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Use of Portable Tuned Mass Dampers for Vibration Control of Pedestrian Bridges

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Abstract

Use of high strength materials, optimized computer analysis and design, and tendency of architects to design long-span footbridges has resulted in many cases of such structures having excessive vibrations due to pedestrian movements. One method of correcting the problem is the use of tuned mass dampers (TMDs). A TMD is a device consisting of a spring, mass and a damper that is be placed on or inside a footbridge to counteract its unwanted movements. This research attempts to develop a small portable TMD (PTMDs) from commercially available components to minimize the fabrication and installation costs. This study describes the details of the PTMD and its application on a pedestrian bridge with annoying levels of vibrations created by pedestrians. It attempts to answer the main research question: “Can the developed PTMD be a viable means of correcting vibration problems in pedestrian bridges?” The developed PTMD consists of a weight box with inserted plates, springs and adjustable damper, so that the mass and damper could be easily tuned on site. The PTMD (approximately 130 lbs) was installed in a pedestrian bridge. The bridge’s resonance frequency was measured using an electrodynamic shaker, and a number of accelerometers connected to signal analyzer. The TMD was first roughly tuned to the two modes of vibration by placing steel insert plates into the weight box. It was then placed on the footbridge and after exciting the structure using the shaker, the PTMD was fine-tuned by adjusting smaller insert plates and the damper element. Once the PTMD was tuned, it was locked and the test was repeated using the electrodynamic shaker and an individual walking over the footbridge at the structure resonance frequencies. A computer model of the structure was also created to predict the effectiveness of the PTMD. From this study it was found that Portable Tuned Mass Dampers (PTMDs) can provide an effective means of alleviating the excessive movements of footbridges at a lower cost and higher convenience to users. Even though the PTMD had only a very small mass compared the total mass of the structure, it significantly reduced the vibration generated by a shaker and a pedestrian. From this study is was also found that the changes in the natural frequency of structure due to temperature variations can present a challenge as this may cause the off-tuning of the PTMD and prevent optimal operation. It was concluded that for such cases, Multiple Portable TMDs (MPTMDs) should be used for which each PTMD can be tuned to a different frequency within the range resulted from temperature changes.

Keywords: Vibration, Portable Tuned Mass Damper, Footbridge

1. Introduction and Background

1.1 Background And Intent

All structures have an innate *damping* property created by the friction within their joints and their connections to each other and the ground. Different materials also have different inherent damping. The *stiffness* of an object allows it to resist deformation when a force is exerted on it. If a structure is made of massive materials with high stiffness values, it is unlikely that it will suffer from vibrational issues. When a structure begins to vibrate it will be most excited at particular *natural frequencies* based on its structural characteristics, mass and stiffness. Each of these frequencies correspond to a mode of vibration. They are identified by the specific *mode shapes* a structure will take at a natural frequency as it is vibrating. If the frequency of the force exerted on a structure get close to its natural frequency, the structure will enter what is called *resonance*. This means the structure may continue vibrating until structural failure if the force is great enough. The resonance frequency is close to the natural frequency for a lightly damped structure. A tuned mass damper (TMD) counteracts the movements of the structure at resonance by moving in the opposite direction. A TMD, typically having a much smaller mass than the structure, will vibrate with a larger amplitude than the structure in order to cause a reduction in the structural response.

To properly reduce structural vibration with a TMD, the device must be tuned to a specific mode of the vibration of the structure. This is done by setting the TMD's natural frequency and damping ratio to specific values so that it can counteract the vibrations of the structure. This process results in the optimal performance of the TMD. If the natural frequency and the damping ratio of the TMD are not set to these optimal levels, it does not perform very effectively.

1.2 Precedents

In an architectural structure that does not have enough internal damping and as a result causes the users to feel perceptible, uncomfortable vibrations, a TMD can be a viable option to fix the problem. A TMD effectively reduces vibration once it is tuned to the structure's natural frequency of a specific mode, by setting the TMD's natural frequency and damping ratio to predetermined values. The first application of TMDs to an engineering problem was presented by Frahm [1]. He used undamped vibration absorbers for reducing the rolling motion of the ship and for the reduction in vibration of the hull of the ship. In their writings, Ormondroyd and Den Hartog [2], Brock [3], and Den Hartog[4] contributed significantly to the theory of vibration reduction using TMDs . Since then, TMDs have been used for vibration reduction of various mechanical and structural systems. Different configurations of TMDs have been used for floor vibration control. Allen and Swallow used TMDs in the form of a steel box, loaded with concrete blocks and supported at each corner by a commercial compression spring and housing to reduce floor vibrations[5]. To reduce the excessive vibrations of a footbridge due to walking Matsumoto used steel boxes containing steel plates suspended from springs [6]. Allen and Pernica devised a simple TMD consisting of a layered system of wooden planks with weights on top for the reduction of the excessive vibrations caused by a subject walking [7]. One familiar example of the use of TMDs is the Millennium Bridge over the Thames River in London. It was closed for 18 months for repairs and installation of large TMDs to decrease the vibration caused by the pedestrians walking across it. The TMDs successfully created enough damping to reduce the amount of perceptible vibration [8].

2. Methodology

2.1 Analytical Explanation

In Figure 5 a model of a structure and PTMD is represented by mass (M_s), stiffness (K_s), and damping (C_s) of the structure and the mass (m_T), stiffness (k_T), and damping (c_T) Of the TMD. X_s and x_T represent the movement of the structure and TMD, respectively. F is the applied dynamic force on the structure. In order to predict what amount of vibrational reduction can be expected from the PTMD on the footbridge, an analytical study was conducted. The response of a structure with a PTMD to a dynamic force can be represented by the Equation 1.

ω_s=Natural Frequency of Structure (M_s)

ω_T= Natural Frequency of TMD (m_T)

$f = \omega_T/\omega_s$ = Frequency Ratio

$\mu = m_T/M_s$= Mass Ratio

$g = \omega/\omega_s$= Force Frequency Ratio

$K_s=M_s*\omega_s^2$= Stiffness of the structure

$k_T=m_T*\omega_T^2$= Stiffness of the TMD

$C_s=2*M_s*\omega_s*\xi_s$ = Damping of the structure

$c_T=2*m_T*\omega_T*\xi_T$= Damping of the TMD

$\xi_s = C_s / 2 * M_S * \omega_s$ = Damping Ratio of the Structure
$\xi_T = c_T / 2 * m_T * \omega_T$ = Damping Ratio of the TMD

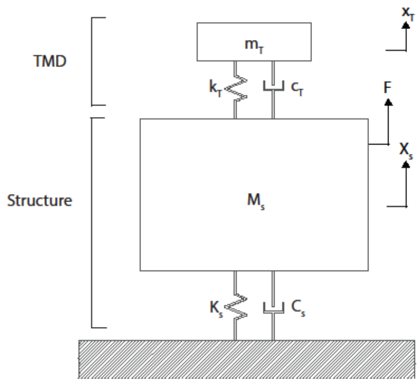

Figure 1. model of the structure with TMD

Equation 1.

$$\left|\frac{\ddot{X}_s}{\frac{F}{M_s}}\right| = g^2\sqrt{\frac{(f^2-g^2)^2+(2\xi_2 fg)^2}{[(1-g^2)(f^2-g^2)-g^2 f(\mu f+4\xi_1\xi_2)]^2+4g^2[\xi_2 f(1-g^2-g^2\mu)+\xi_1(f^2-g^2)]^2}}$$

To find the footbridge response with optimal PTMD parameters, the tuning parameters, ξ_T damping ratio of the PTMD, and f, frequency ratio, were found for the footbridges structure. By using the known parameters of the footbridge, the mass ratio (μ) and the damping ratio of the structure (ξ_S), as inputs into an optimization software the optimization routine was executed. This routine minimizes the maximum amplitude of the structures response, $\ddot{X}_s$, by finding the optimum values of f and ξ_T. Then all known values and optimized values were input into Equation 1. The footbridge had two modes, (torsional and bending modes), mode one and two respectively, that could be excited by the low level of vibration caused by foot traffic. The parameters used for the mode one response were μ=0.066, f=0.97, ξ_T =0.158, and ξ_s =0.00875. For mode two, the parameters were μ=0.004, f =0.998, ξ_T =0.0389, ξ_s =0.00774. The floor responses, R, were plotted using the PTMD mass ratio, μ, and then with μ=0 because this represents the response without the PTMD. Each mode was graphed separately and can be seen in figure 2.

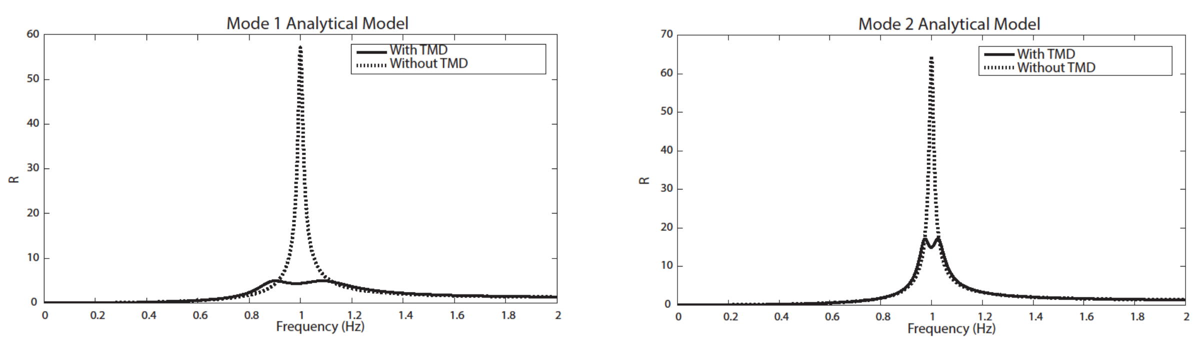

Figure 2. analytical model of the first and second mode response to vibration

In these models the percentage reduction from the response without TMD to the response with TMD is around 90% for the first mode and around 70% for the second mode. This is found by dividing the response with TMD peak value by the response without TMD peak value and subtracting from 1. This is an ideal situation, which does not account for abnormalities in the structure or the imperfections of tuning the PTMD. This result would be the desired outcome of the test on the footbridge since it shows the optimal reduction of vibration possible. This will be attempted by altering the PTMDs parameters to be as similar as possible to the optimized values in these analytical studies.

2.2 Field Testing

This paper introduces Portable Tuned Mass Damper (PTMD) used for reducing the vibrations of a footbridge. It presents the details of the tests conducted and the effectiveness of the device in reducing vibration created by an electrodynamic shaker and pedestrian movements. The developed PTMD consists of a weight box with inserted plates, springs and adjustable damper, so that the frequency ratio and the damping ratio of the PTMD could be easily adjusted on site. By altering the number of plates in the PTMD and the damping force of the adjustable damper, the PTMD can be set to the proper tuning parameters. The PTMD (approximately 130 lbs total) was placed on a pedestrian bridge located in Clifton Forge, Virginia. The footbridge had a total length of 97 feet with an unsupported span of 47 feet. As shown in Figure 3, a section of the bridge and its structural components. The footbridge consisted of three main segments (Figure 5): the ramp, the hub and the bridge which were prefabricated, shipped to site, bolted together, and anchored to the end supports. As shown in the Figure 3, the bridge is 5 feet wide. The deck is made of ¾ in thick wood decking supported by 2 ½ in x 6 ¾ in wood joists, which were nailed to the 1 ½ in x 6 in rim joists bolted to the main structural steel sections (W8x28, W8x24, and W6x20). The slender structure was designed to resist static loads. The architectural design limited the use of larger structural sections, resulting in excessive vibration as pedestrians crossed the footbridge [9].

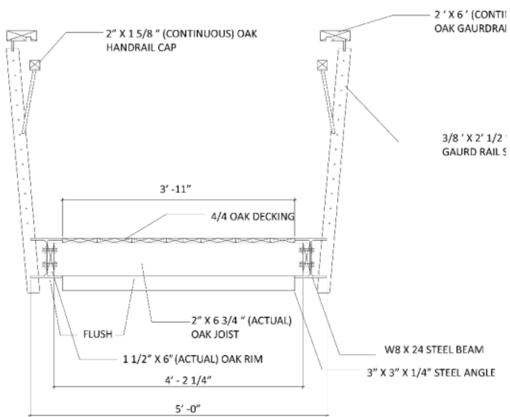

Figure 3. Transverse Section of the Footbridge showing structural components

Figure 4. Photograph of PTMD (Left) and Shaker (Right)

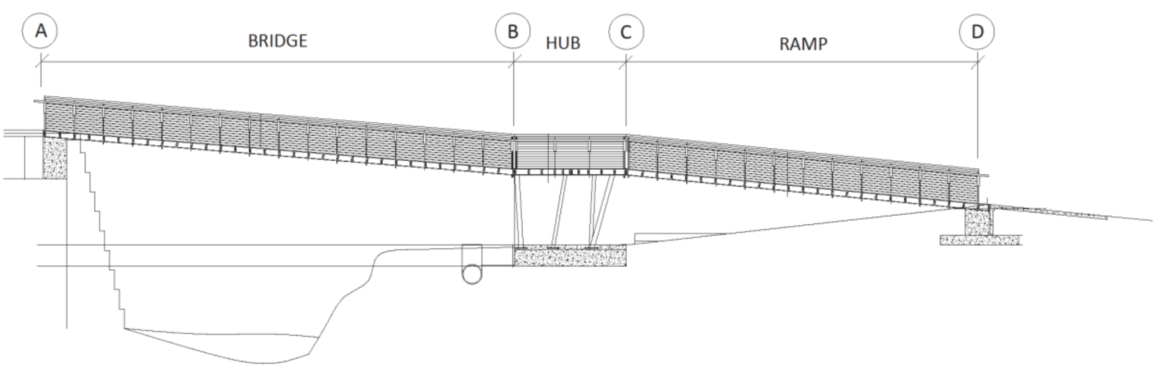

Figure 5. side view of foot bridge with three sections labeled

The test set up comprised of 16 accelerometers (PCB 393C and PCB 393B), an electrodynamic shaker (APS 113) and the developed PTMD (Figure 4) that was fabricated for testing. As can be seen in Figure 6, thirteen of the accelerometers were placed along the two sides of the footbridge. These were channels 3-15. Channel 1 was connected to the force plate, channel 2 to the armature of the shaker, and channel 16 to the top of the PTMD weight box. The PTMD and the shaker were placed next to channel 7, which was approximately mid-span of the bridge segment, as shown in Figure 4.

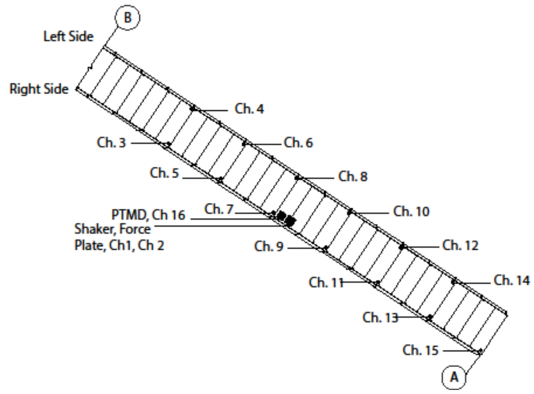

Figure 6. test setup for the vibrational tests conducted on the bridge section of the footbridge

The footbridge's resonance frequency was measured using the shaker and the sixteen accelerometers which were connected to a signal analyzer. This test confirmed that the bridge had two main resonance frequencies that could be excited by pedestrians. These were the torsional and bending modes and occur around 3.75 Hz and 5 Hz, respectively. The PTMD had to be tuned to these particular frequencies to be the most effective. The PTMD was roughly tuned to the first mode while placed on the ground off of the footbridge, by placing steel plates into the weight box. It was moved onto the footbridge to begin testing. The PTMD was locked and the structure was excited using the shaker, to measure the bridge's dynamic properties and dynamic response without the PTMD operating. Then, the PTMD was unlocked and then a number of tests were conducted in an attempt to fine tune the PTMD, each time adjusting either the damper or the number of plates to improve the outcome. The dynamic response of the bridge was recorded for each test by the signal analyzer connected to the accelerometers and force plate. The PTMD was then tuned to the second natural frequency, the bending mode, and the same routine was followed. A walk test was also conducted, in which an individual crossed the footbridge at different frequencies to excite it while the PTMD was locked and unlocked. The subjects pace was synchronized by a metronome. All data was recorded by the signal analyzer to be interpreted later and each test was photographed to have a record of the tuning parameters of the PTMD for each test.

3. Data

3.1 Shaker Test Results

Figure 8 shows two FRFs (frequency response functions) from the tests in which the first mode of vibration was targeted, around 3.75 Hz. The FRF is the ratio of the FFT of the output (accelerometers) to the FFT of the input (force plate). These two responses are from channels 7 and 8 and are representative of the rest of the responses. The solid line on each graph represents the dynamic response of the bridge to the shaker when the PTMD was locked. The three other dotted and dashed lines show the best three responses, Response A, B and C, while the PTMD was being fine-tuned.

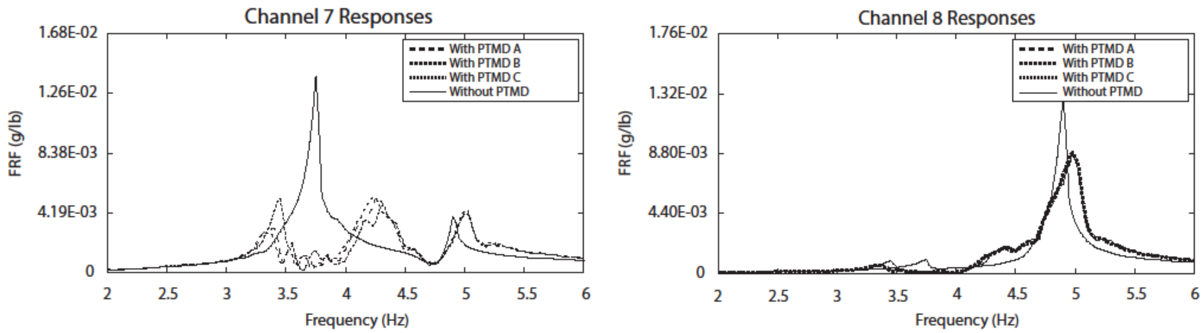

Figure 7. FRF responses from channels 7 and 8 in the first mode tests

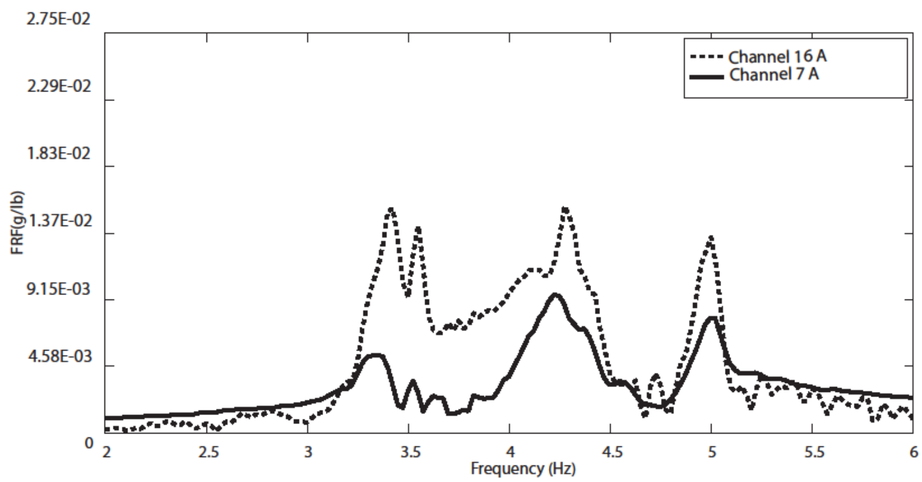

Figure 8. FRF responses from channel 16 and channel 7 when PTMD is tuned to the first mode

To check the efficiency of the PTMD in reducing the first mode vibration, Figure 8 shows the FRF at the drive point (Channel 7) and of the PTMD mass (Channel 16) for Test A. As expected, when the PTMD was placed on the structure and tuned to the first mode, the first mode resonance frequency of the footbridge at 3.75 Hz was split into two frequencies at around 3.3 Hz and 4.2 Hz as shown in Figure 8. As mentioned earlier, the PTMD mass is expected to have much larger accelerations than the structure in order to effectively counteract the footbridge vibrations. This is evident from Figure 8, as the ratio of the PTMD response to floor response at 3.3 Hz is about 3 and at 4.2 Hz is about 1.75.

As can be noted from Figure 7, there is a large difference between the response from the right side of the bridge, (shown by accelerometer channel 7) and the left side of the bridge (shown by accelerometer channel 8). In the channel 7 responses, vibration is being reduced for the first mode, around 3.75 Hz, when the PTMD was unlocked as was intended. This response appears to be similar in shape to Figure 2, the analytical model of the bridge's response. The PTMD has successfully dampened vibration, causing the main peak to split into two smaller peaks even though the reduction is not as much as predicted analytically. However, Channel 8 does not show a significant response contribution at the first mode when the PTMD was locked. This is due to the footbridge mode shape, which is clearly not symmetric.

Table 1. first mode test A response reduction values

Test A			
Channel	TMD locked (g/lb)	Response A (g/lb)	Percentage Reduction
7	1.37E-02	5.30E-03	61%
8	1.29E-02	8.40E-03	35%

Table 1 shows the results obtained from Test A, shown in Figure 7. The reduction percentage was obtained by dividing peak FRF responses from the "Response A" test, (PTMD unlocked) between 3.2- 4.5 Hz, by the "PTMD locked" value around 3.75 Hz, subtracting that value from 1 and multiplying by 100 to get the final percentage. This was done for all of the channels along the bridge, 3- 14.

Figure 9 shows the two FRFs from the tests in which the PTMD was tuned to the second mode, the bending mode. The second mode resonance frequency was around 5 Hz. The first mode, at 3.75 Hz, barely decreased at all because the PTMD was not tuned to that frequency. Once again because of asymmetric mode shapes, the results from opposite sides of the bridge varied considerably. The PTMD was effective at decreasing vibration in all tests, but not the extent as the first mode tuning tests. There is a frequency around 5.3 Hz on both tests in which the FRF response increases. This is a result of the PTMD action, but not effectively enough to split the initial peak at 5 Hz to two smaller ones, as can be seen in Figure 2, the optimized analytical solution. This was a sign that the PTMD was not as well tuned to the second mode as it was in the first mode tests.

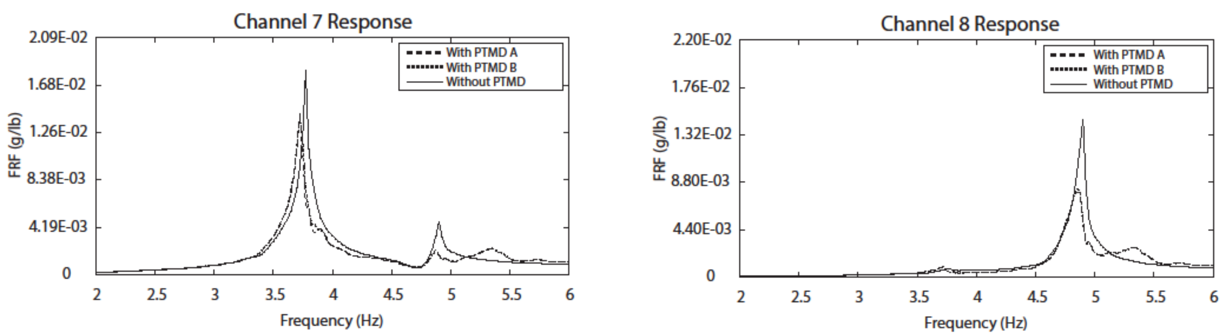

Figure 9. FRF responses from channels 7 and 8 in the second mode tests

To check the efficiency of the PTMD in reducing the second mode vibration, Figure 10 shows the FRF at the drive point (Channel 7) and on the PTMD mass (Channel 16). Similar to the effect shown in Figure 9, when the PTMD was placed on the structure and tuned to the second mode, the second mode resonance frequency of the footbridge at 5 Hz was split into two frequencies at around 4.9 Hz and 5.4 Hz. As stated before, the PTMD mass is expected to have much larger accelerations than the structure in order to effectively counteract the footbridge vibrations. This is evident from Figure 10, as the ratio of the PTMD response to floor response at 4.9 Hz is about 10 and at 5.4 Hz is about 15.

Table 2 shows the peak response from various channels when the PTMD was locked and unlocked (Test A) along with the percentages of the peak response reductions for Mode 2. The computation was conducted in the same way as for the first mode. In this test the PTMD was altered to decrease vibration at 5 Hz, the second (bending) mode of the bridge. The reduction percentages vary from 45% to 55% depending on the location of the accelerometer. The left and right side were more similar in the second mode reduction than the first mode reduction values.

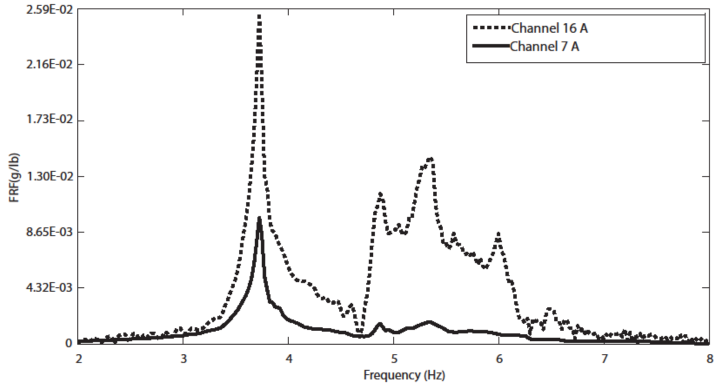

Figure 10. FRF responses from channel 16 and channel 7 when PTMD is tuned to the second mode

Table 2. Second mode test A response reduction values

Test A			
Channel	PTMD Locked (g/lb)	Response A (g/lb)	Percentage Reduction
7	4.67E-03	2.12E-03	55%
8	1.47E-02	7.87E-03	46%

3.2 Walk Test Results

Figure 11 shows the results of one of the walk tests conducted. In these tests an individual crossed the footbridge at different speeds, correlating to the frequencies at which the bridge would be most excited. In the test shown in Figure 11, the individual jogged across the bridge at 225 SPM (steps per minute) using a metronome to keep on pace. This

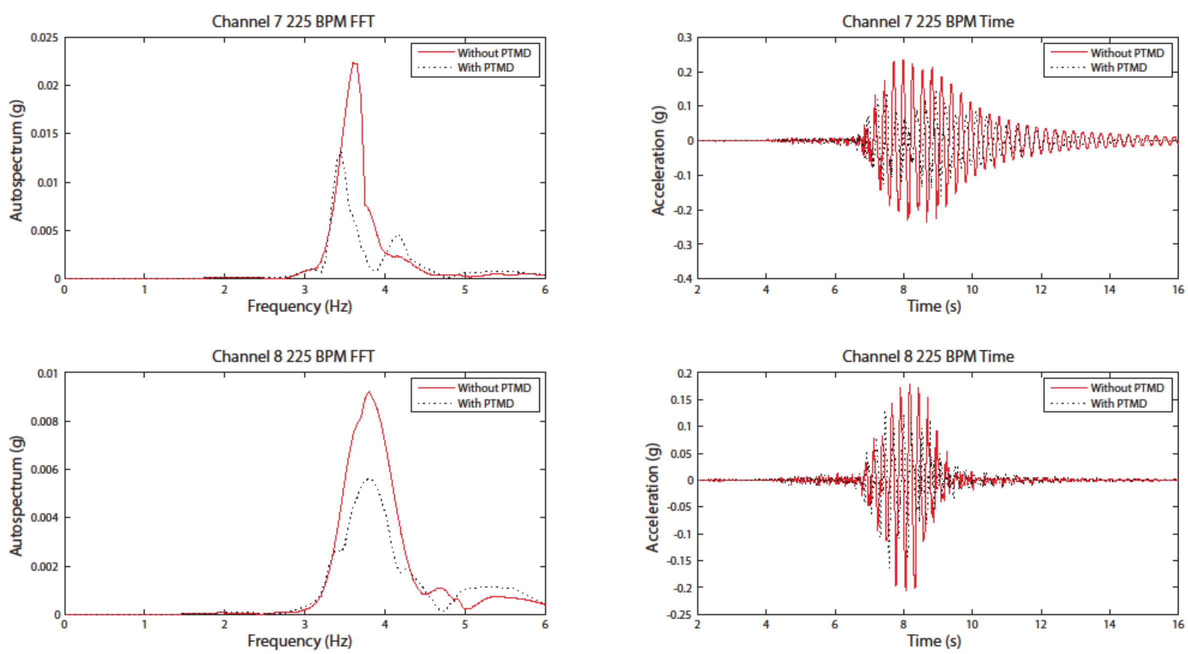

Figure 11. Autopectrum and time responses from 225 walk tests channels 7 and 8

vibration translates to the natural frequency of bridge, 3.75 Hz, at which it is most excited. In these results, the autospectrum and time response were used to analyze the data. Channel 16 shows that the PTMD had a larger acceleration that the floor response. In Figure 12 it can be seen that the ratio of the PTMD response to the floor response was about 2.

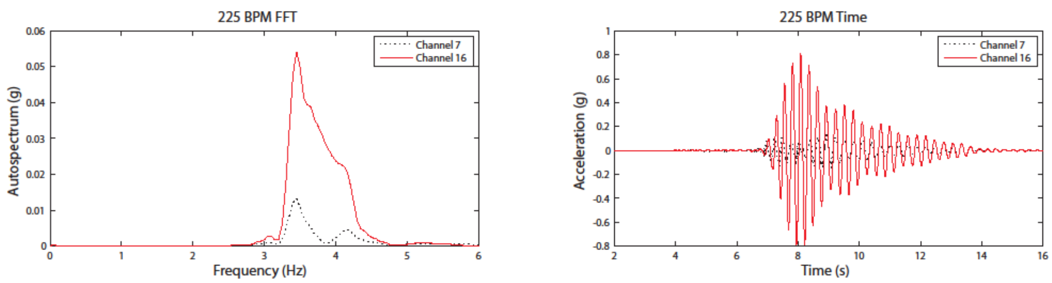

Figure 12. Autospectrum and time response from 225 walk tests channel 16

The vibrational reduction was between 30% and 40% as calculated and shown in Table 3. The reduction was calculated using the FFT response values. This reduction shows that the PTMD can reduce vibrations when a human crossed the footbridge.

Table 3. walk test 225 BPM FFT reduction values

Channel	PTMD Locked (g/lb)	PTMD Unlocked(g/lb)	Percentage Reduction
7	2.26E-02	1.32E-02	42%
8	8.94E-03	5.37E-03	40%

4. Discussion of Results

In a graphical and quantitative comparison of the PTMD while locked and unlocked on a footbridge, it is shown that the device is effective in reducing vibration when excited by a shaker or someone crossing the structure. The reduction varied depending on the mode to which the PTMD was tuned. Although the footbridge vibration reduction after using the PTMD was around 60%, this could be increased if the system had been at optimal values. The analytically optimized system shown in Figure 2 shows that the reduction levels of around 90% and 70% for the first and second modes, respectively, could be reached. This could be caused by the difficulty of tuning the PTMD to the exact frequency ratio and damping ratio needed to produce that ideal curve. The approximation used for determining the mass ratio and structure's damping ratio may have prevented the PTMD from operating ideally. In addition, throughout the day the natural frequency of the footbridge changed slightly due to temperature changes which affected the change in stiffness of structure. Initially the natural frequency of the bridge was 3.93 Hz for the first mode and 4.78 Hz for the second mode. It was then tested right before the PTMD was tuned and the frequencies were 3.78 Hz and 4.9 Hz. After the tuning was completed the frequencies had changed again slightly to 3.75 Hz and 4.9 Hz. Though there was not much change between the time the PTMD was tuned and then tested, the overall change from 3.93 Hz to 3.78 Hz shows the possibility of off tuning throughout the day. To mediate these inaccuracies, several PTMDs could be placed along both sides of the bridge and tuned to slightly different frequencies so to always have at least one device that was working at its optimal performance. In this case, one could expect that the bridge's vibration would be reduced in any situation, regardless of the temperature variations.

5. Conclusion

A PTMD device has the capability to reduce vibration of an unsupported structure such as the slender footbridge in this case study. PTMDs provide the opportunity to reduce the retrofit costs needed for a structure with excessive vibration due to human movements. A PTMD can be moved, installed and tuned easily, reducing the complications involved with larger devices.

6. Acknowledgements

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