level. A distributed multi TMD system consisting of three four-arm dampers was produced and successfully installed.
on the real floor, as depicted in Fig 6. Each damper was dimensioned to have a natural frequency of about 6.2 Hz and damping ratio of around 5%. In fact, minor variations in the dynamic characteristics between different dampers can be expected because of tolerances in their manufacture. The TMD system is very compact with an overall depth of 140 mm and total weight of 280 kg which includes twelve sandwich beams, concentrated end masses, and supports. The system was easily fitted within the false floor cavity on top of the concrete slab. Neither architectural nor structural modifications of the floor were needed.

Physical walking tests performed on the damper-fitted floor revealed an acceleration response of 0.3-0.4% g, which is well within the acceptable range and about 40% lower than the level of 0.5-0.7% g measured on the floor without dampers. A typical measured acceleration history due to walking on the floor with dampers is shown in Fig. 7(a). Furthermore, a series of tests using an electrodynamic shaker was conducted. The shaker generated sinusoidal excitations with a forcing frequency band of 5-7 Hz that covered the natural frequencies of the floor without and with dampers. Fig. 7(b) shows the measured acceleration response to the shaker forcing. It can be seen that the installed TMDs have suppressed the peak floor acceleration by around 40%.

![Dampers installed on the real floor.](image)

**Figure 6:** Dampers installed on the real floor.

![Acceleration history due to walking and shaker tests.](image)

(a) Response to walking, with TMDs  
(b) Response to shaker, without and with TMDs

**Figure 7:** Field test results.
5. Conclusions

A custom-made distributed multi TMD system using viscoelastic material was developed to suppress annoying floor vibrations due to walking activity. The TMD system was numerically predicted to mitigate 48%-56% of the floor response, depending on the number of frequencies to which the dampers were appropriately tuned. The simplest tuning scheme, which involves all dampers being tuned to a single frequency, was found to be efficient enough for the case study floor. Installation of dampers to the troublesome floor bay did not adversely affect the dynamic performance of the adjacent bay. Field tests with human walking and shaker excitations demonstrated a 40% reduction in peak response, resulting in the damper-retrofitted floor being deemed acceptable from a human comfort perspective. The proposed TMD system may be a feasible and non-intrusive solution to rectify problematic vibration levels in existing floors.

References


