MODULAR TUNED MASS DAMPER UNITS FOR THE SPRING MOUNTAIN ROAD PEDESTRIAN BRIDGES

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ABSTRACT

Modern pedestrian bridges tend to be long and slender in form, usually leading to a structural design with relatively low frequency primary modes of vibration. This type of structure can be excited to a nearly resonant response by various types of synchronized crowd activities and added damping is often required to prevent excessive structural motions and loadings. The three Spring Mountain Road pedestrian bridges use unique Modular Tuned Mass Dampers to provide the desired added damping.

INTRODUCTION

The three Spring Mountain Road pedestrian bridges are located in Las Vegas, Nevada and were constructed for the Department of Public Works of Clark County, Nevada in 2005. The site is on the famous Las Vegas "Strip," and new construction in the immediate area was expected to substantially increase pedestrian traffic across the intersections associated with each bridge. Total daily traffic on the bridges was expected to be more than 150,000 people. Two mega resorts were being constructed at the site; the Wynn Las Vegas ($2.5 billion) and the Palazzo-Venetian ($1.7 billion). Existing attractions at the site are the Treasure Island Hotel and Casino (2,700+ rooms/suites), and the Fashion Show Mall (200 stores, 2 million sq. ft.).

Figure 1 is an aerial view of the site. The 157 ft. span West Bridge goes from Treasure Island to the Fashion Show Mall. The 143 ft. span North Bridge goes from Fashion Show Mall to Wynn Las Vegas, and the 165 ft. span East Bridge from Wynn Las Vegas to the Palazzo-Venetian. The three bridges feature an extremely slender steel girder structural section, only 54 inches in total depth, with concrete towers at each end of the main span. The resulting design produced calculated first and second mode vertical frequencies ranging from 1.48 Hz to 1.9 Hz for the three bridges.

In comparison, the Millennium pedestrian bridge in London, England had frequencies in the 0.5 Hz to 1.1 Hz range, and when originally opened exhibited unacceptable high deflections when excited by crowds of pedestrians, as reported by Taylor [1]. Although the Spring Mountain Road pedestrian bridges had appreciably higher frequencies, these still are well within the bandwidth generated by human walking motions. The Fashion Show Mall has music playing much of time, with the potential for groups of people dancing on the bridges. In addition, an exuberant (or rowdy) crowd might be expected to repeatedly jump while on the bridge, and this motion also could be generated in the frequency bandwidth of interest. The major concern was the so-called "synchronized foot-fall" effect documented on the Millennium Bridge by Dallard [2] whereby crowds of only 50-100 people would generate biodynamic feedback between the bridge and people. When this occurs, seemingly unrelated persons walking randomly on the bridge will synchronize their motions within a short period of time, thus causing an uncontrolled resonant response in the structure.

In the fully resonant state, the amplification factor for a simple single degree of freedom (SDOF) oscillator is:

$$\text{Amplification factor} = \frac{X_r}{X_0} = \frac{1}{2\zeta}$$

Where X_r = resonant amplitude
X_0 = zero frequency deflection of the spring-mass system under the action of a steady force
ζ = damping factor, $C/C_{critical}$

Figure 2 lists for reference typical damping factor values and resulting amplification factors for SDOF systems.

Figure 1 - Aerial View of Spring Mountain Road Site

Damping Factor (% of Critical)	Amplification Factor (At Resonance, SDOF System)
0.5%	100
1.0%	50
2.0%	25
5.0%	10
10.0%	5
20.0%	2.5
30.0%	1.66

Figure 2 - Representative Amplification Factors

Although Figure 2 is for SDOF examples, actual testing with up to 2,000 people on the London Millennium Bridge both with and without 20% added fluid damping provided test results within 10% of the above values. It was postulated that since the primary modes of the Millennium Bridge were closely spaced, the bridge response would be similar to the SDOF case. The testing substantiated this.

The design of the Spring Mountain pedestrian bridges required extensive testing and computer modeling to determine the amount of added damping required. From a conservative structural engineering viewpoint, the most effective approach would be to simply add 20% fluid damping using conventional double acting dampers, the same as used on the Millennium Bridge. This would eliminate nearly all of the problems associated with an amplified response. Unfortunately, this was not possible due to the basic design of the bridges and their close clearance to the roadways underneath. Clearance was only 17.5 ft. and the roadways were expected to accommodate both cars and trucks. A conventional damper, much like an automotive shock absorber, must be attached at either end such that bridge motion would push and pull on the damper. Given the design of the bridges this would involve placing the dampers at an angle underneath the bridge, or in chevron bracing elements, spanning from the main girders to the support towers (or a similar foundation or ground node). Unfortunately the dampers would then be limiting the overall clearance to the roadway. This approach was therefore discarded as not being practical or cost effective. An alternate approach was to use multiple tuned mass dampers, essentially spring-mass oscillators moving in opposition to the bridge motion, thus providing an equivalent damping effect. A Tuned Mass Damper requires only one connection to the moving bridge structure, and could be placed within the structure so as not to impact roadway clearance.

TUNED MASS DAMPERS (TMD)

A Tuned Mass Damper is essentially a simple spring mass oscillator sized to move out-of-phase with dynamic structural deflection, thus suppressing motion. In comparison, a direct acting conventional damper, typically of the fluid type, reduces motion by converting mechanical energy to thermal energy and dissipating the thermal energy by the transport processes of conduction, convection, and radiation. The performance of a TMD is usually expressed as an equivalent viscous damping ratio. If used to suppress continuous vibration motion, the TMD need only consist of a mass and spring. However, if the vibration input is not continuous, a fluid damper is normally incorporated into the TMD to allow the TMD’s motion to quickly decay when the vibration input stops. In general, the higher the mass of the TMD’s moving element, the higher the damping effect. However, there are practical limits to the mass of the TMD; if it becomes too large it will drive the entire structural design. In general, the total weight of the TMD moving elements are held to less than 10% of the weight of the effective dynamic mass to be controlled for an effective real world design.

Den Hartog [3], Klembczyk and Breukelman [4] and others have developed the background theory for a TMD and its equivalent viscous damping ratio when it is attached to a structure. Figure 3 is a graph of the effective damping for a TMD at various mass ratios typically found cost-effective for bridges and buildings. Figure 3 also reveals the need for the TMD to be very carefully tuned to the proper frequency to provide a completely out-of-phase response.

As part of Taylor Devices’ effort on this project, an extensive analysis was performed on the potential inputs to the bridge from synchronized crowd motions, as well as atypical events such as groups of people jumping rhythmically on the bridges at resonant frequencies. The resultant loadings were assessed at various damping levels and compared to structural design criteria provided by the owner and the engineer of record for the project. For calculation purposes, structural damping inherent in the bridge was assumed to be in the range of 1% critical. Subsequent verification testing on the as-built structure showed actual structural damping was somewhat lower, measured at 0.65% to 0.8%, thus requiring that an additional loading assessment study be performed.

The final results from this effort determined that the optimum mass ratio for the TMDs was 6%, providing equivalent added damping in the range of 6.5% critical. When added to the 0.65% - 0.8% structural damping, the resulting total damping in the structure was calculated to be approximately 7.25%.

Provisions were made to accommodate six individual TMDs on each bridge to achieve the desired mass ratio, with the ability to add more TMDs should the actual in-service response of the bridges require additional added damping.

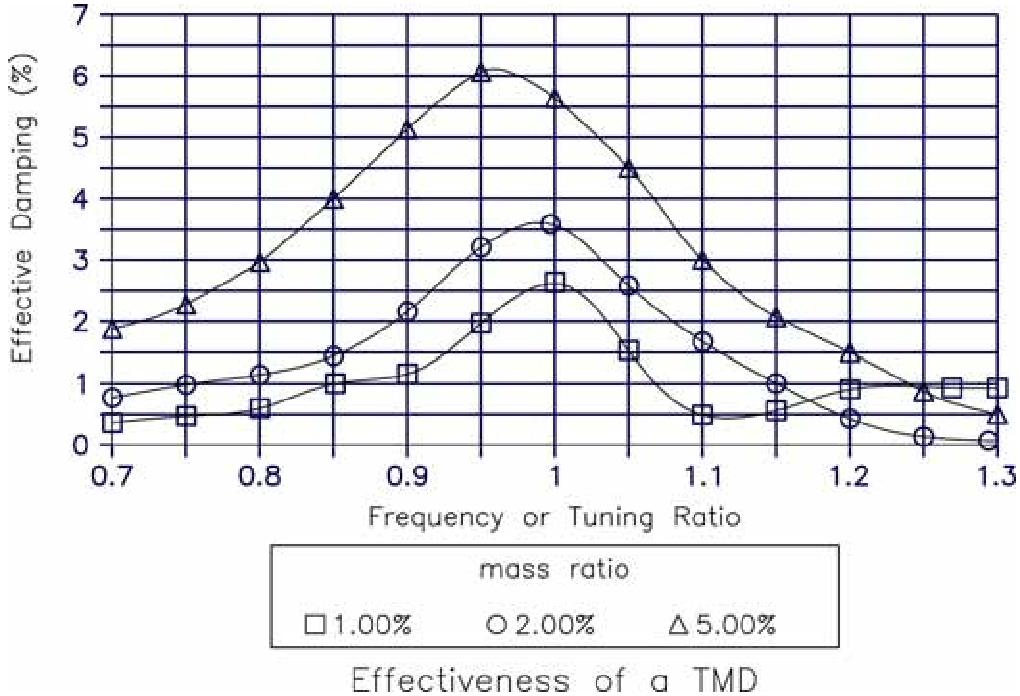


Figure 3 - TMD Equivalent Damping

DESIGN ELEMENTS OF THE SPRING MOUNTAIN TMD UNITS

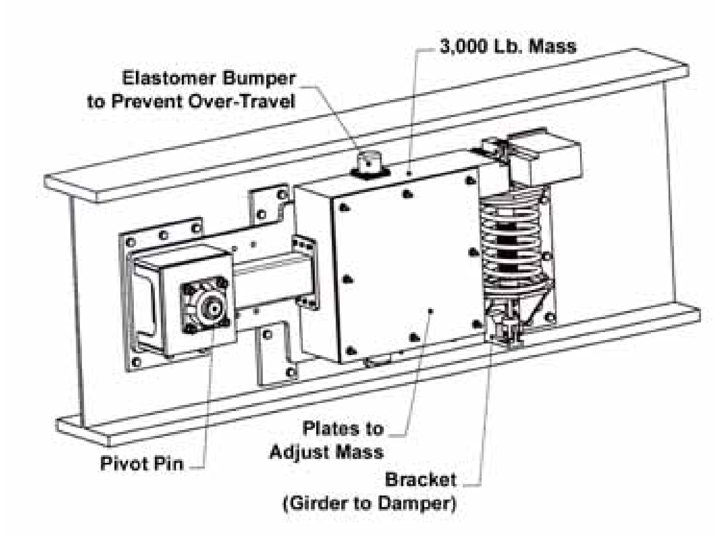
It was desired to mount the TMD units to the interior sides of the main girder webs. Total allowable TMD width was 13 inches, allowing the TMD to be relatively hidden from view and protected by the girder flange. Each TMD required a moving block mass, baselined at 3,000 lb. deadweight. Each block mass is supported by a coil spring and controlled by a parallel fluid viscous damper, one damper per mass, providing 20% critical damping to the TMD mass. End of travel snubbers were required which could be impacted by the TMD mass in either the upward and downward directions in the event of overload.

Since the TMDs might require field tuning, provisions had to be made to quickly alter the mass block, change the springs, or adjust/change the damper's output. Because the TMD was to be totally modular, all design elements had to be attached to a single mounting plate, which would attach to the girder web.

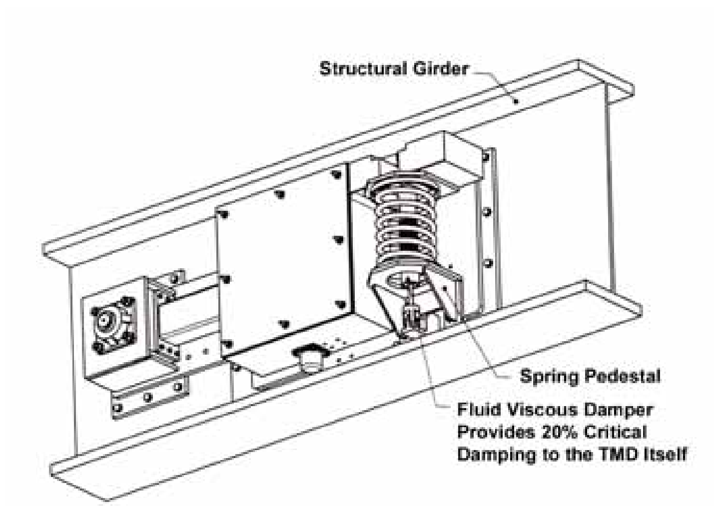
Two types of general arrangements were considered. The first was a style where the block mass traveled only in the vertical direction, supported by flexural elements. The second involved mounting the mass to a rotating arm, allowing the basic motion of the mass to be rotational. The total vertical motion was anticipated as being less than +/- 3.5 inches, therefore if the rotating arm was relatively long then the mass would move essentially in the vertical direction, since the angle traversed would be small.

Evaluation of the two potential general arrangements within the context of the bridge design parameters indicated that the design using the rotating arm to support the mass was clearly superior. The baseline spring rate was 500 lb/in. with an associated fluid-damping constant of 14 lb-sec/in. for each TMD. Note that these are component parameters and are adjusted due to the TMD geometry to compensate for the component mounting radius not being coincident with the radius of gyration of the mass. Figure 4 depicts the overall design in three views.

View 1



View 2



View 3

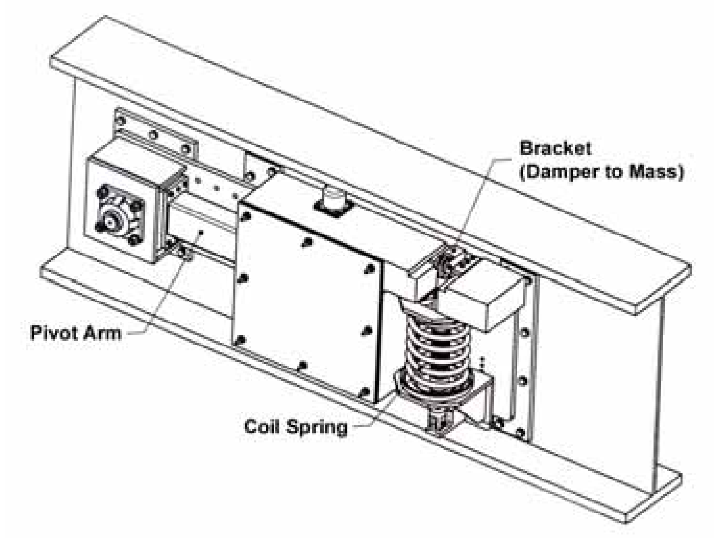


Figure 4 - Modular TMD Design for the Spring Mountain Bridges

Overall outside dimensions of the TMD are 89 inches long, 40 inches high and 13 inches deep. The spring and fluid damper are installed in a similar fashion as automotive suspension struts to facilitate ease in removal for tuning changes. The main mass block is drilled and tapped to accept additional plate masses for field adjustment. Snubbing is provided by elastomer bumper blocks which impact on the bridge girder flanges.

Operating friction is of supreme importance to any TMD. In order to respond to small motions, the mass, spring and fluid damper must be essentially frictionless in response. Any appreciable friction will cause the TMD to exhibit so-called "stick-slip" performance, thus degrading output and potentially causing a perceived instability to people walking on the bridge.

To provide low friction operation, the mass rotates about a pivot pin supported by a commercial roller bearing, and the damper attaches to its mounting brackets with military specification spherical rod end bearings. The fluid damper uses a special low friction seal developed by Taylor Devices for NASA as part of a vibration isolation system for manned spaceflight operations at the International Space Station.

COMPONENT LEVEL TESTING

All eighteen TMDs for the three bridges were assembled and individually acceptance tested before being shipped to the jobsite. Since the fluid damper was the most complex part of the design, each assembled fluid damper was subjected to component level testing before it was installed into the TMD. A total of four separate tests were run on each damper. Two were static tests and two were dynamic. The first static test was a proof pressure test, with the damper statically pressurized to twice the pressure occurring at maximum design force. This maximum overload pressure was held for two minutes, with no yielding of parts or leakage permitted. The second test was a simple static friction test, checking for any binding of internal parts subsequent to proof pressure testing.

The two dynamic tests included a power dissipation test and a damping force vs. displacement test at various velocities using sine sweeps. The power test cycled the damper at +/- 1.5 in. displacement at 2 Hz for one hour, or until the damper reached a steady-state temperature at the specified power level. Figure 5 shows test results for this test, plotting damper external temperature vs. time. The force-displacement testing checked for proper output at peak sinusoidal velocities of 5, 10, and 20 in/sec. Figure 6 is a typical response plot from this test.

SYSTEM TESTING

Each TMD module was assembled and tested without fluid dampers to verify free motion of parts. This was done by log decrement testing, where the TMD was displaced 2.5 inches then released so that it would freely oscillate. Figure 7 is a plot of TMD displacement and velocity vs. time for the log decrement test. After log decrement testing on the undamped TMD, the fluid damper was installed and the tests repeated on the damped TMD system. Figure 8 depicts the results with the fully damped TMD.

SITE TESTING

The TMDs were delivered to the jobsite and installed on all three bridges. Final connections were redundant using both bolts and welds. Installation proved to be simple and took place without any problems. After installation, the bridge with TMDs was subjected to commissioning tests. These included shake testing with an electrodynamic shaker, followed by "walking" and "jumping" tests using groups of construction workers from the jobsite.

During the commissioning tests, comparison testing was also done by repeating all tests with TMDs both free to operate and with TMDs locked. The test results were performed to determine if any field tuning was required, and to verify proper bridge performance with the TMDs functional. All site tests took place without incident, and no field tuning was required, thus demonstrating the fidelity of the as-built bridge and TMD design to the original structural model.

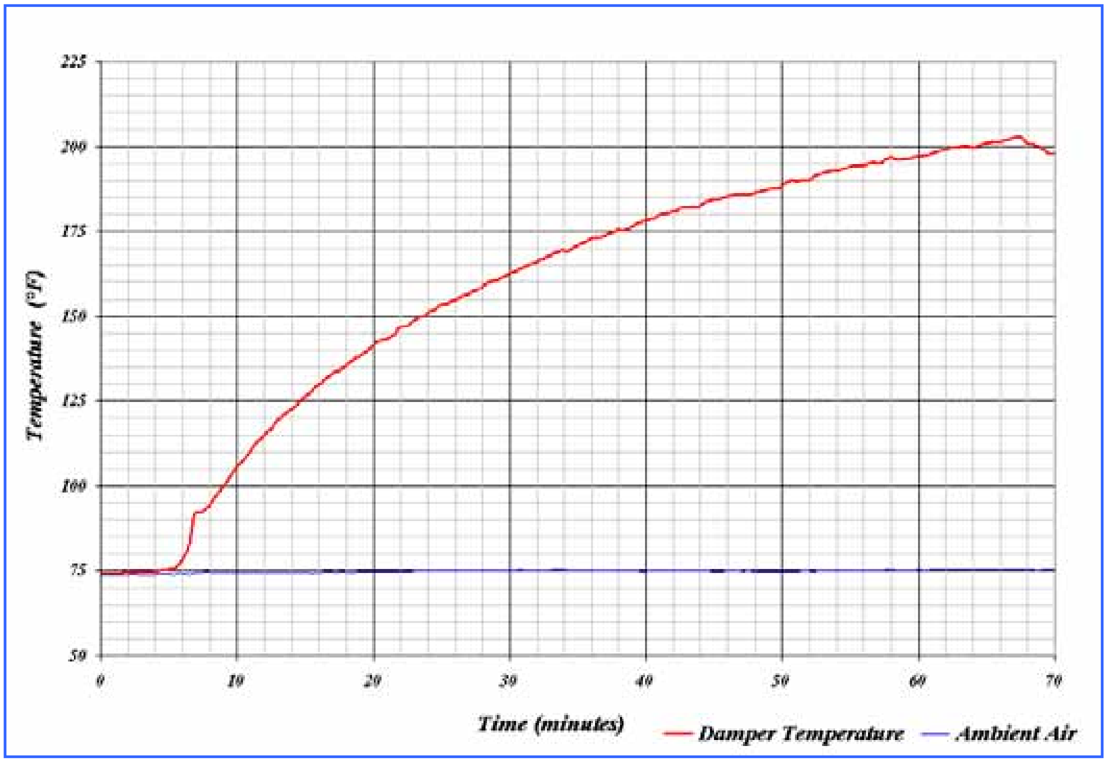


Figure 5 - Test Results, Power Dissipation Test

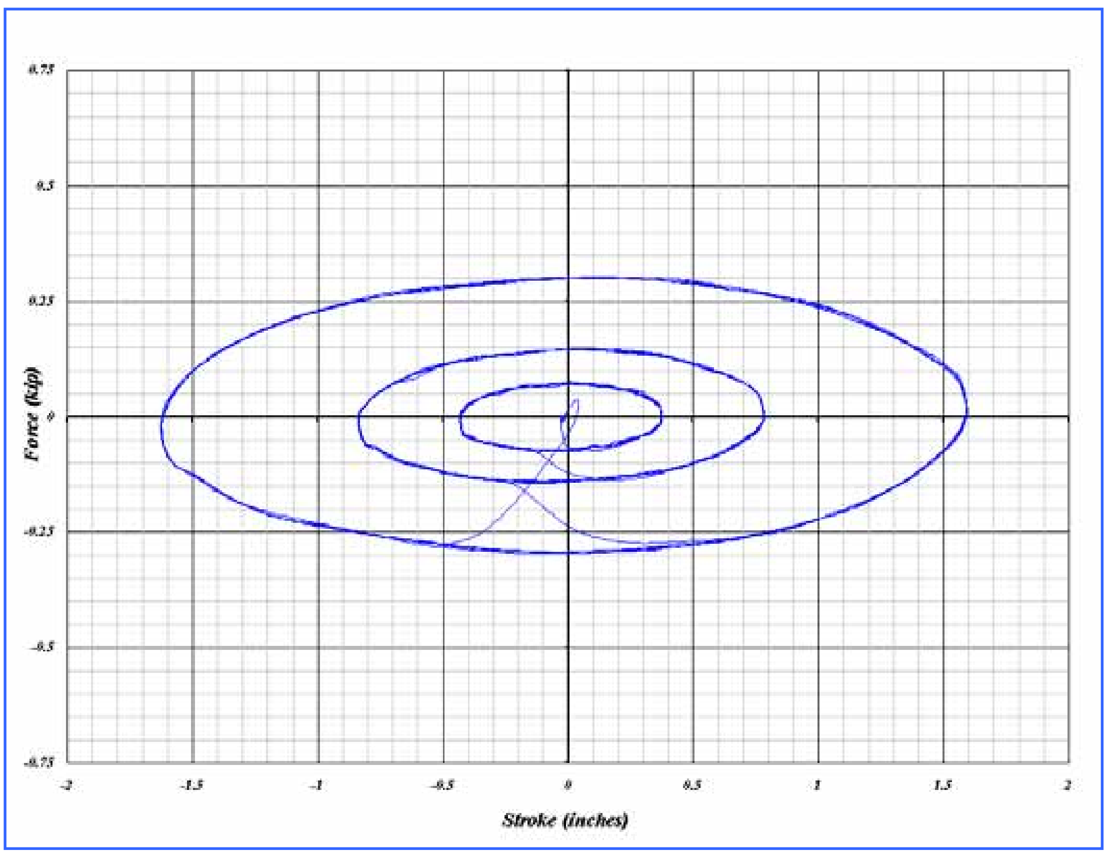


Figure 6 - Damper Force-Displacement Tests

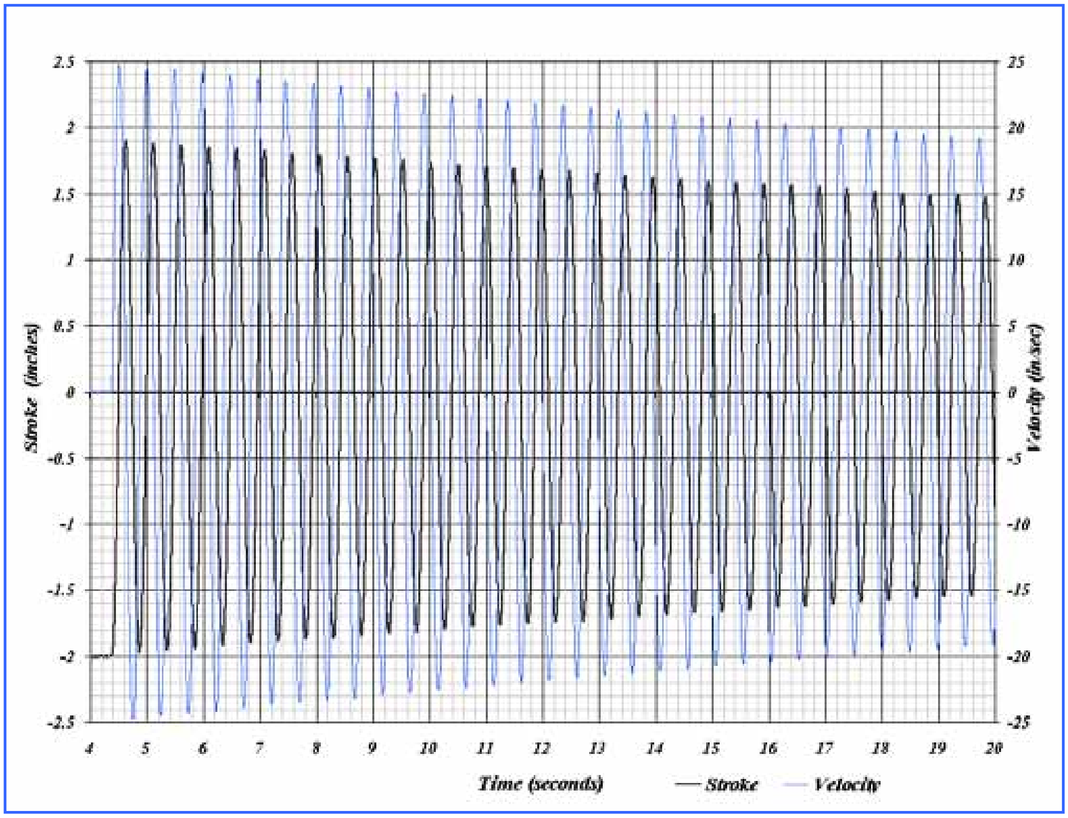


Figure 7 - Plot of TMD Displacement and Velocity vs. Time

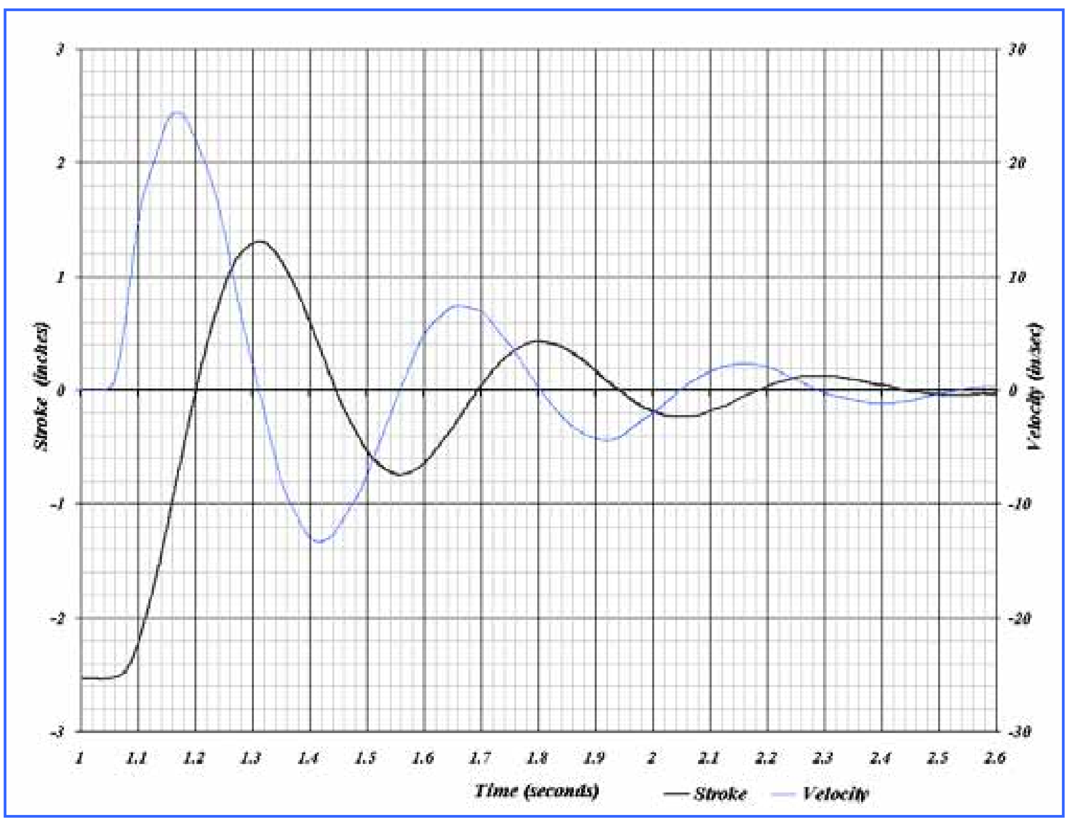


Figure 8 - Results of Fully Damped TMD

CONCLUSIONS

This successful application on the three Spring Mountain Road pedestrian bridges has demonstrated that the concept of modular TMDs added to a structure is both simple to implement and cost effective. The main advantages of TMDs is that they are self-contained and require only a single connection point to the structure for each damping unit, compared to a conventional damper that requires two connections, one of which needs to be connected to a foundation or other suitable effective ground node.

The primary disadvantage of TMDs is that they are not cost-effective if damping levels much above 6% of critical are required. This is due to the TMDs becoming excessively large and heavy if higher amounts of damping are needed. An additional potential problem is that a TMD functions primarily to suppress the response of a single targeted frequency. Therefore, TMDs are often inefficient where higher mode frequencies are also to be suppressed. In case of seismic damping, where values of 20% - 30% critical are common, TMDs should not be considered. Generally, TMDs are considered as effective in applications of controlling structural motion induced by wind, crowds of people, or continuous low-level vibration, where damping levels of less than 10% can be used.

This project also demonstrated that it is possible to design and construct a TMD that can easily be tuned in the field by simply bolting on additional plate masses, or changing damping and spring characteristics with simple bolt-on elements. This allows the overall structural vibration response to be adjusted if necessary to compensate for construction changes from the original model, owner requested changes, design enhancements, or changes in the occupancy requirements as the structure ages.

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