TUNED MASS DAMPER POST-INSTALLATION ASSESSMENT FOR THE INTEGRATED OPERATIONS CENTER

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EXECUTIVE SUMMARY

Several complaints about floor vibration on the second floor of the new Integrated Operations Center (IOC) have led IOC management to pursue a vibration mitigation plan. Tuned mass dampers (TMDs) are designed for the affected bay. Twelve identical TMDs were installed on the concrete slab beneath the raised-floor panels on April 12, 2016 and post-installation vibration measurements show that the TMDs reduce the vibration levels in the area by 60%, which is the practical limit for mitigation for this application. Occupants will continue to feel vibration, but at the reduced level. The TMDs do not require maintenance and, in fact, it is preferable to prevent contractors from working around them because the TMDs can be damaged should someone stand on one or damage the flexible damper element.

1. BACKGROUND

A site survey was performed in several bays of the Integrated Operations Center (IOC) on October 19, 2015 at the request of IOC management and the Architect. The vibration survey was initiated to measure and document the floor vibration levels that a few occupants considered annoying. The source of the complaints is illustrated as the green circle in the partial 2nd floor furniture plan of the IOC shown in Figure 1. The yellow shaded region is the 45 ft by 60 ft structural bay—which is typical for the building—supporting the area of interest. Vibration measurements were acquired at each of the numbered locations in the figure, with Location 3 being the closest to the source of the vibration complaints. Vibration data were acquired to document the resonance frequencies of the structure and computer monitors, the vibration levels caused by one person (the author) walking normally across the floor, and the vibration levels near the area of interest caused by normal office activity recorded over a 5-minute period.

Figure 1 Partial IOC 2nd Floor Plan and Measurement Locations

The vibration level for the 5-minute normal office activity period is shown on the right-hand-side of Figure 1. The relatively short observation period (5 minutes) is unlikely to have captured the worst-case vibration experienced over the course of a work shift; however, the observed levels do exceed the vibration limit normally considered to be desirable for an office environment (which is four times higher than the level where people first tend to perceive vibration). The fundamental cause for the high vibration is that a multiple of the normal walking frequency (2 or 3 times) happens to coincide with the fundamental floor structure resonance frequencies. The floor acts like an amplifier that magnifies the walking-induced vibration. The peak vibration occurs around the floor's dominant resonance frequency of 4.9 Hz. There are additional higher-frequency floor vibration modes that are only slightly higher than 4.9 Hz that also contribute; hence, the peak in the curve is slightly shifted to between 5 Hz and 6 Hz. The higher-than-desired vibration levels are a serviceability issue—there are no concerns for structural safety.

The report issued following the vibration survey provided several options for addressing the vibration levels in the area of interest. The first option provided was to simply accept the vibration levels as a natural consequence of the long spans and open space (*i.e.*, very few floor to ceiling partitions); however, IOC management elected to pursue the more active options of replacing the monitor stands to prevent synchronous vibration with the floor system and installing tuned mass dampers as described in the original report:

> Install tuned mass dampers (TMDs) in those bays where vibration is considered to be excessive. Design TMDs to simply sit on the slab under the access floor. **Pro:** Will reduce the vibration levels by 50% to 70% by increasing the effective damping of the floor system. TMDs are not visible or audible to the occupants. **Con:** Higher cost (< $30,000). Will prevent use of cable trays in those areas (2'x2') where

the TMDs are located. Adding TMDs may require the existing structure to be reinforced depending upon the TMD mass.

2. TUNED MASS DAMPER DESIGN

A tuned mass damper has mass, stiffness (a "spring"), and a damper (for energy dissipation). The mass and stiffness, together, determine a TMD resonance frequency that is "tuned" to about 98% of the floor's vibration mode (resonance frequency) most responsible for amplifying the walking-induced vibration. The damper must be selected to provide about 10% of the critical damping level (for typical floor TMD applications) given the TMD mass and stiffness. One of the challenges in TMD design is that the damper element has stiffness properties as well; hence, the element that provides the stiffness must be undersized to accommodate the stiffness provided by the damper to arrive at the required total stiffness. The TMD mass determines the level of vibration mitigation required given the mass of the existing floor system. In theory, any level of vibration mitigation can be provided by increasing the TMD mass; however, each increment in TMD mass provides a smaller increment in mitigation. Also, there is a limit to adding mass (weight) to an existing floor structure before structural reinforcement is required to support the added weight. Practical levels of vibration mitigation tend to fall in the 50% to 70% range for floor-mounted TMDs.

Typical floor systems do not allow just one TMD to be fabricated and installed. The total TMD mass must be divided into several identically-tuned TMDs with a fraction of the total mass. The IOC has a raised access floor to permit placement of electrical cables and is constructed on a 2-ft by 2-ft grid, so it is desirable to have the total TMD mass divided into smaller TMDs that can fit within a 22"×22"×10" volume. Based on this volume constraint, the desire to occupy as few of these "cells" as possible, and the need to achieve the desired total TMD mass, the total TMD mass is divided into twelve (12) 790-lb TMDs designed to fit within a single raised floor cells.

A series of prototype tests were performed at the Halsey Manufacturing machine shop in Denton, where the TMDs were fabricated, to determine the proper size of the damping elements and dimensions of the steel spring element. The fully-assembled prototype TMD is shown on the left-hand-side of Figure 2. Examples of the various damper elements constructed and evaluated during the prototype test effort are shown in the right-hand-side of Figure 2. The damper elements are constructed from one or more layers of nominally 0.25"-thick special damping material (3M/EAR C-1002 ISODAMP thermoplastic). Various combinations of the number of layers and the width and height of each layer were investigated.

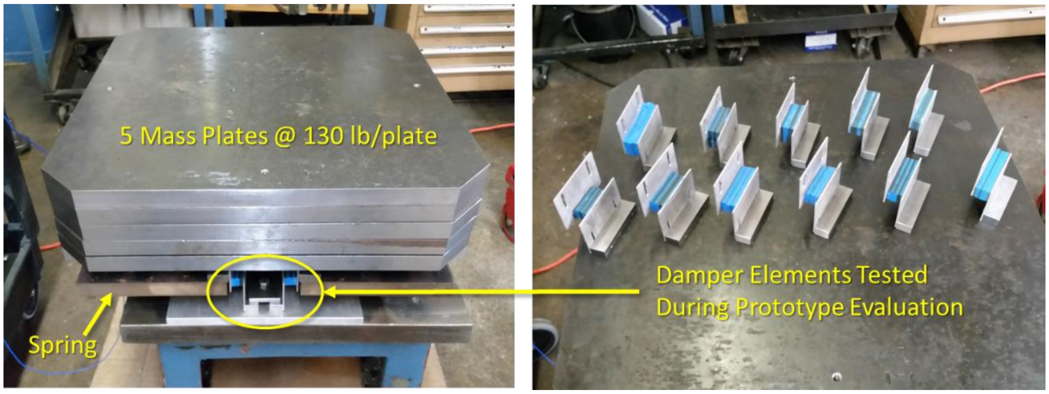

Figure 2 Prototype TMD (Left) and Damper Assemblies Evaluated During Testing (Right)

The complexity of the floor system dynamics plays a significant role in determining TMD effectiveness. TMDs attached to a floor system with minimal two-way stiffness (*e.g.*, a thin non-composite slab on joists) tend to provide better mitigation than TMDs attached to structural systems with a high degree of two-way stiffness (*e.g.*, a thick reinforced concrete slab). The reason for this distinction is that minimal two-way action implies widely-spaced floor mode resonance frequencies, whereas significant two-way action is associated with many closely-spaced resonant modes. A TMD is designed to address a single mode (frequency), so the presence of additional modes with similar frequencies that can be excited by the normal walking pace will not be effectively damped by the TMD. The thick composite slab and steel beam construction of the IOC floor system is more reminiscent of a two-way system than a one-way system from a floor vibration perspective.

Structural dynamics modeling and analysis of the IOC floor system were performed with SAP2000. The structural model is based on the member sizes, slab thickness, material properties and geometry as reflected in the Contract Documents. Unlike routine structural design, it is necessary to explicitly model nonstructural partitions where these are present because they can have a fairly significant effect on the floor modes. The measured resonance frequencies from the original floor vibration survey were used to fine tune the structural floor model. The dominant floor mode shape observed at 4.9 Hz is illustrated in the left-hand-side of Figure 3. The mode shape may be thought of as a single frame of a video of the up-down motion of the floor system. The amplitude of the mode shape illustrated here is grossly exaggerated for illustrative purposes (the actual range of motion is about ±0.005”).

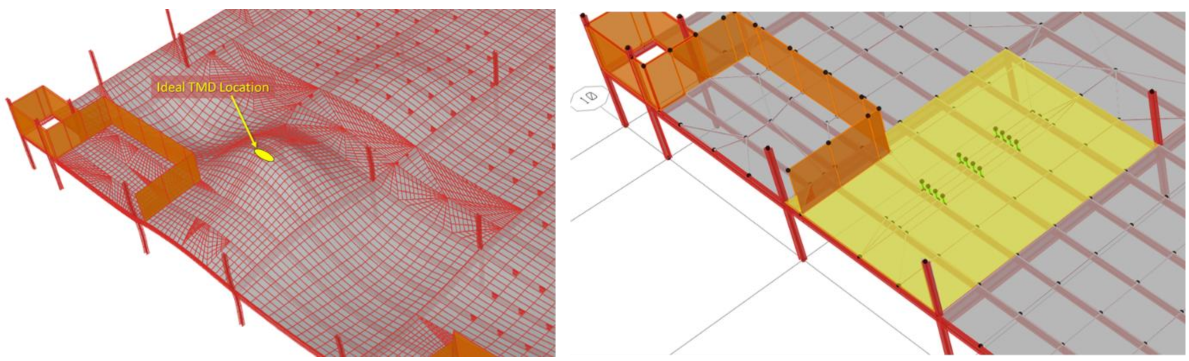

Figure 3 Primary Floor Vibration Mode Shape (Left) and the Optimal Locations of the 12 TMDs (Right)

The mode shape plays a critical role in guiding the placement of the TMDs. In an ideal world, the total TMD mass would be placed at the location on the mode shape with the highest response amplitude (identified in the left-hand-side of Figure 3). TMDs do not act “locally”—they act on a mode of vibration (resonance frequency and mode shape). People feel vibration caused by a single mode in proportion to the amplitude of the mode shape at the location where they sit. Likewise, TMDs respond in proportion to the mode shape amplitude where they are placed—the greater the TMD response, the more effective they are. Maximum benefit from TMDs is achieved if they are placed where the mode shape reaches its maximum amplitude. It is also important to recognize that the analysis-derived mode shapes are only estimates of the true mode shapes.

There are a number of practical issues that prevent the total TMD mass from being placed at a single point. It is physically impossible to place all of the TMD mass (9,500 lb) within a single 22”×22”×10” volume—it simply cannot fit. It is more desirable from structural considerations to place the TMDs directly above the supporting steel beams below the slab. Finally, existing cable trays are present that prevent placement of TMDs in those cells. Based on these various competing considerations, the preferred arrangement of the twelve TMDs is shown in the right-hand-side of Figure 3, with four (4) TMDs placed along the midspan of the three center beams in the bay.

3. INSTALLATION AND PERFORMANCE ASSESSMENT

The 12 TMDs were installed on April 12, 2016 over a period of about 5 hours very close to the locations illustrated in the right-hand-side of Figure 3, subject to access limitations presented by the presence of cable trays and cubicle partition supports that prevented the removal of the floor panel below. The southernmost and middle TMD installation locations are shown in Figure 4. Installation of the TMDs proceeded smoothly and without incident.

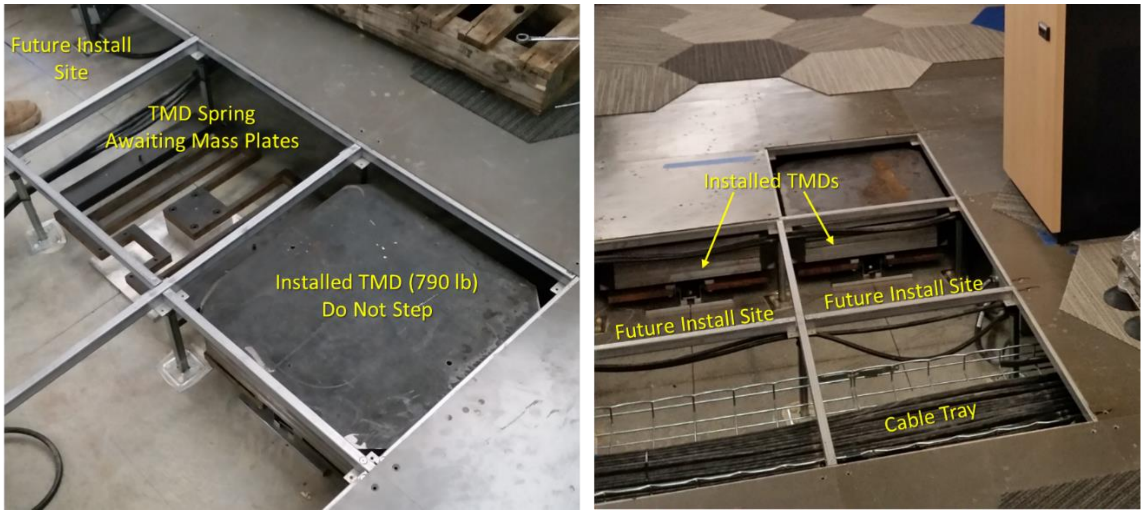

Figure 4 Installed TMDs on the Floor Slab

The floor vibration was recorded at Location 3 (Figure 1) after all of the floor plates and carpet panels were replaced and related construction worker activity ceased. A proper before/after comparison of the vibration environment requires that a consistent source of vibration be used for both tests. Floor vibration data were recorded following TMD installation with one person (the author) walking across the floor exactly as was done during the original site survey on October 19. The floor responses recorded before and after TMD installation are shown in Figure 5.

The amplitude of the “before” curve is lower than the curve shown in the right-hand-side of Figure 1 because the “before” curve in Figure 5 does not include the effect of more than one person walking in the area at the same time, which was the case during the 5-minute period when the higher vibration levels were recorded that produced the curve shown in Figure 1. More people walking in the area necessarily implies higher vibration. The “after” curve was recorded under the same conditions as the “before” curve, so the vibration levels resulting from these two tests represent an apples-to-apples comparison.

TMDs are designed to absorb vibration energy from a single floor vibration mode and have essentially no effect at frequencies below or above the frequency they are tuned to address. The IOC TMDs are designed to address the primary floor vibration mode at 4.9 Hz, so it most appropriate to compare the vibration at 4.9 Hz before the TMDs were installed to the vibration level at 4.9 Hz after the TMDs were installed. Based on this comparison, the response at 4.9 Hz is 60% lower after the TMDs were installed. A 60% reduction in the vibration is midrange between the quoted range of 50% to 70%, and is actually very good considering the relatively high degree of two-way action the IOC floor system permits.

The effect of multiple, closely-spaced floor vibration modes can be seen in Figure 5. Before the TMDs were installed, the peak of the measured vibration response occurred at 4.9 Hz. The TMDs have effectively damped the response of this mode. The peak in the response curve after the TMDs were installed is at about 5.9 Hz, which corresponds to the frequency of a secondary floor resonance observed during the original site survey as shown in Figure 6.

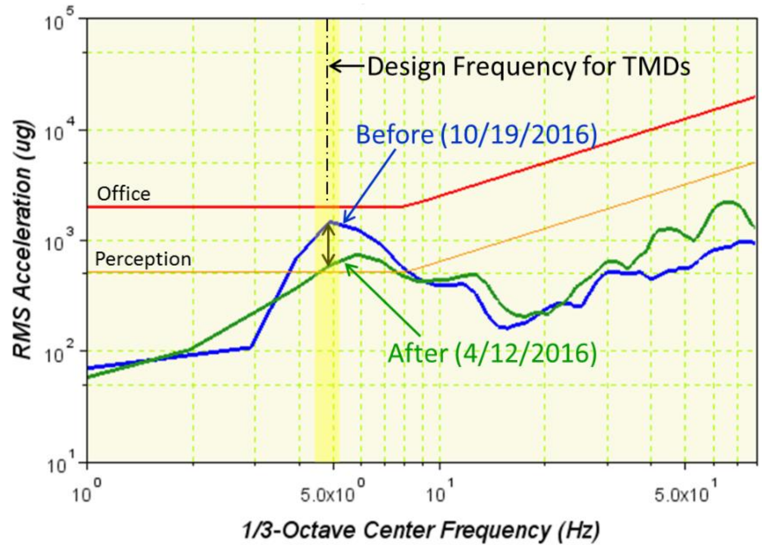

Figure 5 Comparison of Floor Vibration Before and After TMD Installation

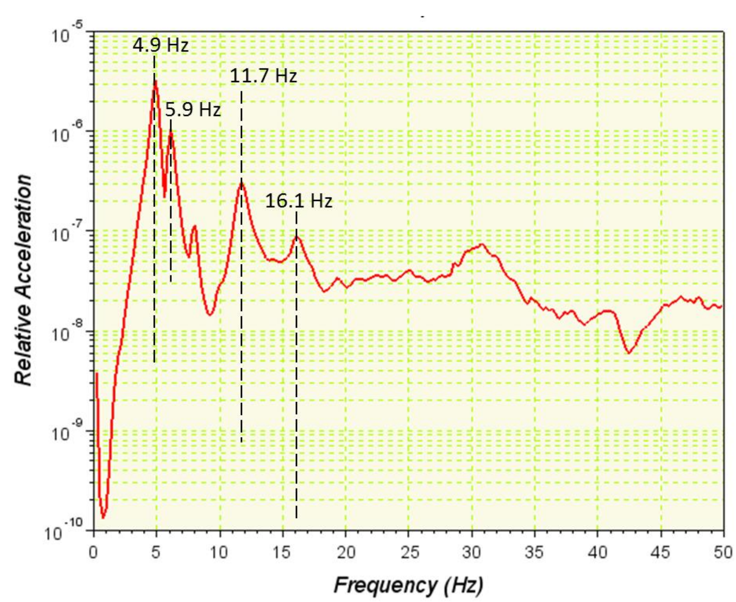

Figure 6 IOC Floor Frequency Response Recorded on October 19, 2016

4. CONCLUSIONS AND RECOMMENDATIONS

The TMDs installed in the IOC are performing as expected and reduce the vibration environment by 60% compared to the vibration level in the area of interest before the TMDs were installed. It is worth noting that vibration levels still exceed the Perception threshold, so occupants will still feel vibration, but at a 60% reduced level. The Perception threshold is an appropriate criterion for surgical suites and hospital patient rooms, but is not applied to typical office buildings (and was not applied to this building when it was originally designed). Nevertheless, occupant expectations also play a significant role in their perception of whether the TMDs are "successful". Occupants most affected by the vibration are seldom brought into the preliminary discussions of what can be done and what can be expected from a vibration mitigation perspective. An occupant may simply hear that "management have agreed address the vibration problem." The occupants might reasonably conclude that they will no longer feel vibration once the mitigation plan is implemented. There is a limit to the vibration mitigation that can be achieved, without radically altering the structure, given the long spans and open sightlines (no interior partitions) in this building.

IOC management and the affected occupants should also understand that once the final planned arrangement of cubicles are installed, there will be more people working in the area of interest with more instances of people walking into, out of, and through the area. In addition, the presence of the new cubicles will tend to channel people along the bay midspan, which enhances the vibration. Occupants may comment on increased vibration and erroneously conclude that the TMDs are not working as well as when they were first installed. In fact, the apparent increase in vibration is caused by an increase in pedestrian traffic activity in the area.

The TMDs do not require maintenance. The mass and stiffness properties of steel do not change with time; however, the flexible spring element may be permanently bent if someone should step on an installed TMD. The damper elements can be affected by extreme changes in temperature, but these extremes will not occur in the conditioned space where the TMDs are installed. The dampers provide optimal performance between 55°F to 105°F. It is preferable to prevent maintenance and electrical contractors from working around the installed TMDs to avoid inadvertently damaging the TMDs.