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Reducing Fatigue in Wind-Excited Traffic Signal Support Structures using Smart Damping Technologies

Final Report for NCHRP-IDEA Project 141

Prepared by:

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University of Connecticut

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TRANSPORTATION RESEARCH BOARD

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Reducing Fatigue in Wind-Excited Traffic Signal Support Structures using Smart Damping Technologies

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February 2009 - January 2011

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Transportation Research Board

National Research Council

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EXECUTIVE SUMMARY

The product developed and tested as part of the NCHRP-IDEA 141 project is an innovative signal head vibration absorber (SHVA) that provides energy absorption for lightly damped signal support structures to reduce vibration and fatigue in these structures from excessive wind-induced vibration. The SHVA is a modified vehicle signal head that incorporates a reliable and robust spring and damper inside of the signal housing to allow for the signal head to move vertically relative to the mast-arm. As the mass of the signal head moves up and down relative to the mast-arm, energy is dissipated and vibration is greatly reduced. A picture of the SHVA is shown in Figure 1.

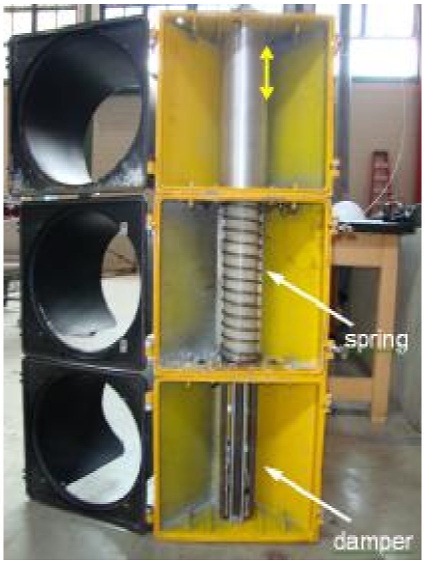

Figure 1: Components of signal head vibration absorber.

Traffic signal support structures are flexible, lightly-damped structures that are highly susceptible to wind-induced vibration. The sustained large amplitude deflections due to excessive wind-induced vibrations can result in fatigue cracking – observed in 3% of the structures in Connecticut to over 30% in Wyoming. This fatigue cracking will ultimately lead to brittle failure of these structures and represents a significant cost to signal owners. The SHVA, applied to new signals, or as a retrofit to problem poles, can reduce fatigue in traffic signal support structures in a cost effective and reliable manner. The AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals contains provisions for the fatigue design of cantilevered traffic signals. The fatigue design load that typically governs the design of the pole and mast arm is galloping-induced cyclic loads. The AASHTO code specifies in 11.7.1 that: “In lieu of designing to resist periodic galloping forces, cantilevered sign and traffic signal structures may be erected with effective vibration mitigation devices. Vibration mitigation devices should be approved by the Owner, and they should be based on historical or research verification of its vibration damping characteristics.” This research will provide the necessary verification of the SHVA as an effective vibration mitigation device.

Work in the first stage of this project has focused on designing and building a research model SHVA. A full-scale traffic signal support structure with a 35-foot mast arm has been erected in the University of Connecticut Structures Research

Laboratory and instrumented with sensors. The experimental setup of the structure is used to conduct free-vibration tests for system identification.

Work in the second stage of this project involved the experimental validation of the performance of the SHVA. The research model performance is evaluated by experimentally measuring the increased level of damping in the structure from free vibration response. The SHVA has been experimentally shown to significantly increase the damping in a 35 foot signal support structure from 0.2% of critical to 10.1%. For steady state vibration this is equivalent to a 98.3% reduction in the response, virtually eliminating any deflections. Analysis has shown that a single SHVA maintains the ability to achieve good performance for a wide range of signal support structures without the need for retuning. This report provides the guidelines and specifications for the SHVA for use in wind-exposed traffic signal structures. The report starts with a detailed background on the vibration problem of traffic signal support structures and an overview of the previous research on the topic to better understand the need for an effective mitigation technique. This is followed by a sound theoretical background to better facilitate the use of this product by future users. The results of the experimental testing are shown at the end part of this report. A streaming video describing these efforts can be found on the internet at: mms://159.247.0.209/mediapoint/Uconn/NCHRP_Idea_141_v4.wmv.

A U.S. patent application has been filed [“Smart Vibration Absorber for Traffic Signal Supports”, Application Serial No. 61/335,571] for the SHVA by the University of Connecticut in January 2011.

IDEA PRODUCT

This IDEA product focuses on developing an effective, simple and inexpensive vibration absorber for the widely used cantilever signal support structures that are highly susceptible to wind induced excitation due to inherent low damping. As a solution a signal head vibration absorber (SHVA) is proposed where the signal head hanging from the cantilever mast arm will act as a tuned mass damper. This requires no additional mass to be added to the structure thus providing an easy and simple solution to add damping to the mast arm for either new construction or as a retrofit.

BACKGROUND AND OBJECTIVES

Traffic signals are used extensively all over the world to control conflicting flows of traffic. The traffic signal heads are attached to tall traffic signal poles or cables spanning over a considerable length of the roadway cross section to ensure clear visibility for the drivers or pedestrians. Cantilevered support structures make up 62% of all traffic signal support structures as it is both cheaper and safer compared to other supports since it consists of less material with only one vertical pole (less of a hazard for vehicles to run into than two poles). However, cantilevered structures are very flexible due to its inherent low damping which makes it susceptible to wind induced vibration (NCHRP, 2002). This excessive and sustained vibration results in damage due to fatigue. The fatigue resistance of traffic and sign structures across the U.S. in recent years has become a concern (McManus et al. 2003; South 1994; McDonald et al. 1995; Kaczinski et al. 1996; Cook et al. 1998; Gray 1999; Hamilton et al. 2000; Hèctor, 2007). Thirty states reported to have excessive vibrations or fatigue cracking of sign, signal, or light support structures under a survey by The National Cooperative Highway Research Program (NCHRP, 2002). Almost all states reported some sort of problem with traffic sign or signal structures. The state of Missouri had over 12 traffic signal mast arms failure in a period of six years, leading the Missouri Department of Transportation (MoDOT) to fund research projects carried out by the University of Missouri – Rolla and the University of Missouri – Columbia (Hèctor, 2007). Full scale testing by Hartnagel and Barker (1999) on cantilevered traffic signal structures mainly concentrated on finding the effects of truck gust load on this type of failures. Chen et al. (2001) suspected that the Missouri failures were a result from overstressing, poor welding quality, and low fatigue strength and concluded that the strains caused by truck passage are significantly lower than the ones caused by the natural wind gusts. Based on the recent failure of two cantilever traffic signal structures in the state of Wyoming; research on this topic commenced at the University of Wyoming. In Lubbock, two similar failures occurred from 2001 to 2005 (Hèctor, 2007).The cause of the collapses has been identified by WYDOT inspections to be the result of failures at the box connection between the mast arm and the vertical pole. WYDOT visual inspections of approximately 840 poles indicated that roughly 1/3 of the poles inspected have fatigue cracks ranging in length from 6 to 500 mm (1/4 to 20 in.) around the box connection between the pole and mast arm (Hamilton et al., 2000). From field tests and finite element analysis Gray et al. (1999), Hamilton et al.,(2000) also reported that the failures occurred at the connection between the mast and the pole and were due to fatigue cracking on the pole near the base of the weld resulting from vibrations caused by the wind. They stated that both in-plane (galloping) and out-of-plane (gust) motions are significant contributors to the fatigue damage of the Wyoming structures (Hèctor, 2007). Researchers at the University of Texas at Austin conducted full-scale experiments to study wind-induced vibrations of cantilever traffic signal structures. Albert (2006) determined that overall natural wind gusts produce a larger response in cantilevered traffic signal structures than gusts produced by trucks passing beneath the signals. These results agree with the ones obtained by Hartnagel and Barker (1999) and Chen et al. (2001). In early, 2002 a cantilevered "Stop ahead'' sign in Stratford, Connecticut collapsed. After a thorough investigation of the structural components, it was determined that the failure occurred at the arm's connection to the post. A weld at this connection developed a fatigue crack that propagated over time, ultimately resulting in brittle failure. To ensure the safety of the traveling public, a statewide inspection of all cantilever traffic signal supports sponsored by ConnDOT found that 24 of the 801 mast arms had cracks at arm to post connection.

Kaczinski et al. (1998) stated that mast arm displacements in excess of 1.2 m (48 inch) have been reported under steady state winds with speeds in the range of 16 to 56 km/hr (10 to 35 mph) and identified vortex shedding, galloping, natural wind gusts, and truck-induced gusts as the most critical fatigue-loading mechanisms in cantilevered supports of signals, signs, and lights. Vortex shedding is defined as a steady uniform airflow that passes an obstacle such as a cylinder or a pipe in its path resulting in thin sheets of tiny vortices behind the obstacle. As the flow speed increases, vortices are alternately shed on each side. The asymmetric pressure distribution around the cross section results in a sinusoidal forcing function transverse to the air flow's direction (in the case of horizontal mast arms, this result in vertical motion). When the vortex shedding frequency matches the resonance frequency of the structure, the structure begins to resonate and the structure's movement can become self-sustaining. Based on results reported by McDonald et al. (1995) and Kaczinski et al. (1998), this phenomenon does not appear to have a significant effect on cantilevered mast arm structures due to their tapered shape and small cross-sectional area (Cook et al., 2001) but it is galloping that is most likely the primary cause of excessive vibrations in these type of structures. Galloping is an unstable phenomenon caused by aerodynamic forces generated on certain cross-sectional shapes resulting in displacements transverse to the wind (Smith 1988). For horizontal structures subjected to wind, the resulting motion occurs in the vertical plane. At low wind speeds, vortex shedding or gustiness in the wind initiates the vibrations. As the wind picks up beyond the critical speed, the signal structures exhibit the galloping phenomenon (Pulipaka et al., 1998). Natural wind gusts arise from the variability in velocity (speed and direction) of airflow. These wind gusts are characterized by a spectrum of velocity components that oscillate over a broad range of frequencies as a result of turbulence inherently present in any natural airflow (Kaczinski et al. 1998, Cook et al., 2001). Truck-induced wind gusts on cantilevered mast arm structures are the result of large vehicles passing beneath the structures. Finding by Hamilton et al. (2000) that random wind gusts (whatever the source may be) may be a major contributor to out of plane mast arm vibrations is supported by visual inspections by Cook et al., 2001.

The excessive vibration results in live load stresses which significantly reduce the fatigue life of signal support structures. Reducing the effective stress range (the difference between the maximum and minimum stress) in the structure by reducing the amplitude of the vibration can significantly increase the fatigue life of that structure. This can be done by increasing the damping of the structure with an effective damping device in place that would decrease the amplitude and number of cycles, thus extending the service life of these structures. A number of researchers have proposed methods to reduce vibrations in traffic signal support structures. Hamilton et al (2000), Cook et al. (2001) and McManus et al. (2003) performed detailed study on a number of different dampers to find out an effective and convenient damper to mitigate the wind induced vibration of traffic signal poles. A list of these dampers is shown in Table 1. The methods of mitigation have also varied widely (Gray, 2000). But none of these were judged suitable for in field implementation for either being ineffective, expensive or distracting to the driver.

TABLE 1: Damper Type Studied for Their Effectiveness in Increasing Vertical Damping of the Traffic Pole.

Type of Dampers	Variation	% Critical damping	% Increase	Disadvantage (as identified by prior research)
Tuned mass damper[1]	Traditional	8.71	32	Different natural frequency requires separate tuning
	Stockbridge	0.42	1.5	
	Batten	1.82	6.7	
Liquid damper[1]	Horizontal	0.38	1.4	Ineffective
	U- tube	0.40	1.5	
Friction damper[1]		6.49	23.9	Unattractive
Elastomeric pads[3]	Pad at mast arm	0.28	1.9	Ineffective
	Pad at mast arm and base	0.43	2.9	
	Pad at base	0.39	2.6	
Arm Pole connection[1]	Belleville Spring	0.65	2.4	Ineffective
Strut[2]		2.4-6.0	16-40	Requires luminary extension
Flat bar [2]	Unconfined	1.1	7.3	Ineffective
	1.0 s period	0.30-1.1	2.0-7.3	
	1.2 s period	0.25-0.91	1.7-6.1	
	1.4 s period	0.30-0.37	2.0-2.5	
Strand[2]	1.0 s period	0.54-1.3	3.6-8.7	Large size and noise
	1.2 s period	0.72-1.6	4.8-10.7	
	1.4 s period	0.97-1.4	6.5-9.3	
Alcoa Dumbbell[2]		0.26	1.7	Ineffective
Shot-put[2]	0 degree	0.20-0.29	1.3-1.9	Ineffective
	45 degree	0.20-0.28	1.3-1.9	
Hapco[2]		0.31	2.1	Ineffective
Impact [2]	Vertical Spring/mass impact dampers	6.79	25	High cost
	Horizontal Spring/mass impact dampers	0.78	2.9	Ineffective
	Spring/mass liquid impact dampers	6.12	22.5	High cost
	Tapered	4.01	14.7	Unattractive

1. *Cook et al., (2001)*
2. *Hamilton et al., (2000)*

The AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals contains provisions for the fatigue design of cantilevered traffic signals. The fatigue design load that typically governs the design of the pole and mast arm is galloping-induced cyclic loads. The AASHTO code specifies in 11.7.1 that:

> "In lieu of designing to resist periodic galloping forces, cantilevered sign and traffic signal structures may be erected with effective vibration mitigation devices. Vibration mitigation devices should be approved by the Owner, and they should be based on historical or research verification of its vibration damping characteristics."

The ASSHTO code also specifies in 11.8 that Galloping and Truck gust induced vertical deflections of cantilevered traffic signal arms should not exceed NCHRP 412 recommended value of 8 inches. The galloping and truck induced wind loads transfer the energy to the mast arm through the attachments, i.e., signal heads. The proposed SHVA isolates the mast arm from the signal head through energy dissipation.

The objectives of this project were as follows.

- To propose and effective, inexpensive and easy to implement vibration absorber for cantilevered traffic signal support structure for mitigating the vertical deflection due to wind induced vibration.
- To build and demonstrate the performance of a research model vibration absorber.
- To conduct full scale testing of a traffic pole mast arm to verify the effectiveness of using the vibration absorber.
- To propose guidelines and specification to implement this vibration absorber in the field.

BENEFITS FROM RESEARCH

The most significant benefit from this product is the improved safety for the drivers and pedestrians. A number of cantilevered traffic signal support mast arms have failed in service over the last fifteen years causing a safety concern for the departments of transportation. With the SHVA in place the fatigue stress at the connection between the mast arm and pole will be significantly reduced and as a consequence the probability of any in service mast arm failure will be diminished. It will also make the drivers feel more comfortable driving under the traffic poles that would otherwise move more than a couple of feet vertically.

This product also has the potential to make traffic signal poles more economical. With an effective SHVA in place the cross-sectional size of a new traffic signal pole can be made smaller and the service life of an existing traffic signal pole can be greatly increased. It can also bring a pre-updated code mast arm that no longer meets fatigue code up to date since ASSHTO specifies that a mast arm showing excessive vibration may be equipped with a vibration mitigating device as quickly as possible after the galloping problem occurs.

One of the most attractive features of the SHVA is its low cost. The components used are easily available and it requires simple machining. These two factors help to keep the cost low. For example, the laboratory developed and tested research model material costs are less than $500. While additional machining, fabrication and shipping costs will be offset in part by mass production and economies of scale, the relatively cost effective nature of this device will facilitate the widespread use of this product as a vibration mitigation device.

Another attractive feature of the SHVA is its reduced inspection cost. Without the presence of any fluid damper there is no requirement for frequent inspection to check any kind of leakage. The permanent magnets will provide the same damping over the years. Also the design is frictionless with all moving parts independent of each other such eliminating any wear.   There is also no need for any sophisticated instrument to construct a SHVA. The spring, damper, hollow tube, aluminum plate, iron block are easily available. Following the guidelines provided in this report it is easy to implement.

The device can serve as an effective mitigation device to allow for galloping forces to not be considered in the design of the mast arm and pole. This will allow for smaller, less expensive poles to be used. Additionally, with vibration not a main concern, States that currently limit the length of cantilevered traffic poles can use longer poles when this will benefit the intersection design. Along these lines, current poles that have been built at capacity might use a SHVA to provide for increased capacity when additional signage of lights is needed. This will allow for the existing pole to be used and not call for replacing the pole. This will save cost and time.

CONCEPT AND INNOVATION

The reason for excessive wind induced vibration in traffic poles can be found in the construction and design of the traffic signal poles themselves. The traffic poles are constructed of thin-walled circular members capable of spanning over 50 feet and their cantilevered configuration, with a support on only one end, makes them very flexible (Gray, 1999). This flexibility gives cantilevered signal poles a low natural frequency (Hèctor, 2007). The natural frequencies present in mast arm structures are typically in the range of 0.7 Hz to 1.4 Hz (Cook et al., 1998). The inherent damping is also very low. The percent of critical damping, or damping ratio, in traffic signal support structures has been measured in prior research studies to be from 0.15 to 0.47% (Hamilton et al., 2000). This low damping results in a dynamic response many times larger – 5, 10 or 50 times larger at resonance (1 frequency ratio) for poles with 10%, 5% and 1% damping ratio – than the static response (0 frequency ratio) as shown in Figure 2.

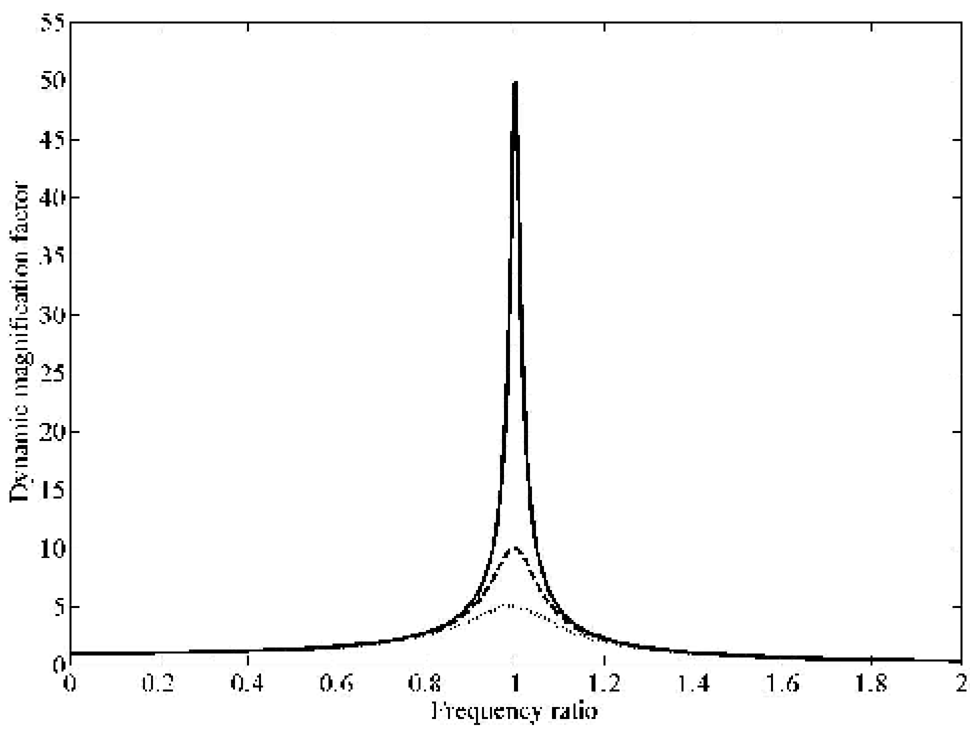

Figure 2: Magnification factor versus frequency ratio for 1 % critical damping ratio (solid), 5 % critical damping ratio (dashed) and 10% critical damping ratio (dotted).

The Dynamic vibration absorber (DVA) or Tuned mass damper (TMD) was invented in 1909 by Hermann Frahm (US Patent #989958, issued in 1911), and since then it has been successfully used as a passive vibration control device to suppress wind-induced vibration and seismic response in buildings. A simple TMD consists of a supplemental mass and a spring. When a mass–spring system (primary system) is excited by a harmonic force, its vibration can be suppressed by attaching a TMD as shown in Figure 3(a). However, adding a TMD to a single degree-of-freedom (SDOF) system results in a two-degree-of-freedom (2DOF) system that remains lightly damped. If the exciting frequency coincides with one of the two natural frequencies of the new system, the system will be at resonance and the dynamic response again greatly amplified. To overcome this problem, a damper can be added to the DVA. Figure 3(b) shows a primary system with a damped DVA attached (Liu and Liu; 2004). Characteristics of the TMD and damped vibration absorber were studied in depth by Den Hartog (1940) and a brief summary relevant to the signal head vibration absorber provided subsequently.

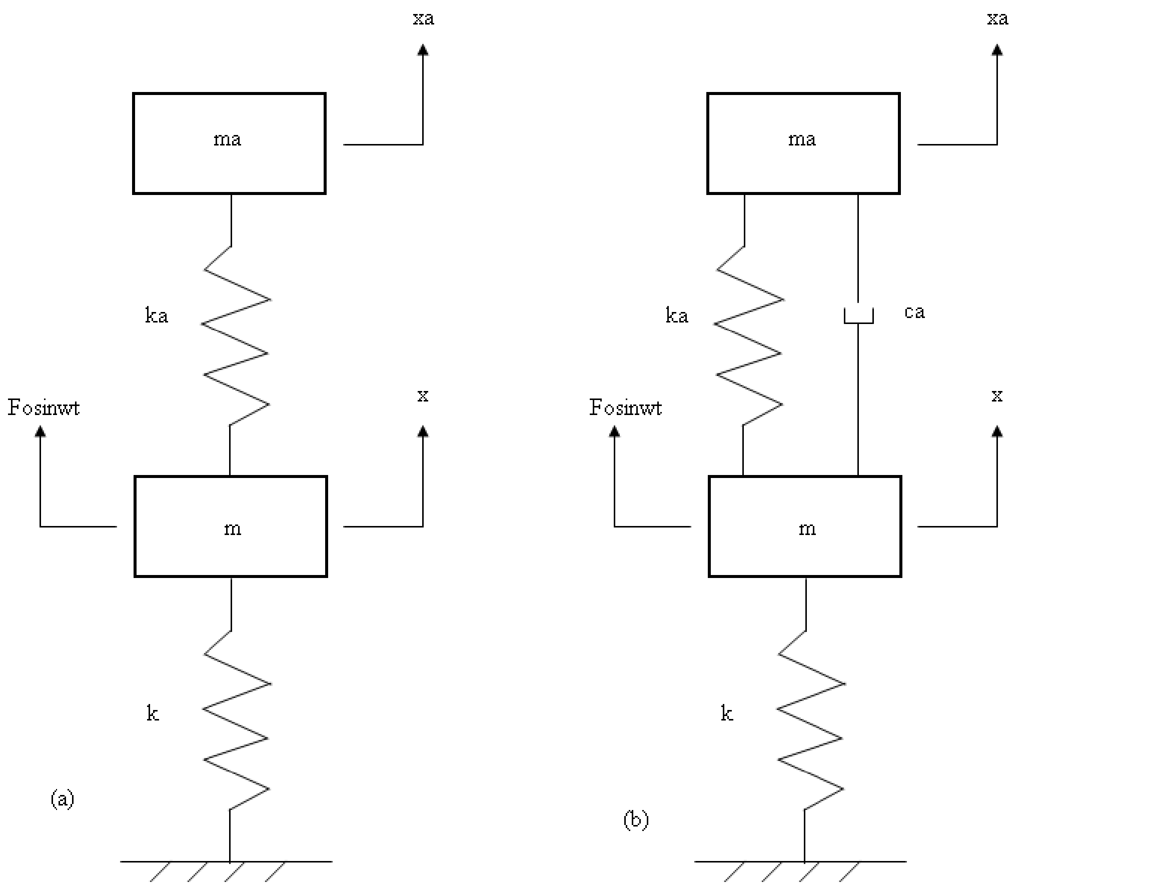

Figure 3: Two types of vibration absorbers (a) Dynamic vibration absorber (b) Damped dynamic vibration absorber.

The equation of motion with passive control for a SDOF system with a TMD can be written as a 2DOF:

$$m\ddot{x} + c_a\dot{x} - c_a\dot{x}_a + (k + k_a)x - k_a x_a = F_o \sin(wt), \qquad m_a\ddot{x}_a - c_a\dot{x} + c_a\dot{x}_a - k_a x + k_a x_a = 0 \tag{1}$$

Where m and m_a are the primary mass and the absorber mass, respectively, k and k_a are the primary stiffness and the absorber stiffness and c_a is the damping value of the damper. F_o is the force amplitude and ω is the exciting frequency. The normalized amplitudes of the steady state responses of the primary and absorber mass are gives as:

$$\frac{X_1}{X_{st}} = \sqrt{\frac{(2zl)^2 + (g^2 - l^2)^2}{(2zl)^2\{1-(1+m)l^2\}^2 + \{(1-l^2)(g^2-l^2) - mg^2l^2\}^2}} \tag{2}$$

$$\frac{X_2}{X_{st}} = \sqrt{\frac{(2zl)^2 + (g^2)^2}{(2zl)^2\{1-(1+m)l^2\}^2 + \{(1-l^2)(g^2-l^2) - mg^2l^2\}^2}} \tag{3}$$

where $m = m_a / m =$ Mass ratio= Absorber mass/Main mass, $w_n{}^2 = k_a / m_a =$ Natural frequency of absorber, $\Omega_n{}^2 = k/m =$ Natural frequency of main system, $l = w_a/\Omega_n =$ Frequency ratio , $g = w/w_n =$ Forced frequency ratio, $x_{st} = P_o/K =$ Static deflection of system, and $z = c/(2m\Omega_n) =$ critical damping.

Figure 1.4 shows $\frac{X_1}{X_{st}}$ .vs. γ for $m = 1/20$ and λ=1 for three different values of the damping ratio z as shown in the book Mechanical Vibrations (1940). In this classical book Den Hartog observed a remarkable occurrence in the figure that all three curves intersect at two exact points. He proved that this is no accident and there exist the two fixed points independent of damping.

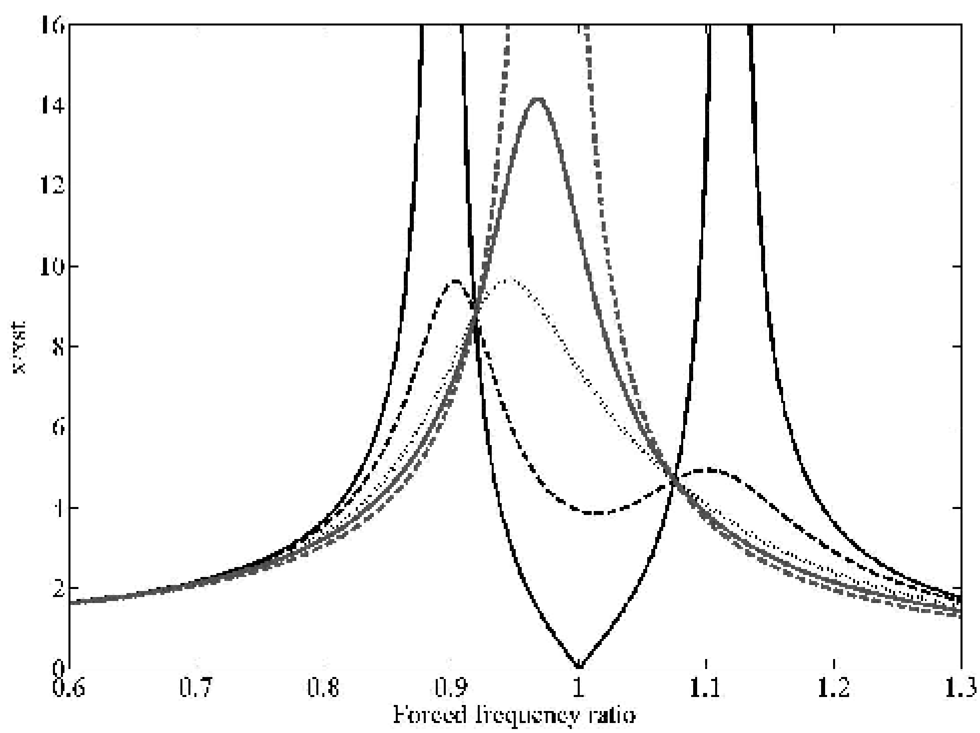

Figure 4: Normalized amplitude of the steady state response of the primary mass for damping coefficient: 0.00 (Solid black), 0.10 (Dashed black), 0.20 (Dotted black), 0.32 (Solid grey), and 10000 (Dashed grey).

Den Hartog further found that the optimum tuning parameter should be,

$$g = \frac{1}{1+m} \tag{4}$$

such that the y-coordinates ($\frac{X_1}{X_{st}}$) of the two fixed points are equal in magnitude. He also indicated that the optimum damping ratio should be a value of z for which the curve passes horizontally through either one of the fixed points. Den Hartog claimed that this optimum value can be found by differentiating Eq. (2) with respect to λ; thus finding the slope, and equating the slope to zero for the fixed points. Recognizing an undue amount of labor of this method, he did not present an analytical result (Liu and Liu, 2004). Seto (2010) showed that from the differentiation the optimal damping can be found to be

$$z = \sqrt{\frac{3m}{8(1+m)^3}} = z_{opt} \tag{5}$$

In such a manner the optimal spring and damping of a traffic signal head can be identified to turn the signal head into an optimally tuned damped vibration absorber. This is referred to herein as a signal head vibration absorber (SHVA). The distinct and novel features of the SHVA proposed in this project are:

a. The vibration absorber uses the mass of the signal head to serve as the moving mass of the vibration absorber. This has not been done in prior research. In this approach no additional mass is added to the signal structure. This provides for increased performance of the absorber without adding any significant extra weight to the signal structure. Additionally, simulations and full-scale laboratory experiments indicate that the signal head actually moves less in this configuration than if it were rigidly attached to the mast arm (as currently done).

b. The design of the system is simple to allow for practical application in the field. A linear spring is used to provide the required spring force. An eddy current damper is used to provide the damping force (although many different types of damper might be used). Thus the same hardware can be used for a variety of different traffic signal supports, based on a simplified design procedure.

INVESTIGATION

To provide research verification of the vibration damping characteristics of the SHVA a series of experimental and numerical investigations are conducted.

EXPERIMENTAL SETUP

The experiment was conducted at the Structures Research Laboratory at the University of Connecticut. The steel traffic pole with a mast arm of 35 feet was provided by the Connecticut Department of Transportation (ConnDOT). The tapered mast arm has an outer radius of 5-1/4 inch to 2-9/16 inch and the thickness is 1/8 inch. There is one traffic head with a 3 light signal box. The signal head is 3 feet in length with each box equal to 12 inch by 9 inch. The weight of the signal head is 13.4 kg. The effective weight of the mast arm is 93.3 kg. From equation 4 this gives a required optimal damping of 39.2 N-sec/m.

The acceleration at the tip of the mast arm was of particular interest for this study to understand the effect of placing the TMD on the time history response of the mast arm. Two accelerometers were attached 6 in. (305 mm) from the mast arm tip. The sensors were configured orthogonal to one another to isolate in-plane and out-of plane motions. In general out-of-plane motions were not excited. As such, only the in-plane accelerations are reported in this study. Additionally a third accelerometer was connected to the top of the signal head to measure vertical acceleration of the signal head itself. The accelerometers are PCB Model 3701G3FB3G with a sensitivity of 1000mV/g or 102 mV/m/s^2.

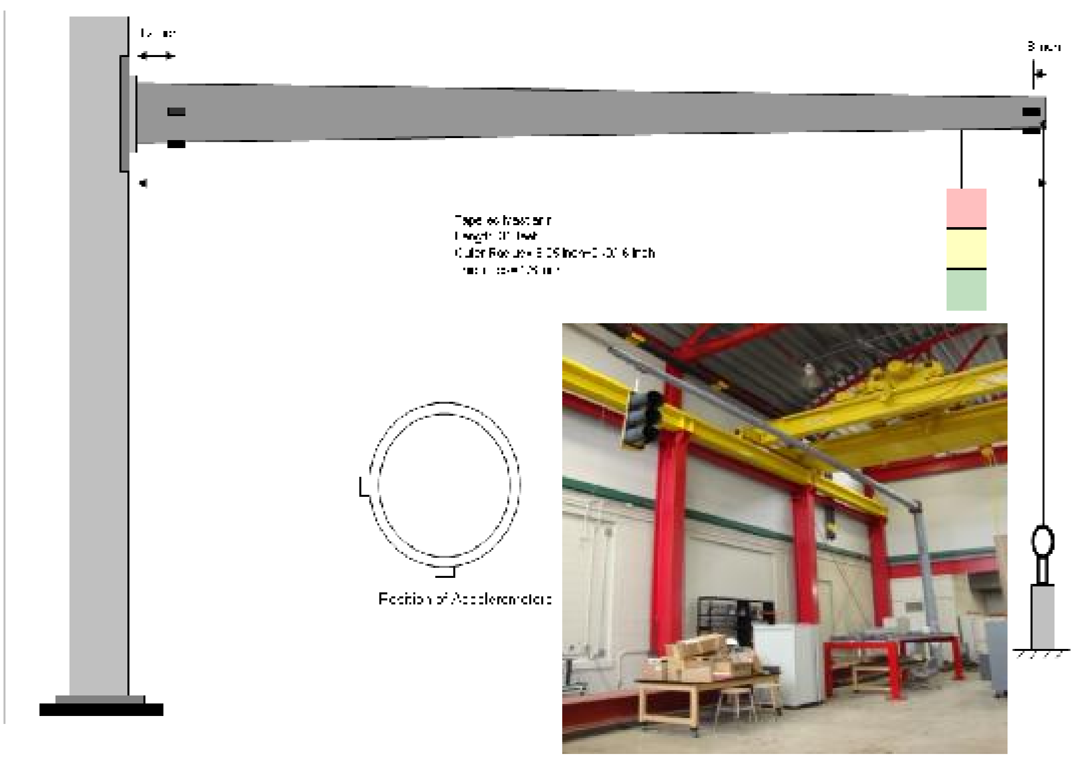

Figure 5: Test structure in Advanced Hazards Mitigation Laboratory in University of Connecticut.

Portable dynamic signal analyzer SignalCalc ACE, powered by Quattro was used for data acquisition. It provides 32 bit floating-point DSPs delivering up to 204.8 kHz sample rate on all channels. The four inputs are coupled to dedicated 24 bit sigma-delta ADCs while two outputs have 24 bit DACs. Integral anti-aliasing filters protect the inputs and outputs. It has 120 dB dynamic range with up to 94 kHz real-time rate while measuring and displaying 1600 line Transfer Functions, Coherence and all other related measurements.

A string attached to tip of the mast arm was used to give an initial displacement to the cantilever to excite it in the first mode. The initial displacement given was in the range of 4 to 8 inches for controlled and uncontrolled tests.

SYSTEM IDENTIFICATION OF TRAFFIC POLE

Initially Pluck Test was conducted to find the natural frequency and damping ratio of the traffic pole mast arm. The tests were conducted by pulling the tip of the arm in the vertical direction and then letting the arm vibrate freely until it would stop. While conducting the run, the strain sensors would record the time history of the displacement (fig 6). The natural frequency is calculated from the time required to complete the cycles of vertical deflection. Logarithmic decrement method was used to find the damping ratio. The natural frequency of the mast arm without the signal head attached was found to be 1.373 hz and with signal head 1.267 hz. The damping ratios were 0.2 and 0.14 respectively. These values were plugged in later to find the mass of the mast arm, required spring constant and damping ratio of the TMD from numerical analysis.

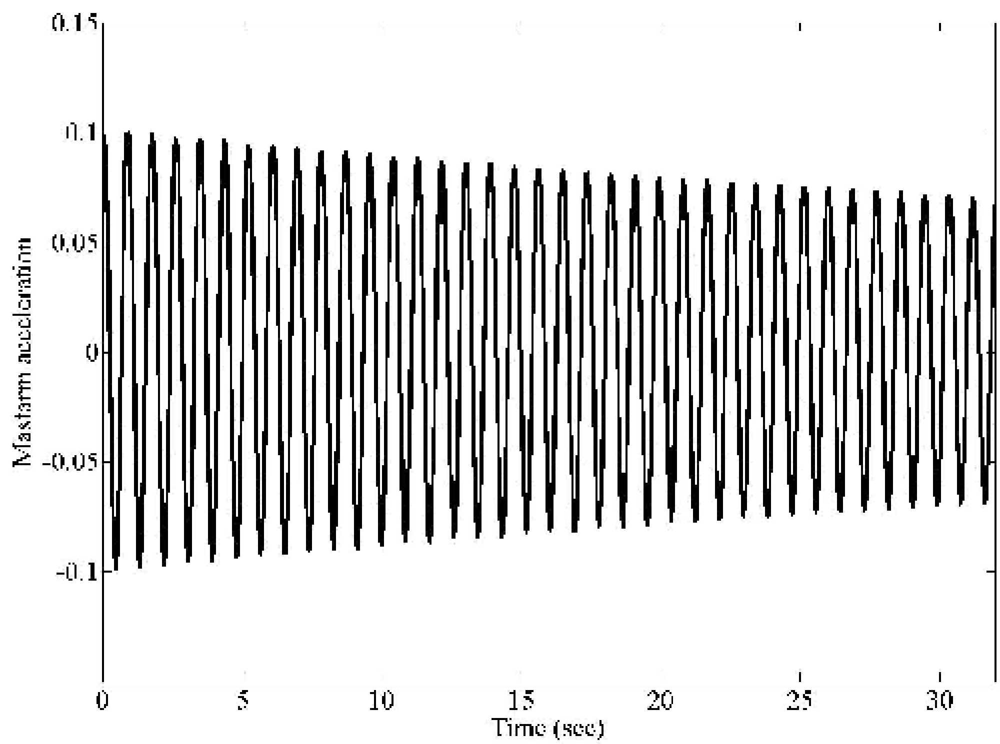

Figure 6: Vertical displacement of traffic mast arm used to find natural frequency and damping ratio by Logarithmic decrement method.

SIGNAL HEAD VIBRATION ABSORBER DESIGN

The 2 DOF systems of the mast arm and traffic signal head is represented in the state space form. Mass of the traffic arm, M is calculated from the difference in the mass and natural frequencies found from stage I of laboratory testing.

$$\frac{M}{m} = \frac{w_2{}^2}{w_2{}^2 - w_1{}^2} \tag{6}$$

Where, m = mass of the traffic signal head, ω_1= natural frequency of the mast arm without attached signal head ω_2= natural frequency of the mast with signal head. The stiffness and damping coefficient of the mast arm is then calculated simply as K= $Mw_1{}^2$ and C= $2xMw_1$ where ξ is the critical damping ratio found from stage I of laboratory testing. The optimal damping ratio of TMD, c is calculated and the stiffness of TMD, k = $(fw_1)^2 m$ where f = m/M .

The state space of the traditional system where the traffic signal head is rigidly connected to the mast arm is:

$$A_r = \begin{bmatrix} 0 & 1 \\ -K/M+m & -C/M+m \end{bmatrix} \ , \ B_r = \begin{bmatrix} 0 \\ 1/M+m \end{bmatrix} \ , \ C_r = \begin{bmatrix} 1 & 0 \end{bmatrix} \ , \ D_r = [0]$$

With the introduction of TMD the above system behaves as a 2 DOF system where the mast arm and TMD moves independently. The state space representation for this system is:

$$A_c = \begin{bmatrix} 0_{2x2} & I_{2x2} \\ M1K1^{-1} & M1C1^{-1} \end{bmatrix} \ , \ B_c = \begin{bmatrix} 0 \\ 0 \\ M^{-1} \\ 0 \end{bmatrix} \ , \ C_c = \begin{bmatrix} I_{2x2} & 0_{2x2} \end{bmatrix} \ , \ D_c = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

where,

$$M1 = \begin{bmatrix} M & 0 \\ 0 & m \end{bmatrix} \ , \ K1 = \begin{bmatrix} K+k & -k \\ =k & k \end{bmatrix} , \ C1 = \begin{bmatrix} C+c & -c \\ -c & c \end{bmatrix}.$$

The weight of the signal head is 33.9 lb. As such the mass ratio is determined to be 17% (μ=0.17). The optimal stiffness is determined from Eq. (4) to be k_a= 3.98 lb/inch (λ=0.86 and ω_n=6.73 rad/sec). The optimal damping coefficient can be determined from Eq. (5) to be c_a=0.23 lb-sec/inch.

Spring

The spring rate is equal to 3.98 lb/inch with a free length of 15 inch and a maximum solid length of 3.314 inch. The spring has an outside diameter of 3.25 inch +/- 0.045inch and made of 0.187" thick stainless steel wire as shown in Figure 7.

Damper

When a nonmagnetic conductive metal is placed in a magnetic field, eddy currents are generated. The process of the eddy currents being generated causes a repulsive force to be produced that is proportional to the velocity of the conductive metal. Since the currents are dissipated, energy is being removed from the system, thus allowing the magnet and conductor to function like a viscous damper. Different configurations of magnetic damper have been used for vibration control. For example, Teshima et al. investigated the effects of an eddy current damper on the vibrational characteristics of superconducting levitation and showed that the damping of vertical vibrations was about 100 times improved by eddy current dampers. Kienholtz et al. investigated the use of a magnetic tuned mass damper for vibration suppression of a spacecraft solar array and a magnetically damped isolation mount for the payload inside of a space shuttle. The magnetic tuned mass damper system targeted two modes of the solar array first torsion at 0.153 Hz and first out of plane bending of 0.222 Hz and increased the damping by 30 and 28 dB respectively (Sodano et. al.).

The damper is designed as a magnetic damper following the configuration proposed by Seto as the required damping coefficient from numerical analysis is close to the value used by Seto (Makita et. al., 2007), shown in figure 7. Three steel plates are fixed to a steel connector between the spring and the plates. The 2 inch x 0.5 inch x 9 inch plates are placed at 0.75 inch apart. Magnets of equal strength are attached to the outer plates and a hollow Aluminum tube that acts is the conducting plate is placed through the middle plate. Each magnet (2 inch x 1 inch x ¼ inch) has a surface 2451 Gauss. The thickness of the aluminum plate is calculated to be 3/16 inch to provide the necessary damping of 0.23 lb-sec/inch. The magnets are attached to the steel plates on the surface as these are magnetized through the thickness. The air gap between magnet and the conducting plate is 0.1875 inch.

Connection

The SHVA is connected in two different ways to the mast arm: (i) rigid connection, allowing the signal head to move conventionally without any damping effect; (ii) controlled connection, allowing the rod to move with the mast arm incorporating the effect of the vibration absorber. The hook connection used is not a typical connection , but it provided a steady support for the traffic signal head and showed no twisting effect. We are also considering different mounting systems for future testing.

Signal head

The signal head weighs 33.9 lb. and it has three hollow boxes for the traffic light. Since the test was conducted on a relatively shorter traffic pole, only one signal head was used. Typically, there is more than one signal and sign on the mast arm and the ASSHTO specifies to use 21 pounds per square foot (psf) static vertical shear should be applied to the entire frontal area of each sign and traffic signal attachment. This implies that the SHVA needs to be installed for each traffic signal attached for improved performance.

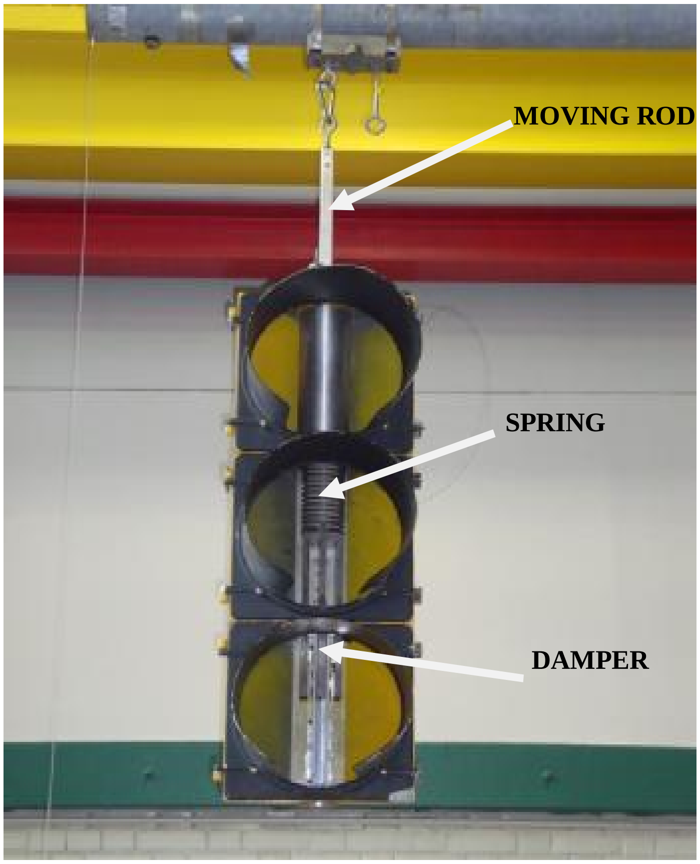

Figure 7: Research model SHVA developed at the University of Connecticut.

Verification of SHVA Design

Free vibration test of the signal box was conducted to collect the time history data from the accelerometer attached to the top of the box. Data was collected at 200 Hz for 4 different damping conditions: no magnets, 1 pair of magnets, 2 pairs of magnets, 3 pairs of magnets and 4 pairs of magnet. The damping co-efficient from the test is shown in fig 8. From these results we can see that 4 pairs of magnets are adequate for getting a damping coefficient close to the optimal damping.

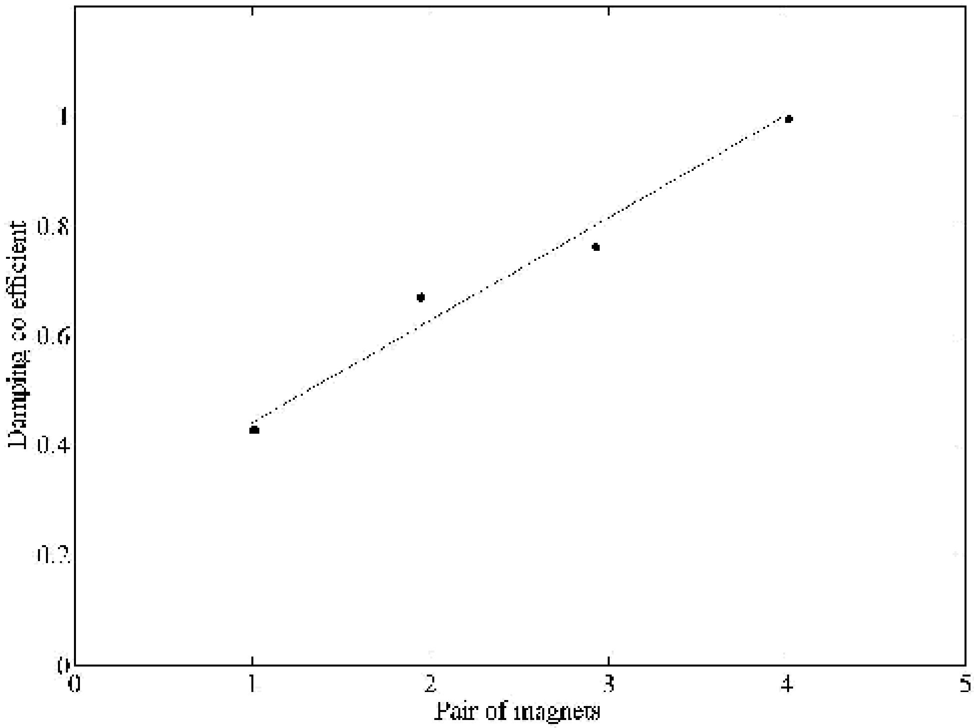

Figure 8: Damping coefficient of eddy current damper for different pairs of magnets.

EXPERIMENTAL VERIFICATION

The pluck test was repeated after converting the traffic signal head into TMD. The signal head had two options to be connected to the mast arm. At first the signal head was connected to the mast arm rigidly with a hook attached to the top box so that the signal head behaved typically where the displacement of the signal head is equal to the displacement of the mast arm. Because the spring and damper inside the signal box remained static relative to the signal head and did not influence the response of the mast arm or the signal head. Then the signal head was attached to the mast arm with a hook attached to the moving rod that runs through the signal head thus allowing the spring and damper inside the signal head to deflect vertically and as a result reducing the vertical deflection of the mast arm. Acceleration from the three sensors was collected at 200 Hz and repeated at 10 Hz.

Figure 9 shows the experimental time histories of the tip displacement of the traffic pole mast arm for rigid (without TMD) and controlled (with TMD) connections. The mast arm was given an initial displacement of 4 inches for rigid connection and an initial displacement of 3 inches for the controlled connection. The controlled connection shows a much higher damping than the rigid connection. The setting time is dramatically reduced. While it takes 5 minutes for the mast arm acceleration to attenuate to 0.06 g, the acceleration of the mast arm with the SHVA is reduced to less than 0.06 g after only 2.75 seconds, more than 100 times faster. The critical damping ratio is also determined from the free vibration tests. The measured critical damping ratio of the signal support structure is increased from 0.2% for the rigidly connected signal head to 10.1% for the SHVA system. This would correspond to a reduction in the vibration of the mast arm at resonance from 48 inches to 0.84 inches or a 97.5% reduction. In practice this means that as a result of using the TMD the traffic pole mast arm will go through a much lower number of cycles of vibration with smaller amplitude thus significantly decreasing the cyclic stress induced at the connection between the mast arm and the vertical pole. As a result decreasing the risk of the mast arm connection failure and increasing the effective life of the structure.

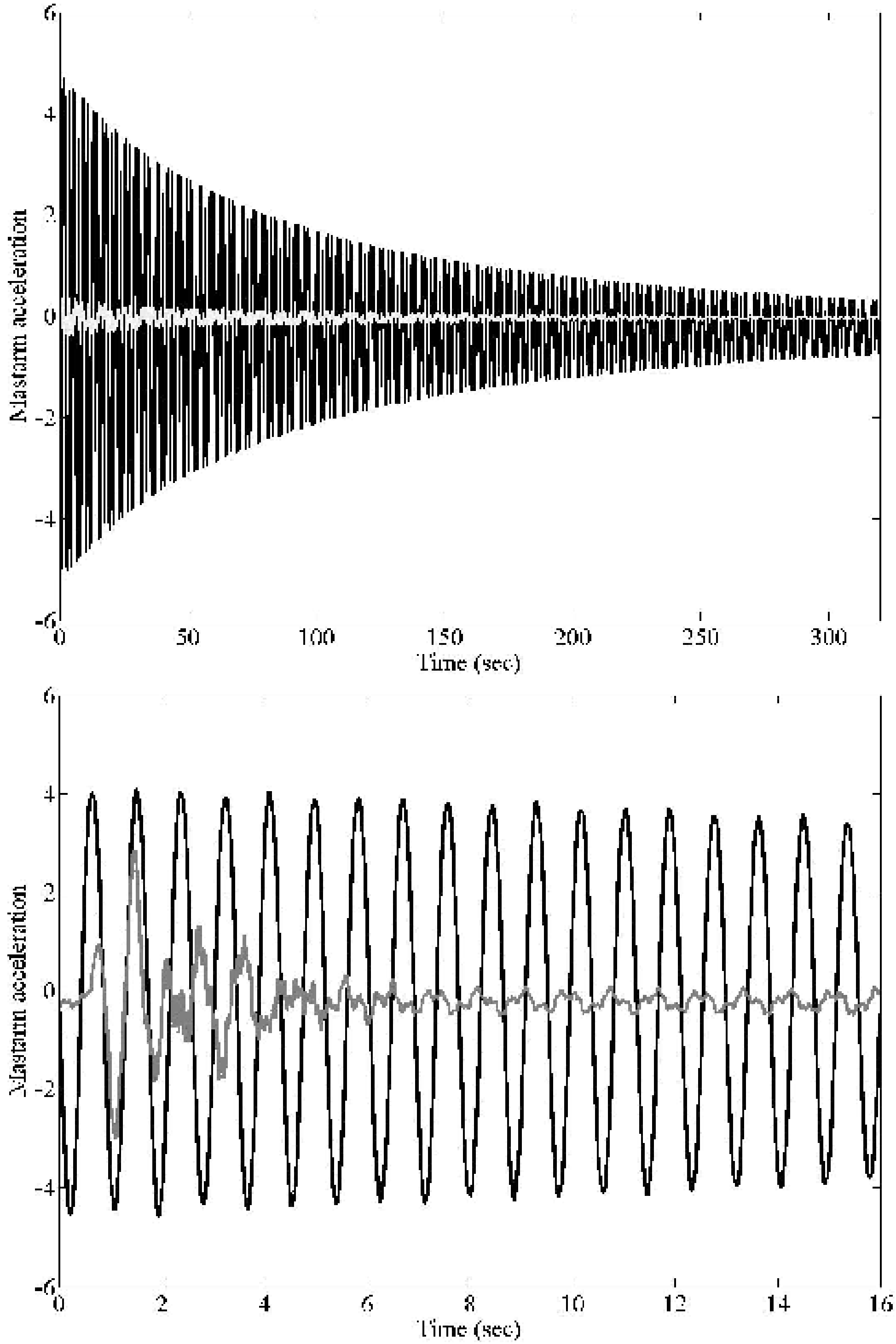

Figure 9: Tip acceleration of traffic pole mast arm without TMD (black) and with TMD (grey).

Figure 10 shows the experimental and predicted response of the traffic pole mast arm for rigid and controlled systems. A good agreement between the numerical and experimental results can be observed. This indicates that the numerical model can be used in future to find the response of the traffic signal mast arm given the natural frequency and mass of the mast arm and signal head are known separately. These can be calculated easily from free vibration tests of mast arm for two conditions: with and without traffic signal head attached (rigidly) using equation 6.

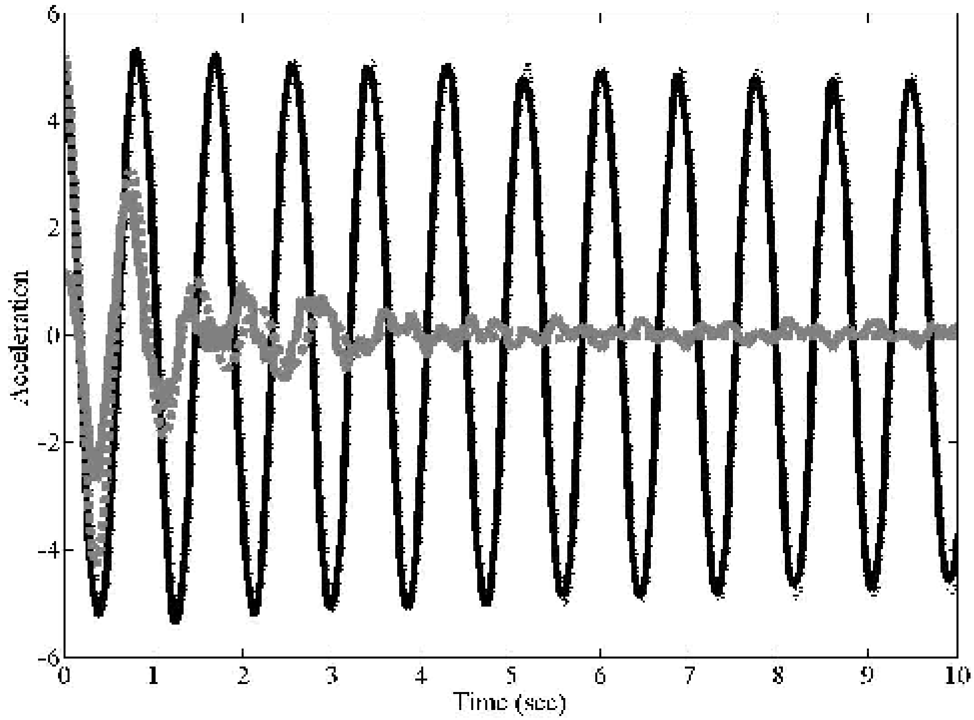

Figure 10: Traffic pole mast arm acceleration for un-controlled (black) and controlled (grey) systems; numerical (dashed) and experimental (solid).

Figure 11 shows the time history response of the traffic signal head for controlled measured, controlled predicted, rigid measured and rigid predicted. The conformity between the measured and predicted response condition further reinforces the accuracy of the numerical model. The response of the signal head dies down after 5 seconds for the controlled case in concurrence with the response of the traffic mast arm whereas the maximum response for the rigid and controlled conditions does not change like that of the mast arm. This is a direct result of the basic principle of the TMD as explained by Den Hartog where the vibration is transferred from the main mass (mast arm) to the TMD (signal head).

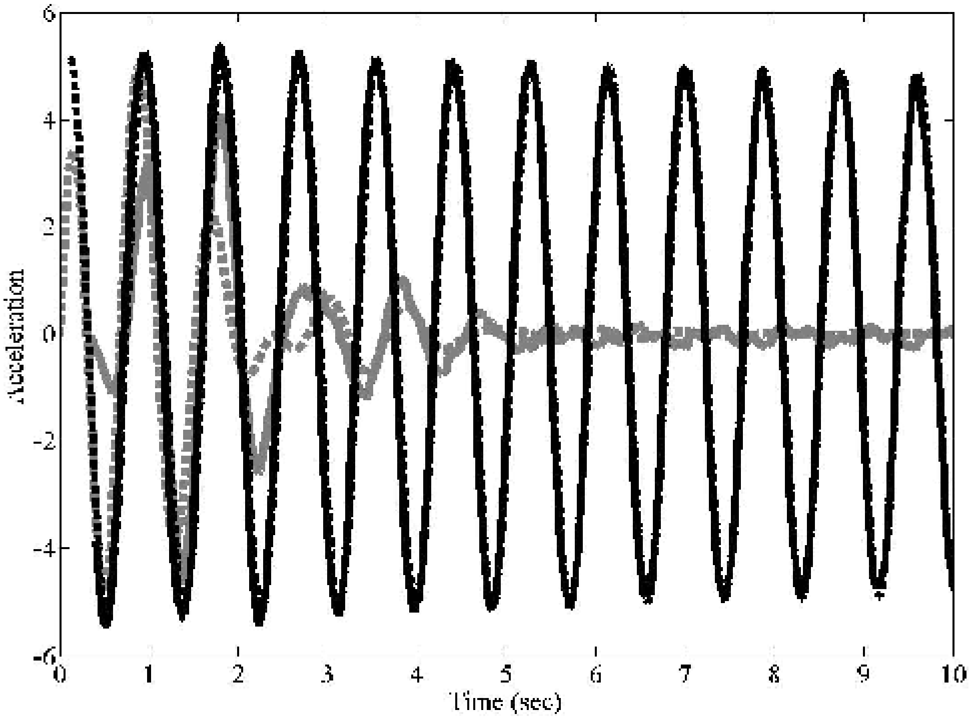

Figure 11: Traffic pole signal head acceleration for un-controlled (black) and controlled (grey) systems; numerical (dashed) and experimental (solid).

INTERESTING AND UNEXPECTED RESULTS

The proposed system was intending to make use of sensors and controllable dampers to provide smart damping control. It became evident within the first year of the project from discussions with the advisory committee that a low technology (no sensors or controllable devices) solution was preferred. This desire for a low-tech solution has been echoed by various owners, manufactures and fabricators. As such, a low technology solution was pursued and that is what has been described here.

PLANS FOR IMPLEMENTATION

The proposed system is expected to reduce the wind-induced vibrations of traffic signal support structures, thereby reducing fatigue and increasing the safe life of the structure. For signal support owners across the nation, this means that fewer resources will need to be devoted to replacing and repairing fatigued signal support structures ultimately resulting in a safer and more efficient surface transportation infrastructure. The sheer number of traffic signal support structures within the transportation infrastructure makes any innovation that can be implemented to extend the life of these structures a great benefit to DOTs, simply from an economy of scale. The proposed low-cost retrofit would be applied to only those signal structures that exhibit vibration problems in the field, thus making the application and use of resources more efficient. The monitoring capabilities would supplement visual inspections.

The proposed smart vibration absorber is relatively inexpensive and easy to install and can provide great savings in the form of increased life of the structure and providing supplemental information for signal support inspection. The results of this work will be disseminated through the Connecticut Technology Transfer Center. Additionally, communications have been and will continue to be established with traffic signal head manufactures and traffic pole fabricators in the United States. Opportunities to further partner with these and additional manufacturers and fabricators will continue to be explored and further developed.

Field testing of the SHVA is recognized as a critical step toward implementation. State and federal funding is currently being sought, through coordination with the Connecticut Department of Transportation, to conduct field tests of the SHVA.

CONCLUSIONS

An innovative vibration absorber to reduce fatigue in traffic signal support structures using the mass of the signal head for the damped vibration absorber is developed and experimentally tested. The SHVA is an inexpensive retrofit to traffic signal support structures experiencing excessive in-plane wind-induced vibration. A research model SHVA is constructed and is tested on a full-scale traffic signal support structure with a 35 foot mast arm located at the University of Connecticut. The SHVA has a simple, low maintenance design utilizing a compression spring and an eddy current damper. A short video describing these efforts can be found at:mms://159.247.0.209/mediapoint/Uconn/NCHRP_Idea_141_v4.wmv.

Free vibration tests are conducted for the rigidly connected signal head and the SHVA system and acceleration responses measured. The time history of the free vibration response shows significant improvement in the attenuation of the response of the SHVA system. The SHVA is able to reduce the acceleration of the mast arm from 0.5 g to 0.06 g (approximately 3.5 inches to 0.4 inches) in 2.75 seconds instead of 300 seconds for the rigidly connected signal head.

From the free vibration tests, the SHVA is experimentally measured to increase the damping in the 35 foot traffic signal support structure from 0.2% of critical to a critical damping ration 10.1%.

The increased damping in the system corresponds to a response reduction of the mast arm in resonance from 48 inches to 0.84 inches, a 98.3% reduction. The response of the signal head, while larger than that of the mast arm, would be similarly reduced from 48 inches to 1.22 inches, or a 97.5% reduction. This significant reduction in vibration amplitude reduces dynamic stresses and can effectively protect the signal support structure against fatigue cracking in the critical components. It is further identified that a SHVA tuned to one specific structure could be applied to a wide range of other signal support structures while still maintaining acceptable performance.

The SHVA is shown to provide dramatic response reduction in an inexpensive and field-ready solution. The SHVA can be applied to either new signal support structures or as a retrofit to existing structures, with installation entailing little more than changing the signal head. The SHVA can potentially change the way vibration in transportation support structures are mitigated.

Future research will focus on testing of the SHVA applied to a variety of traffic signal support structures. In addition to the 35 foot long mast arm a 60 foot long mast arm will be tested in the laboratory at the University of Connecticut. State and federal funding is currently being sought, through coordination with the Connecticut Department of Transportation, to conduct field tests of the SHVA.

Figure 12: Recently acquired 60 foot traffic pole at the University of Connecticut.

INVESTIGATOR PROFILE

The PI, Richard Christenson, earned his Ph.D. degree in civil engineering and geological science at the University of Notre Dame in 2002 and began his academic career at the Colorado School of Mines, Golden before joining UConn in 2006. Dr. Christenson is currently the United Technologies Corporation Professor in Engineering Innovation within the Civil and Environmental Engineering Department. Dr. Christenson has established an internationally-recognized and externally-funded research program in smart structures. His current funded projects are in the areas of structural control, real-time hybrid simulation, and bridge monitoring. Dr. Christenson has been awarded 17 research grants since 2003 with his portion totaling over $2.3M. He has secured over $90k in equipment donations and has built an experimental test facility for research and education in smart structures at the University of Connecticut. He has three 200kN Magneto-Rheological (MR) fluid dampers that have been used for experimental testing at the University of Colorado at Boulder, Lehigh University, and University of Illinois at Urbana-Champaign and is upgrading a network of six permanently monitored highway bridges in Connecticut for bridge health monitoring. External funding sources for his research include the National Science Foundation (NSF), Federal Highway Administration (FHWA), Department of Homeland Security (DHS), National Cooperative Highway Research Program (NCHRP), and Connecticut Department of Transportation (ConnDOT). Dr. Christenson has 14 journal articles and a monograph chapter, with these works cited over 120 times. Dr. Christenson has supervised 16 graduate students (5 PhD and 11 MS). He is Director of Research Program Development for the Department of Civil & Environmental Engineering, Member at Large for the ASCE Structural Control Committee, Steering Committee Member for the 2006 and 2009 American Control Conferences (ACC), and faculty advisor for the UConn ASCE Student Chapter. He has served on numerous NSF Review Panels, and is a Peer Reviewer for 9 different journals and 3 conferences. Dr. Christenson has organized 9 Special Sessions at Conferences and a Workshop on Fast Hybrid Testing of MR fluid dampers. Dr. Christenson's background is in experimental structural dynamics and control with an established expertise in passive, active and semiactive control strategies.

The graduate student, Sharida Hoque, is a Ph.D. candidate in the Department of Civil and Environmental Engineering at the University of Connecticut. Ms. Hoque received her B.S. in Civil Engineering at Bangladesh University of Engineering and Technology (BUET) in 2004 and her M.E. in Structural Engineering at Asian Institute of Technology (AIT) in 2006. She joined the University of Connecticut as a Graduate Research Assistant in 2009. Her research interests are vibration control, structural health monitoring, nondestructive testing of concrete and real time hybrid simulation.

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