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Adaptive-length pendulum smart tuned mass damper using shape-memory-alloy wire for tuning period in real time

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Abstract. Due to the shift in paradigm from passive control to adaptive control, smart tuned mass dampers (STMDs) have received considerable attention for vibration control in tall buildings and bridges. STMDs are superior to tuned mass dampers (TMDs) in reducing the response of the primary structure. Unlike TMDs, STMDs are capable of accommodating the changes in primary structure properties, due to damage or deterioration, by tuning in real time based on a local feedback. In this paper, a novel adaptive-length pendulum (ALP) damper is developed and experimentally verified. Length of the pendulum is adjusted in real time using a shape memory alloy (SMA) wire actuator. This can be achieved in two ways i) by changing the amount of current in the SMA wire actuator or ii) by changing the effective length of current carrying SMA wire. Using an instantaneous frequency tracking algorithm, the dominant frequency of the structure can be tracked from a local feedback signal, then the length of pendulum is adjusted to match the dominant frequency. Effectiveness of the proposed ALP-STMD mechanism, combined with the STFT frequency tracking control algorithm, is verified experimentally on a prototype two-storey shear frame. It has been observed through experimental studies that the ALP-STMD absorbs most of the input energy associated in the vicinity of tuned frequency of the pendulum damper. The reduction of storey displacements up to 80 % when subjected to forced excitation (harmonic and chirp-signal) and a faster decay rate during free vibration is observed in the experiments.

Keywords: smart tuned mass damper; adaptive passive tuned mass damper; short time fourier transform; tuned vibration absorbers; dynamic vibration absorbers; shape memory alloy

1. Introduction

Semi-active control of structural systems using innovative devices such as variable damping systems (Kurata *et al.* 1999) and variable stiffness systems has gained considerable attention over the past two decades (Spencer and Nagarajaiah 2003). The key idea behind the development of these devices is to change the stiffness or damping of this external-device to create a non-resonant structural system as compared to direct application of control force as in the case of fully active systems; hence, these systems need nominal power (Nagarajaiah *et al.* 2010). Reliability of the

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semi-actively controlled systems is an added advantage, as these can operate as a passive device in extreme cases (Nagarajaiah and Pasala 2010). A non-resonant system can be achieved by tuning the instantaneous frequency either by changing the stiffness or damping of the device. It is more efficient to use variable stiffness to effect the change in instantaneous frequency rather than variable damping (Nagarajaiah *et al.* 2010). Variable damping devices are rarely developed for re-tuning frequency, their main objective is energy dissipation (Spencer and Nagarajaiah 2003). Various variable-stiffness-devices and smart-tuned-mass-dampers capable of mitigating the structural response are discussed next.

Kobori *et al*. (1993) developed world's first active variable stiffness (AVS) system. In the AVS system the building stiffness is altered based on the nature of the earthquake, to keep the structure in a non-resonant state. The AVS system has been implemented in a full-scale structure in Tokyo, Japan (1993). The observed response of the structure with the AVS system in two earthquakes in Tokyo indicated the potential of such devices; however, abrupt switching in the AVS system was a limiting factor as observed in one of the earthquakes (Yamada and Kobori 1995). Stiffness of the AVS is changed using hydraulic systems (Yamada and Kobori 1995, Dyck *et al.* 2006). Researchers have developed variable stiffness devices, which are similar in nature to AVS (Yang *et al.* 2007, Yang *et al.* 2000), but are based on pneumatic systems. A new semi-active continuously and independently variable stiffness (SAIVS) device has been developed by Nagarajaiah *et al.* (Nagarajaiah 2000, Nagarajaiah and Sahasrabudhe 2006, Pasala *et al.* 2012) to overcome limitations of AVS systems. This device can switch the stiffness continuously and smoothly. Analytical and experimental studies on SAIVS device indicate the potential of the device in reducing the response (Nagarajaiah and Mate 1998, Chu *et al.* 2005).

The tuned mass damper (TMD) is a passive energy-absorbing system (Ormondroyd and Den Hartog 1928) consisting of a secondary mass, a spring, and a viscous damper attached to a primary system to reduce undesirable vibrations. The TMD has many advantages compared with other passive damping devices: reliability, efficiency, and low maintenance cost to name few. Hence in recent years it has been widely used in civil engineering structures (Nagarajaiah and Pasala 2010). Many researchers have studied the advantages and effectiveness of TMD and have proposed various schemes to improve their robustness and reliability. Most often, in a structure, the first natural frequency and the corresponding mode of the primary system plays a dominant role in the dynamic response. To be effective TMD must remain tuned to the first mode frequency of the original primary system (Ormondroyd and Den Hartog 1928).

However, as it is well known, the TMD is very sensitive to even a small change in the tuning, which can be a disadvantage. The use of more than one TMD i.e., multiple TMD (MTMD) (Abe and Fujino 1994, Jangid 1999, Kareem and Kline 1993) with different dynamic characteristics to improve the robustness has been proposed. However, like a single TMD, MTMDs are not robust under variations in both the primary structures natural frequencies and the damping ratio. The use of an active TMD (ATMD) provides one possibility to overcome these drawbacks (Chang and Soong 1980, Ikeda *et al.* 2001). ATMD and active mass dampers (AMD) have also been developed and implemented widely for applications in response control (Spencer and Nagarajaiah 2003, Chang and Soong 1980, Ikeda *et al.* 2001) of buildings and bridges. ATMD can be more robust to tuning error with the appropriate use of feedback and can be effective in reducing response, but with associated need for application of active forces and substantial power requirement to operate.

Semi-active control of TMD (Hrovat *et al.* 1982, Nagarajaiah and Varadarajan 2005, Nagarajaiah and Sonmez 2007, Contreras *et al.* 2012) and smart tuned liquid column STLD (Yalla *et al.* 2001) offer an attractive alternative to provide a comparable performance with an order of magnitude less power requirement (Nagarajaiah and Varadarajan 2005). The smart TMDs (STMD) and smart MTMDs, developed by Nagarajaiah and coworkers (Nagarajaiah and Varadarajan 2005, Nagarajaiah and Sonmez 2007), is capable of continuously varying its stiffness and re-tuning its frequency due to real time control, and is robust to changes in building stiffness and damping. In comparison, the passive TMD can only be tuned to the first mode frequency of the building. The building fundamental frequency can change due to damage or other reasons. The STMDs developed by Nagarajaiah (2009) overcomes the limitations of the TMD (i.e., detuning) by retuning the frequency in real time and requires an order of magnitude less power (Nagarajaiah and Varadarajan 2005, Varadarajan and Nagarajaiah 2004).

STMD can be tuned to the first mode of the primary system or the dominant response frequency (close to a selected mode–usually the first mode), at which the primary system is responding (Nagarajaiah and Varadarajan 2005), or can be tuned to the dominant excitation frequency (Nagarajaiah and Sonmez 2007). In this paper we tune to the dominant frequency, at which the primary system is responding, by tracking it using the displacement response of the building. ALP-STMD performance in the presence of real-time primary system stiffness change is presented in the companion paper (Contreras *et al.* 2012).

1.1 Adaptive-passive TMD (APTMD) and adaptive TMD

The concept of APTMDs and adaptive-TMDs was first introduced by Nagarajaiah (Nagarajaiah 2009). APTMD is a TMD in which a tuning parameter such as frequency is adjusted passively based on some local mechanical feedback (displacement, velocity, rotation, etc.), but without associated sensing and computer feedback needed in a STMD. In adaptive-TMD the tuning parameter is adjusted in real-time using the local mechanical feedback. Also, the concept of adaptive-TMD is further developed in this paper and a mechanism to practically implement this method is presented. Systems with semiactive variable stiffness devices and TMD/APTMD are linear time varying systems (LTV); hence, algorithms are needed for their identification and control. Recently, Nagarajaiah and his coworkers have developed instantaneous frequency tracking control algorithms (Nagarajaiah 2009). In this experimental study, short time fourier transform (STFT) is used for tracking instantaneous frequency from the measured displacement signal.

This paper presents the development of a new STMD to reduce the vibrations of structures. The new STMD is an adaptive length pendulum (ALP) damper. The length of the pendulum is varied in real time to match the dominant frequency of the structure. A mechanism is developed using shape memory alloy (SMA) actuator, and pulley system to change the length in real time using a DC power supply. The length of the pendulum is adjusted, using a battery, to match the instantaneous frequency calculated using STFT algorithm. Experimental studies are carried on a two-storey scaled model building with ALP-STMD to validate its effectiveness.

This paper is organized as follows: Section 2 presents the STFT time frequency technique. Section 3 details the experimental setup and working principle of the proposed ALP-STMD. Section 4 contains the experimental results for forced vibration, for free vibration and for non-stationary input (sine-sweep). Concluding remarks are presented in section 5.

2. Real time tuning of adaptive length pendulum STMD using STFT control algorithm

The instantaneous natural frequency of the pendulum, ω, is given by

$$\omega = \sqrt{g / L} \tag{1}$$

where, g is acceleration due to gravity, and L is the length of the pendulum. If the length of the pendulum is varied in real time, so does its instantaneous frequency. Pendulum length is adjusted using SMA wire actuator. Thus, the name adaptive length pendulum - smart tuned mass damper (ALP-STMD) and adaptive passive tuned mass damper (APTMD) depending on whether length is controlled in real-time or adjusted passively using mechanical feedback.

2.1 STFT Control Algorithm for Real Time Tuning of ALP-STMD

The Fourier transform (FT) of a signal $s(t)$ is given by

$$S(\omega) = \frac{1}{\sqrt{2\pi}} \int s(t) e^{-j\omega t} dt \tag{2}$$

The short time Fourier transform (STFT), the first tool devised for analyzing a signal in both time and frequency, is based on FT of a short portion of signal $s_h(\tau)$ sampled by a moving window $h(\tau - t)$ (Cohen 1995). The running time is τ and the fixed time is t. Since the time interval is short compared to the whole signal, this process is called the STFT.

$$S_t(\omega) \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(\tau) e^{-j\omega\tau} d\tau \tag{3}$$

where $s_h(\tau)$ is defined as follows

$$s_h(\tau) = s(\tau) h(\tau - t) \tag{4}$$

in which $h(\tau - t)$ is an appropriately chosen window function that emphasizes the signal around the time t, and is a function $\tau - t$, i.e., $s_h(\tau) = s(\tau)$ for τ near t and $s_h(\tau) = 0$ for τ far away from t. Considering this signal as a function of τ, the spectrum can be calculated. Since the window has been chosen to emphasize the signal at t, the spectrum will emphasize the frequencies at that time and hence give an indication of the frequencies at that time. In particular, the spectrum is

$$S_t(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} s(\tau) h(\tau - t) e^{-j\omega\tau} d\tau \tag{5}$$

which is the short-time Fourier transform (STFT). The STFT control algorithm (Nagarajaiah 2009) is adopted to re-tune the ALP-STMD. STFT controller is effective in both mono-component harmonic excitations, as well as in multi component non-stationary earthquake excitations. The instantaneous frequency is identified based on STFT algorithm (Nagarajaiah 2009, Nagarajaiah *et al.* 1999, Narasimhan and Nagarajaiah 2005). The STFT algorithm developed to choose the length of the ALP-STMD is as follows:

1. A moving window is chosen to determine the STFT dominant frequency from the top floor displacement feedback.
2. The dominant frequency, f_d, in each window is identified.
3. If the dominant frequency, f_d, is in the range $0.7 f_{p1} < f_d < 1.3 f_{p1}$, then $f_{STMD} = f_d$, else go to next step.

4. Set f_{STMD} to the optimum value of f_{TMD}.

Once the dominant instantaneous frequency at which the system is responding is identified, the length of the ALP-STMD is changed to tune to the dominant frequency and maximize the response reduction.

3. Experimental Setup

3.1 Description of actual structure

A prototype two-storey shear frame is used in this work, with aluminum flats as columns and 0.25 *in* x1.5 *in* steel flats as slabs, as shown in Fig. 1. The frame is fastened on a shaking table such that the direction of ground motion will cause only in plane motion in the shear frame. The displacement of the frame at floor level is measured using a laser displacement sensor. ALP-STMD is placed on the second-floor. In this paper all the studies are carried with the ALP-STMD at the second-floor level. Shape memory alloy (SMA) wire is used to change the length of pendulum in real time. SMAs are smart materials which have the ability to return to a predetermined shape when heated. When an SMA is below its transformation temperature, it has very low yield strength and can be deformed quite easily upon the application of load. However, when the material is heated above its transformation temperature, it undergoes a change in crystal structure which causes it to return to its original shape. The most common shape memory material, an alloy of nickel and titanium called Nitinol, is used in this experiment. This particular alloy has long fatigue life and high corrosion resistance. Nitinol also has high electrical resistivity which enables it to be actuated electrically by Joule heating. Nitinol SMA wire actuator of 0.010 mm diameter and a transition temperature of 90^{o} C is used in this research. Preliminary tests indicate 0.69 A current is required to raise the temperature of SMA wire beyond the transition temperature.

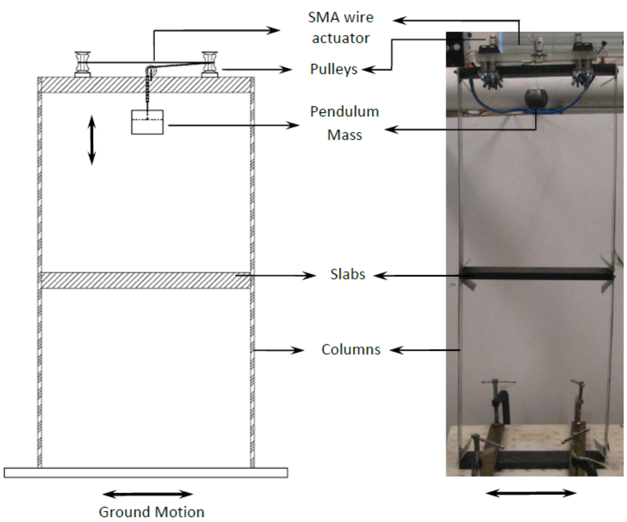

Fig. 1 Elevation of two-storey frame. Left: Schematic representation. Right: Actual setup

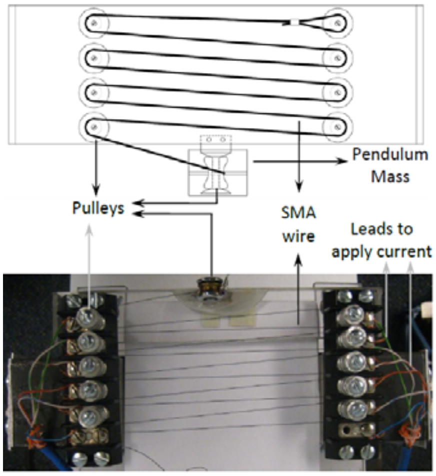

Fig. 2 Top view depicting the mechanism to change the length of pendulum in real time. Top: Schematic representation. Bottom: Actual setup

3.2 ALP-STMD mechanism

Two rows of pulleys are placed at a spacing of 13 cm, aligned in parallel, on the second-floor slab as shown in Fig. 2. Each pulley is made of steel bearing and it is held intact on the screw using aluminum holders. A provision is made to apply voltage to any of the pulleys independently as shown in Fig. 2(bottom). SMA wire is coiled around the pulleys in each row as shown in Fig. 2. One end of the SMA wire is fixed and the other end is connected to a mass weighing 8 oz. The mass is suspended over a pulley as shown in Figs. 1 and 2. Change in overhang length of pendulum can be achieved in two ways:

1. *Changing the current in SMA wire*: By choosing any two specific pulleys, assuming the length of SMA wire coiled between these two pulleys (L_0) produces enough elongation, changing the amount of current in L_0 will result in a variable length pendulum. In this experimental study, an input current of 0.69 A will result in maximum contraction of the SMA wire and the pendulum mass comes all the way up and sits against the ceiling, this configuration has zero pendulum length and is considered as original structure, shown in Fig. 3(left). By reducing the amount of current the length of pendulum starts increasing and when there is no current in the wire longest pendulum length is achieved, shown in Fig. 3(right).
2. *Changing the effective length of SMA wire*: Alternative way to achieve this variable pendulum length is by keeping the current constant and changing the pulleys through which the current is sent. By choosing different pulleys, effective current carrying length of the SMA wire is changed. One limitation of this approach is that it cannot be used to achieve any desired length of pendulum. Only some discrete lengths are achievable, depending on the number of pulleys used in the setup. The choice of the mechanism depends on many factors like availability of the desired relays to regulate the current, constant-current power supply source and ease of implementation. In this work the first approach is used. Whole length of coiled SMA wire is used and the current through the SMA wire is regulated in real time using an electronic-relay and dSPACE data-acquisition board.

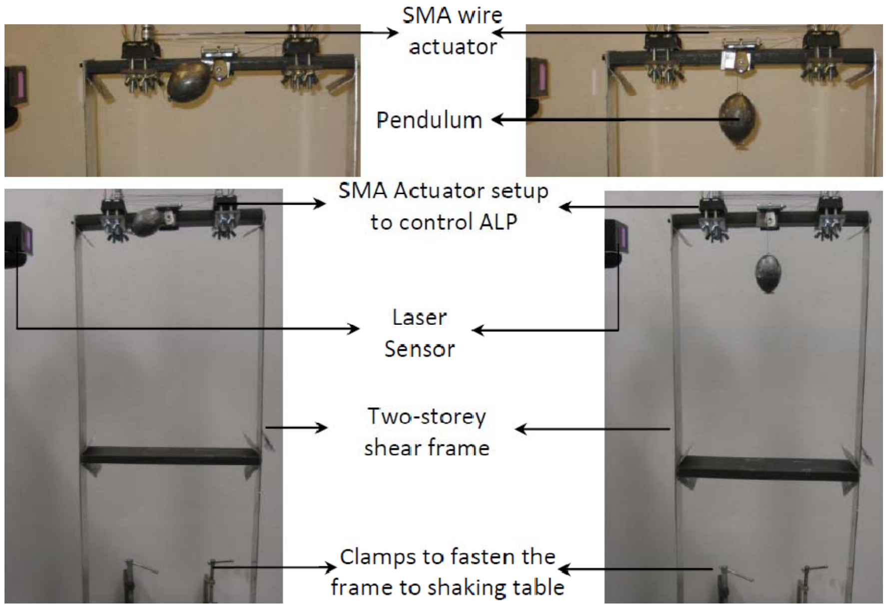

Fig. 3 Experimental setup (Elevation of two storey frame). Left: Maximum current is sent in the SMA wire and in this position TMD is not engaged; Right: Current in the SMA is reduced resulting in a smart pendulum damper

4. Experimental results

As a proof of concept, in this work, the effectiveness of the proposed ALP-STMD is demonstrated for three different input conditions:

1. Steady state response reduction
2. Faster decay of free vibration and
3. Real time response control for a non-stationary input

Displacement response is measured at both first and second-floor level using a laser displacement sensor.

4.1 System identification

Using the chirp signal as input and the displacement as output, frequency response functions (FRFs) obtained for the first and second-floor are shown in Fig. 4. First and second natural frequencies are at 2.341 Hz and 7.09 Hz respectively. The tuning length of pendulum corresponding to each of these frequencies is 4.53 cm and 0.5 cm, respectively. Total length of SMA wire is adjusted such that when there is no current in the SMA wire the overhang length, or the length of the pendulum, is close to 4.53 cm, this configuration will be called as first-mode controlled APTMD from here on. When a current of 0.69 A is applied to the SMA wire the mass will be held all the way up against the ceiling and this is regarded as the original structure (or no TMD). By reducing the current in SMA to 0.51 A the length of the overhang will be 0.5 cm and this is regarded as second-mode controlled APTMD.

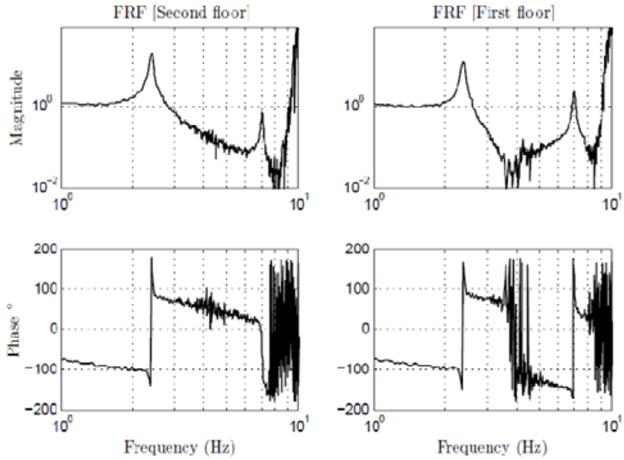

Fig. 4 Frequency response function (FRF) of original structure. Left: FRF from input to second floor displacement. Right: FRF from input to first-floor displacement

4.2 Frequency domain results

All the three configurations, described in section 4, are subjected to the chirp signal and the FRF magnitude obtained for first and second-floor displacement is shown in Fig. 5. In Fig. 5(left) the FRF magnitude of the structure with first-mode controlled APTMD at fundamental frequency (2.341 Hz) is close to 0; whereas, the original structure is 12.5 and 21.5 in the first and second floors, respectively. This shows that, when the length of pendulum is tuned with the first-mode the pendulum damper absorbs all the energy corresponding to that frequency. Similarly, from Fig. 5(right) it can be seen that the FRF magnitude at the first-floor with the second-mode controlled APTMD is 60 % of the original structure.

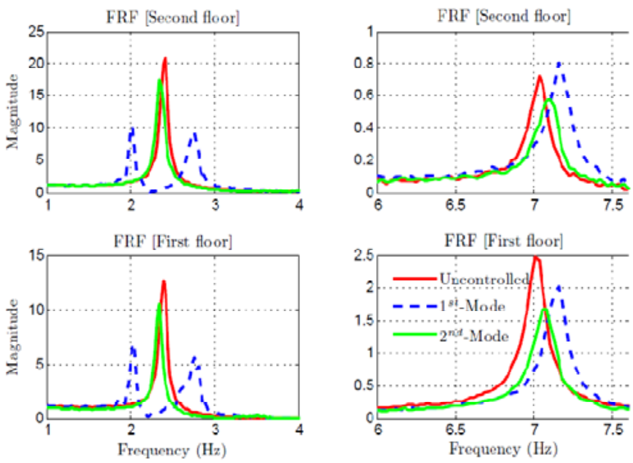

Fig. 5 Comparing the FRF magnitude from input to displacement output Top: FRF from input to second-floor displacement. Bottom: FRF from input to first-floor displacement

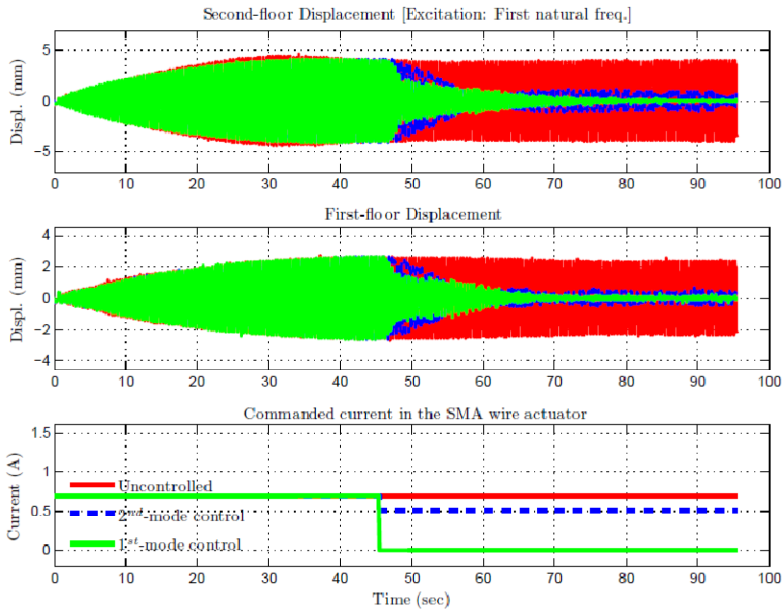

Fig. 6 Response of structure for sinusoidal excitation, excited at first natural frequency

4.3 Time domain results

Steady state response reduction: To examine the effectiveness of ALP-STMD as a vibration absorber, two-storey frame is subjected to sinusoidal ground motion and allowed to achieve steady state. After the frame reached the steady state, the pendulum damper is engaged with first-mode length and second-mode length in two different cases; these responses are in turn compared with uncontrolled case. The second-floor and the first-floor displacement responses when the frame is subjected to sinusoidal excitation at first natural frequency are shown in Fig. 6(top and middle). ALP-STMD is engaged after 45 seconds as shown in Fig. 6(bottom). Since the tuning frequency of the first-mode controlled ALP-STMD and the excitation frequency are matching it gives the optimal control performance. Although there is reduction in response with the second-mode controlled ALP-STMD it is not as effective as the first-mode controlled ALP-STMD because it is in off-tuned state. This is clear from both the first-floor and second-floor displacement response in Fig. 6. Similarly, for sinusoidal ground motion at second natural frequency, second-floor and the first-floor displacements are shown in Fig. 7(top and middle) for all the three configurations and the corresponding plot depicting current variation in ALP-STMD is shown in Fig. 7(bottom).

It is evident from the Figs. 6 and 7 that when the excitation frequency matches with the frequency corresponding to the pendulum length substantial reduction in the displacement responses are achieved; this is called tuning condition. Off-tuned reductions have also been observed but they are not as effective as they are in the tuned case. In the tuned-condition the higher percentage reduction in floor displacements is achieved at the second-floor when the structure is subjected to harmonic excitation at first natural frequency, shown in Fig. 6(top). When the structure is excited at second natural frequency, higher percentage reduction is achieved in the first-floor, shown in Fig. 7(middle).

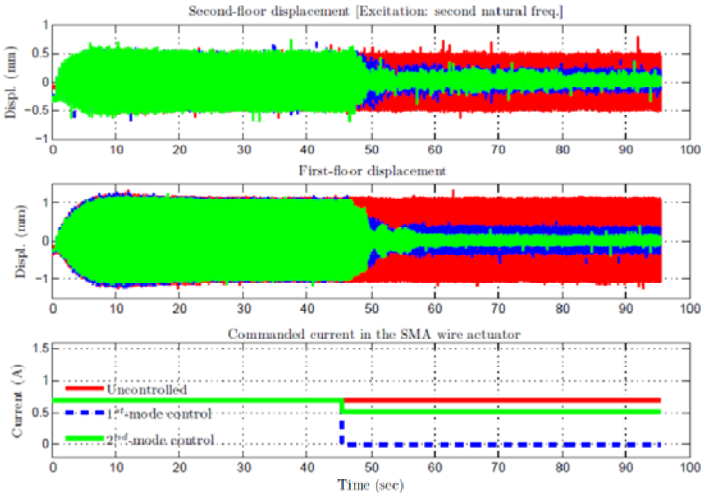

Fig. 7 Response of structure for sinusoidal excitation, excited at second natural frequency

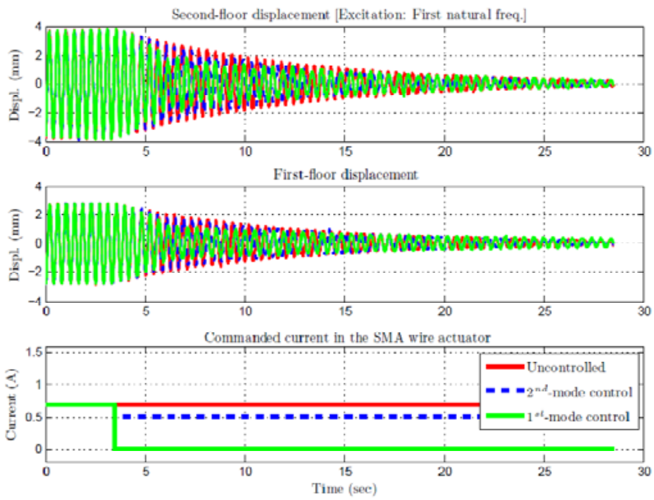

Fig. 8 Free vibration response of structure, after exciting system at first natural frequency up to 3 seconds

Free vibration: To verify that the ALP-STMD increases the damping of the structure, the two-storey frame is subjected to sinusoidal ground motion, once it reaches the steady state the external excitation is stopped and it is allowed to vibrate freely until the oscillations die out. At the same instant when the external excitation is stopped the ALP-STMD is engaged with first-mode length and second-mode length in two different cases; these responses are in turn compared with free-vibration results of the uncontrolled structure. The structure is excited at first natural frequency to reach the steady state and after stopping the excitation, the free vibration displacements of second-floor and the first-floor for all the three configurations are shown in Fig. 8(top and middle) and the corresponding plot depicting the current variation in ALP-STMDs is shown in Fig. 8(bottom). Similarly, for the free vibration after exciting the structure at second natural frequency free vibration displacements of second-floor and the first-floor are shown in Fig. 9(top and middle) and the corresponding plots depicting the current in ALP-STMDs is shown in Fig. 9(bottom). It is clear from free vibration results that the ALP-STMD increases the damping properties of the structure both in the tuned and off-tuned conditions but the reductions will be slightly higher in the tuned case, shown in Figs. 8(top) and 9(middle).

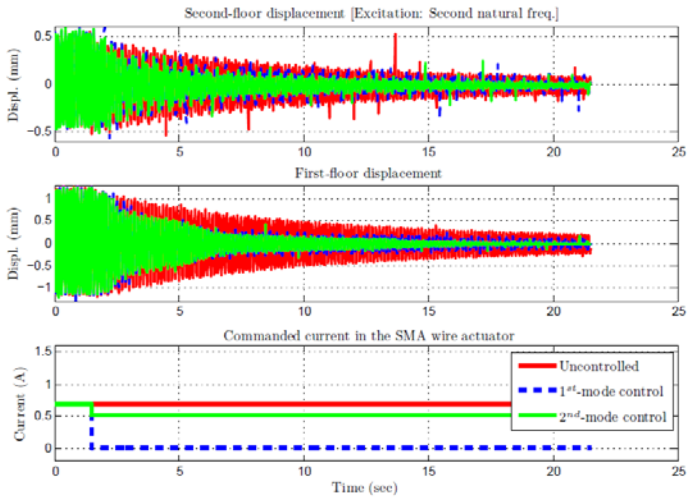

Fig. 9 Free vibration response of structure, after exciting system at second natural frequency up to 2 seconds

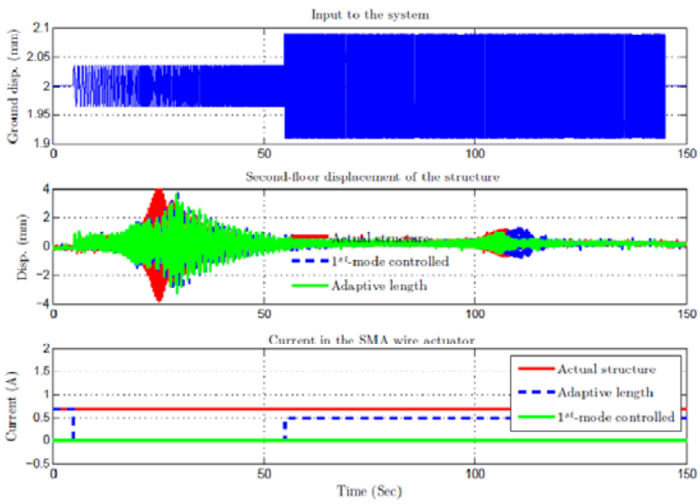

Fig. 10 Response of structure, excited using sinsweep input and displacement measured at second floor

Non-stationary input: To show the capability of ALP-STMD to adapt in real time, modified chirp signal is used as ground motion, shown in Fig. 10(top), to excite both first and second modes of the two-storey frame. Response of the uncontrolled structure is compared with a APTMD tuned to first-mode and an ALP-STMD which is capable of changing the length of pendulum in real-time by tracking the instantaneous dominant-frequency of the structure. Instantaneous frequency of the structure is found by applying STFT algorithm on the second floor displacement signal. It can be seen that the input chirp signal has two different amplitudes, at high frequencies larger amplitude is chosen because the higher modes need a large amount of energy to excite. In the APTMD the current is kept constant at 0 A, shown in Fig. 10(bottom). In ALP-STMD, before exerting the ground motion on the structure the current in ALP-STMD is 0.69 A (uncontrolled state), then the current is reduced to 0 A after 5 seconds because the instantaneous frequency of structure is close to first natural frequency. Then the length of the pendulum is changed from first mode length to second mode length at 55 seconds by increasing the current in SMA to 0.51 A, shown in Fig. 10(bottom). Response of all the three structures is shown in Fig. 10(middle). Since both the APTMD and ALP-STMD are in tuned-condition from 5 seconds to 55 seconds the large peak observed in the uncontrolled structure at 25 seconds is avoided, shown in Fig. 10(middle). At 110 seconds, in Fig. 10(middle), since the APTMD is off-tuned it has higher response compared to ALP-STMD; but, it is still significantly lower than the uncontrolled structure. It is evident from the Fig. 10 that the ALP-STMD will have all the advantages of passive TMD and additionally, the length of the pendulum can be adjusted in real time resulting in a reduced structural response. Exact trend is observed in the FRF plots shown in Fig. 11. Both ALP-STMD and APTMD have very low magnitude at first natural frequency, shown in Fig. 11(left) but ALP-STMD has 50 % less magnitude at second natural frequency, shown in Fig. 11(right).

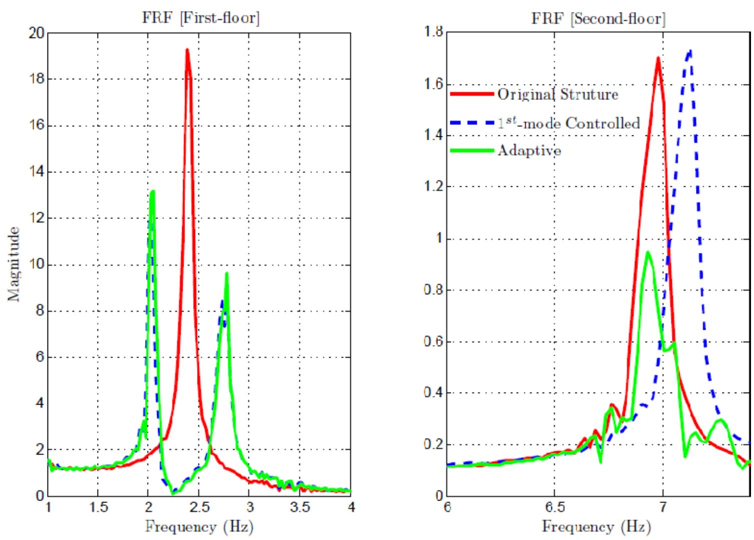

Fig. 11 FRF magnitude from input to second-floor displacement, for sinsweep excitation

For all the experimental results presented in this paper, the pendulum length is zero when the current in the SMA wire is maximum (0.69 A). Essentially, to disengage the TMD maximum current has to be sent through the SMA wire and the TMD engages when the amount of current is reduced. From the practical implementation of view, it is desired if the TMD has zero pendulum length when there is no current in SMA wire and the length increase proportionally as the current in the SMA is increased. To achieve this, a mechanical system using four springs is proposed next. Schematic diagram of the proposed setup is shown in Fig. 12. The setup has two rigid plates (green and blue color plates in Fig. 12) placed vertically and separated by four linear springs. The green plate is fixed at the bottom and the blue plate has rollers at the bottom allowing the plate move freely without friction. Two cables are connected to the blue plate through the clear holes in green plate. One cable (cyan color) will be the SMA wire and the other cable (magenta color) is to connect the suspended mass. Length of the cable that connects the suspended mass is designed such that the TMD has zero length when there is no current in SMA wire. By passing current through SMA wire, the blue plate is pulled closer to the green plate and the suspended length of the TMD increases. When the current in removed, the blue plate moves back due to the linear springs; bringing the TMD back to its initial position.

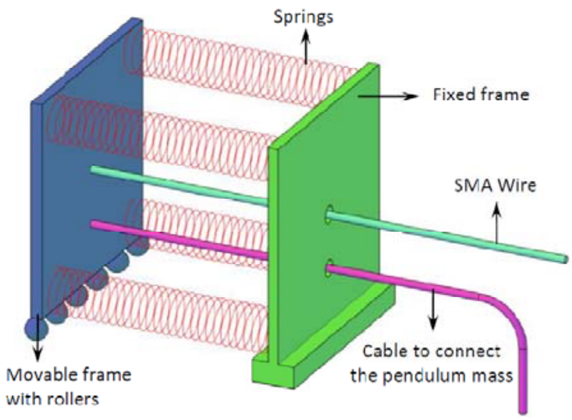

Fig. 12 Mechanism to implement the ALP-STMD in real life structures

5. Conclusions

In this paper, a novel method to control the response of structural system using adaptive length pendulum smart tuned mass damper (ALP-STMD) is proposed. A mechanism to achieve the variable pendulum length is developed using shape memory alloy wire actuator. The effectiveness of the developed ALP-STMDs has been verified through experimental studies. STFT algorithm is used to find the instantaneous frequency of the structure. ALP-STMD acts as a vibration absorber and since the length is tuned to match the instantaneous frequency all the vibrations pertaining to the dominant frequency are absorbed. The performance of the ALP-STMD is verified for forced vibration (stationary and non-stationary) and free vibration. It has been found that the novel ALP-STMD developed in this study is capable of absorbing all the energy pertaining to the tuned-frequency of the system. APTMD, wherein, the length is adjusted passively (offline) is an ALP-TMD in which the frequency is adjusted by changing the length of pendulum passively without any associated sensing and computer feedback signal. The new ALP-STMD and the APTMD proposed in this study have a great deal of promise for practical implementation.

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