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Application of pre-stressed SMA-based tuned mass damper to a timber floor system

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Abstract

Shape memory alloy (SMA) is becoming a popularly studied smart material in the field of structural control. The feasibility of utilising an SMA in a tuneable mass damper to reduce the excessive vibration of a timber floor system was revealed in a pilot study. However, the in-service excitations on a floor can be complex and involve more frequencies and randomness; therefore, this paper aims to assess the effectiveness of the SMA-based semi-active TMD in a real-scale timber floor, where the free vibration and human footfall-induced vibration are considered as inputs. This study is conducted using numerical simulations on OPENSEES. By reducing the floor vibration at a range of frequencies, both cooling and heating the SMA are effective in retuning the off-tuned TMD and reducing the structural response. Footfall excitation involves more than one excitation frequencies, and the higher dominant frequencies can resonate with the off-tuning frequencies, increasing the structural response. Simulation results demonstrate that retuning using SMAs can effectively lower the structural response at a wide range of frequencies, thus attenuating the footfall-induced vibration.

Keywords

Shape memory alloy; Timber floor; Tuned mass damper; Retuning; Footfall vibration

1. Introduction

Timber floor is a common structural system utilised around the world, as such flooring materials can add benefits to construction; for example, they are light-weight, pre-fabricated and environmentally friendly because of their carbon storage capacities. However, human activities and machine operations can cause excessive vibrations in timber floors. Such excessive vibration can lead to building occupants experiencing uncomfortable sensations or even feeling anxious, which is a problem that designers should address (Hu et al., 2001, Smith and Chui, 1988, Thelandersson and Larsen, 2003). In order to investigate how to reduce timber floor vibration, several studies have examined the design criteria for this type of floor (Smith and Chui, 1988, Kalkert et al., 1995, Foschi et al., 1995, Al-Foqaha'a et al., 2001). The traditional passive approach requires the floor natural frequency to be higher than 8 Hz, which avoids resonance with human-induced vibration and requires less root mean square (RMS) acceleration response. With the development of vibration control techniques, studies on tuned mass damper (TMD) systems have been conducted in order to assess their application in floor systems as a more effective vibration reduction approach, with various levels of success (Breukelman and Haskett, 2001, Setareh et al., 2007, Baxter and Murray, 2003).

However, the mass on a floor system always changes, the stiffness of the floor system is usually modified owing to ageing or moisture variance, and the damping changes as a result of furniture or excitation changes. In such cases, the traditional passive TMD is unable to function effectively because of off-tuning (Setareh et al., 2007). Moreover, in civil structures, excitations can involve a broad range of frequencies and, once resonance occurs, the serviceability of the floor system could be significantly reduced. Installing an active TMD is an approach that attenuates the vibration by exerting forces; however, it is considered to be expensive and power-consuming, as demonstrated by Connor (2003) and Setareh et al. (2007). Semi-active TMDs are becoming increasingly studied devices, as they provide adjustable dynamic parameters and are mechanically simple (Lin et al., 2005, Varadarajan and Nagarajaiah, 2004, Sun et al., 2013). The variable properties of the semi-active TMD enable it to retune the natural frequency of the main structure, so as to reduce the structural response. Compared with active TMDs, semi-active TMDs do not introduce energy to the entire system; however, semi-active TMDs can provide comparable vibration control capacities and can even behave in a more effective manner. More importantly, semi-active TMDs are more cost effective, easier to install and possess energy-saving capabilities.

To achieve the purpose of retuning, shape memory alloy (SMA) can be of significant benefit in respect to its self-centring capacity, temperature controllability and adequate fatigue life compared to traditional construction materials. SMAs have two particular phases: austenite and martensite, which are highly dependent on the in-service temperature. As illustrated in the literature, as well as in Figure 1 (a), M_s, M_f, A_s and A_f indicate the start and finish temperatures of the martensitic and austenitic transformations, respectively. When the in-service temperature is above A_f, the SMA exhibits superelastic behaviour, as shown in Figure 1 (c), where the hysteresis is self-centring. When the in-service temperature is below the phase transformation temperature, the SMA exhibits shape memory effect, as one can see in Figure 1 (b), where the recovery strain requires external heating. Superelasticity is the main focus of this study, as it induces faster self-centring and has higher elastic modulus compared with that of the shape memory effect. Overall, the mechanical properties of SMAs, such as the elastic modulus and damping ratio, are highly dependent on the in-service temperature (Araya et al., 2008, Andrawes and DesRoches, 2007, Huang et al., 2016), which augments their potential for use in semi-active TMDs with temperature control in terms of retuning.

Williams et al. (2002) devised a NiTi SMA wires-based TMD and applied it to a cantilever beam. Heating the SMA wires through a power supply led to changes in the stiffness of the TMD; thus, excessive vibration in the primary structure could be attenuated for several discrete frequencies. Furthermore, Rustighi et al. (2005), Mani and Senthilkumar (2015), Savi et al. (2011) and Aguiar et al. (2013) developed temperature control techniques to change the stiffness of the SMA so as to semi-actively control the vibration of the main structure for a wider frequency range, and the effectiveness of the SMA-based TMD was proved. The aforementioned applications of semi-active TMDs using SMA were predominantly developed to reduce machine-induced vibration in mechanical domains. However, in civil engineering, buildings commonly experience vibrations that have a wider frequency range and are more random, e.g. excitations caused by earthquakes, wind and human activities. Thus, excitations with a wider range of frequencies should be considered in the assessment of SMA-based semi-active TMDs. Unlike the method of using SMA wires in previous studies, temperature control utilising SMAs with the larger size, such as SMA bars, should be considered and studied regarding their feasibility for use in large-scale construction.

As illustrated in the feasibility study conducted by the authors, a temperature controlled semi-active TMD with pre-stressed SMA bar was studied for timber floor applications and was proved to be effective in reducing the response of a timber floor system (Huang et al., 2016). This paper continues the study and investigates its application in a real-scale timber floor system under various excitations. The study is based on a structural dynamic analysis program on OPENSEES software, in which the modelling code is developed by the authors. Firstly, the response of the floor system is analysed in the frequency domain in order to control the vibrations over a wide range of frequencies owing to the serviceability of civil structures; moreover, human footfall-induced vibrations is taken into consideration as inputs to assess the effectiveness in the time domain.

2. Assessment of the semi-active TMD in the frequency domain by free vibration

As explained previously, the variable main structural mass could induce off-tuning in a TMD, which means that retuning is required to reduce the vibration. In this section, a timber floor is simulated and designed to be off-tuned; the feasibility of a SMA-based semi-active TMD in retuning the structure by shifting its natural frequencies is then investigated. A timber floor can experience a wide range of excitation frequencies during its service; therefore, the response in the frequency domain is analysed initially.

2.1 Materials and method

The tested timber floor is a joist-free mass timber floor – profideck with plan dimensions of 6 m × 6 m and a thickness of 190 mm, as shown in Figure 2. The strength class of the profideck is GL 24h; the self-weight of the floor system is 2,394 kg. The timber floor is a one-way system, which means the floor slab is supported on two opposite sides only and bent in one direction. The equivalent viscous damping ratio of the timber floor (denoted by c_1) is 2%, as is commonly practised (Thelandersson and Larsen, 2003, McKenzie and Zhang, 2007).

The tested timber floor system with SMA-based TMD was modelled on OPENSEES software (version 2.5.0). The floor system model on OPENSEES is based on a structural dynamic analysis program. The elements are modelled using bar elements, for example, the timber floor is modelled using the elasticBeamColumn element and the SMA-based TMD is modelled using the nonlinearBeamColumn element. The elasticBeamColumn element is an elastic body determined by the cross-section area, the elastic modulus and the moment of inertia while the behaviour of the nonlinearBeamColumn element is controlled by 10 element integration points. The boundary condition of the floor system is that it is simply supported, i.e. one support is constrained longitudinally and horizontally and another is constrained longitudinally; the connection between the SMA-TMD and the floor system is rigid. The convergence analysis type is NormDispIncr with a tolerance of 1.0e-4 and max iterations of 50. The time integration method employs Newmark's method, which can compute the structural transient responses. The constitute nonlinear behaviour of SMA is considered by the SelfCentering model on OPENSEES. As there is no large deformation in the structural system induced by the human footfall, the geometric nonlinearities are not considered in the analysis.

In Figure 2, the SMA-based TMD is installed in the centroid location and connected with the floor using a rigid steel support. When the floor experiences vibrations, the SMA cantilever beams can be bent, and the load is transferred vertically. The SMA bar was modelled using superelastic Cu-Al-Mn SMA (Cu = 81.9%, Al = 7.4% and Mn = 10.7% by weight), and the mechanical properties were the same as the SMA bar tested in our feasibility study (Huang et al., 2016). The phase transformation temperatures are $M_s = -74$℃, $M_f = -91$℃, $A_s = -54$℃ and $A_f = -39$℃, so superelastic deformation occurs at room temperature. Figure 3 shows a comparison between the static tested stress-strain curve (black dot curve) and the modelled stress-strain curve on OPENSEES (red curve). The unloading curve on OPENSEES was modelled to be self-centring owing to superelasticity, and the damping ratio of the material was set as approximately 2% at a strain level of 3%. As seen in Figure 2, the TMD system includes two SMA cantilever beams on both sides that transfer the force vertically and prevent rotational force being exerted on the floor. Each SMA cantilever beam is 100 mm long, 48 mm wide and 10 mm thick, and is rigidly clamped onto the steel support.

The mass attached to the end of the SMA cantilever beam (denoted by m_T) was 110 kg. At a room temperature of 21℃, the natural frequency of the SMA cantilever beam (denoted by f_T) was found to be 8.38 Hz by eigenvalue analysis. Through carrying out a static loading test on OPENSEES, it was determined that the mass of 110 kg attached to the SMA beam can cause a pre-stressed level of 129.5 MPa by measuring the stress at the end of the clamping side. Therefore, the temperature effect on the stiffness of the SMA can be referred to the experimental results at a pre-stressed level of 131 MPa demonstrated by Huang et al. (2016). At a pre-stressed level of 131 MPa, the stiffness can be increased by 4.32% under heating to 120℃ and decreased by 11.40% under cooling to 11℃. Therefore, in terms of the stiffness variance, the natural frequency of the SMA cantilever beam modelled in this section is able to shift from 8.38 Hz to 8.56 Hz by heating to 120℃ and to 7.88 Hz by cooling to 11℃. According to the phase transformation temperatures of SMA, it is noticed that the SMA is austenitic and there is no phase transformation during the temperature variance. As indicated in the previous study (Huang et al., 2016), the damping ratio of SMA reduces when the temperature goes higher. Because the low damping ratio could lead to limited effectiveness, in this simulation, supplementary damping materials were modelled to complement the TMD system in order to increase the damping of the SMA cantilever beam. Thus the damping of the TMD system is contributed from both the hysteretic loop of SMA and the hysteretic loop of the supplementary damping materials. The equivalent viscous damping ratio of the TMD system (denoted by c_T) was set at 10.9% using Rayleigh damping, which was estimated using the optimal design formula proposed by Warburton (1982).

In accordance with Den Hartog (1956)'s theory, in frequency domain, one peak response of SDOF system is divided into two peaks by installing a TMD. In the condition that the damping ratio of TMD is optimised, by varying the natural frequency ratio between the TMD and the primary structure, the height of these two peaks can be shifted up and down. Therefore, it can be seen that the nearly-optimal tuning condition is where the response amplitudes of the first two modes are equal by adjusting the natural frequency ratio between the TMD and the primary structure. Therefore, based on the nearly-optimal tuning theory, the mass designed to be added on the timber floor was 4,209 kg, and the total mass of the timber floor (denoted by m_1) including the self-weight was 6,603 kg. These loads were uniformly distributed on the floor. Through eigenvalue analysis, the natural frequency of the timber floor without TMD (denoted by f_1) was determined to be 8.00 Hz. Because the tested timber floor system is joist-free and one-way, the first natural frequency is quite low. In summary, the nearly-optimally designed dynamic parameters are tabulated in Table 1. The mass ratio between the TMD and the primary structure is a crucial parameter in the design process. According to Bachmann (1995)'s theoretical study, a further increase in mass ratio between TMD and the primary structure beyond a certain value can lead to negligible effect to the structure. Also, a large mass ratio would induce a big loading to the structure and increase the construction difficulties and costs. If the mass ratio is too small, the effectiveness of TMD could become negligible. An optimal range 1/50-1/15 of the mass ratio is given as a practical hint by Bachmann (1995) to design the TMD more effective. The mass ratio of the timber floor-TMD system in this study is 3.33%, which is in the recommended range of 1/50 to 1/15 (Bachmann, 1995).

Table 1 Nearly-optimally designed dynamic parameters for main structure and TMD

Timber floor	f_1	8.00 Hz
	m_1	6603 kg
	c_1	2.00%
TMD system	f_T*	8.38 Hz
	m_T*	110 kg
	c_T*	10.90%
Mass ratio		3.33%

*These parameters are only for one SMA cantilever beam

The frequency domain analysis was conducted by using 5 seconds of free vibration acceleration data. The free vibration was initiated by applying a vertical impulse of 1 kN at the centroid of the timber floor, and the acceleration was also measured at this point. The testing sequences are tabulated in Table 2. Test No.1 demonstrates the vibration response without TMD control and Test No. 2 displays the effect of the nearly-optimally designed TMD on the structural response. To break the optimal condition, the main structural mass was increased by adding 850 kg in Test No. 4; then, the TMD was cooled in order to lower the natural frequency in order to retune it to the optimal condition in Test No. 5. Test No. 7 models the off-tuning by decreasing the structural mass by 150 kg, and Test No. 8 demonstrates retuning by heating. In this study, the damping ratio of the TMD (c_T) remained constant, and retuning was achieved by natural frequency shifting.

Table 2 Testing sequences for the timber floor-TMD system and the corresponding dynamic parameters

	Main structure		TMD			
Test No.	m_1 (kg)[(1)]	f_1 (Hz)[(2)]	T (°C)[(3)]	f_T (Hz)[(4)]	m_T (kg)[(5)]	c_T (%)[(6)]
1	6603	8.00	-	-	-	-
2	6603	8.00	21	8.38	110	10.9
3	6603+850	7.53	-	-	-	-
4	6603+850	7.53	21	8.38	110	10.9
5	6603+850	7.53	11	7.88	110	10.9
6	6603-150	8.09	-	-	-	-
7	6603-150	8.09	21	8.38	110	10.9
8	6603-150	8.09	120	8.56	110	10.9

(1) total mass of the timber floor system
(2) natural frequency of the main structure
(3) working temperature of the SMA beam
(4) natural frequency of one SMA cantilever beam
(5) mass attached to the SMA cantilever beam
(6) equivalent viscous damping ratio of the SMA cantilever beam

2.2 Results

The five seconds of free vibration data in the time domain was transformed to the frequency domain via Fast Fourier Transformation (FFT). As presented in Figure 4, the structural response at the centroid in Test No. 1 and Test No. 2 are shown in the frequency domain. By employing the TMD, the structural response can be significantly reduced. The study conducted by Setareh et al. (2007) stated that a floor response factor R in terms of the highest acceleration amplitude X_1 and force amplitude F_0, is defined as:

$$R = \left| X_1 / \frac{F_0}{m_1} \right| \tag{1}$$

This floor response factor R reduces the influences of the excitation force and structural mass on the vibration. Table 3 compares the structural response in terms of maximum acceleration amplitude and R factor in the frequency domain, and the RMS acceleration in the first five seconds in the time domain. In the frequency domain, the highest acceleration amplitude and floor response factor R can be reduced by approximately 72%, while the RMS acceleration can be reduced by 46.4% in the time domain. The results show that the TMD system can be effective in controlling the structural response.

Table 3 Comparison between Test No. 1 and Test No. 2 in terms of maximum acceleration amplitude in frequency domain, R factor and RMS acceleration in the first five seconds in the time domain

	Maximum acceleration amplitude (m/s^2)	Floor response factor R	RMS (gal)
Test No. 1	1879.80	89290.59	0.827
Test No. 2	530.45	25196.45	0.443
Reduction percentage	71.7%	71.8%	46.4%

However, when the structural mass increases, the TMD becomes off-tuned and the natural frequencies shift towards the higher frequency. This leads to a higher acceleration amplitude, as shown in Test No. 4 by Figure 5. By cooling the SMA to reduce the stiffness, the retuning approach is capable of shifting the natural frequencies back to a lower frequency range, thus they can become more effective in controlling the response in the frequency range between approximately 2 Hz and 14 Hz. According to Table 4, retuning by cooling the SMA can reduce the structural response by 26% in the frequency domain and 1.5% in the time domain in terms of free vibration.

With respect to the off-tuning problem caused by decreasing the structural mass, the off-tuned condition can lead to a higher acceleration amplitude in comparison of the response between Test No. 2 and Test No. 7. As shown in Figure 6, by heating the SMA to increase the stiffness of the TMD, the structural natural frequencies can be effectively shifted to the higher frequency, thus the amplitude in the second mode is lowered. In Table 5, one can see that the acceleration amplitude and floor response factor R can be reduced by 12.9% and the RMS acceleration in the 5-second free vibration can be reduced by 1.5%.

Table 4 Comparison between Test No. 4 and Test No. 5 in terms of maximum acceleration amplitude in the frequency domain, R factor and RMS acceleration in the first 5 seconds in the time domain

	Maximum acceleration amplitude in the frequency domain (m/s^2)	Floor response factor R	RMS (gal)
Test No. 4	636.50	35644.07	0.457
Test No. 5	470.86	26368.35	0.450
Reduction percentage by retuning	26.0%	26.0%	1.5%

Table 5 Comparison between Test No. 7 and Test No. 8 in terms of maximum acceleration amplitude in frequency domain, R factor and RMS acceleration in the first 5 seconds in the time domain

	Maximum acceleration amplitude in the frequency domain (m/s^2)	Floor response factor R	RMS (gal)
Test No. 7	581.70	26,757.97	0.455
Test No. 8	506.42	23,295.17	0.448
Reduction percentage by retuning	12.9%	12.9%	1.5%

2.3 Discussion

The results in this section concur with the experimental results in the study by Huang et al. (2016), who tested a cantilever beam with a pre-stressed SMA-based TMD. The temperature control on the SMA can effectively shift the natural frequencies to an optimal tuning condition, thus reducing the vibration. In the study by Huang et al. (2016), the damping loss of the SMA while heating increased the structural response. In this section of the study, additional damping materials were applied to the TMD, and the equivalent viscous damping ratio of the TMD system was maintained at a constant satisfactory level. The results show that the acceleration amplitude does not increase after SMA heating. Therefore, in future applications of SMAs in semi-active TMDs, supplementary damping should be implemented. According to the study by Berardengo et al. (2015), eddy currents were utilised in a TMD as an additional device that not only provided more damping but also adjusted the damping ratio. The device developed by Berardengo et al. (2015) was employed for mechanical applications and operated with SMA wires. For civil engineering applications with larger excitation amplitudes and wider frequencies, there is potential for further analysis into the possible utilisation of eddy current in semi-active TMDs. As demonstrated in the literature review, the application of magnetorheological systems in damping control for TMDs could also be studied further (Lin et al., 2005).

The reduction of vibration in this study is predominantly focused on lowering the vibration amplitude in a wide range of frequencies. This is because, when timber floors are in service, people's activities and machine-induced vibrations could combine and cause complex excitation, even at higher frequencies. However, if there is a single harmonic loading, the response at a specific frequency should be considered. For instance, as seen in Figure 5, when there are harmonic excitations at approximately 7 Hz, the retuning can function effectively. However, when the frequency range is between 8 and 9 Hz, the retuning could potentially induce larger vibration. Therefore, a control system incorporating a sensor should be developed in future studies, which can detect the excitation frequency and avoid resonance with that frequency.

It is important to note that the dimensions of the SMA cantilever beams in this study are different from that in the study by Huang et al. (2016), because the SMA size should be larger for a real-scale main structure. The effect of temperature on stiffness may be different for different sizes of SMA, as the transmission of heat can differ. The variance of the stiffness of SMAs under heating and cooling in this study is an estimation based on the results of material characterisation by Huang et al. (2016). For practical usage, studies on the effect of temperature should focus on the specific size of the SMA component. With the development of heating and cooling techniques, faster and more effective temperature control approaches could be applied to avoid the variance of the temperature effect. In this study, it is found that, when heating SMAs, the stiffness is altered in a small range, because the transformation temperatures of the modelled SMA are low at approximately -25 to 5°C. A SMA with higher transformation temperatures should be developed in the future in order to increase the sensitivity in higher temperature control.

2.4 Summary

In this section, a timber floor system with the SMA-based semi-active TMD was simulated on OPENSEES. When the parameters of the TMD are nearly-optimally designed, the structural response can be effectively reduced in a wide range of frequencies. When off-tuning occurs by changing the main structural mass, the acceleration amplitude increases. To retune the main structure, the stiffness of the SMA can be increased or decreased to allow the frequency to shift to the optimally designed range through temperature control. After retuning, the structural response can be effectively reduced in a wide variety of frequencies under both heating and cooling.

3. Reducing the footfall-induced vibration on timber floor systems by controlling the TMD using an SMA – time domain analysis

Human-induced vibration on structures is an issue of serviceability and can be a source of discomfort for building occupants (Thelandersson and Larsen, 2003). The human activities that could occur should be considered in the design of a floor system. In this section, the structural response under the excitations caused by footfall is examined. When the TMD installed on the floor becomes off-tuned because of mass variance, it is particularly important to assess the vibrations caused by footfall. The retuning approach using SMA heating/cooling aims to control the vibrations in off-tuning subject to footfall.

3.1 Methodology

The timber floor-TMD system shown in Figure 2 was put for continuous use. The initial parameters for the timber floor and TMD were set to the levels presented in Table 1. Because the frequency of people walking normally ranges from 1.7-2.3 Hz, which is significantly less than the natural frequencies of the timber floor system, the response was consequently small. In this section of the study, the footfall of running is considered as the excitation frequency. As shown in Figure 7 (a), the distance between each running step is set to be 600 mm, which means that a person exerts a total of nine steps each time when he/she traverses the floor. In Figure 7 (b), the force-time history of each running step is modelled by two peaks, according to the measurement and characterisation of footsteps conducted by Galbraith and Barton (1970), Ohlsson (1982) and Thelandersson and Larsen (2003). The first peak denotes the heel strike, and the second corresponds to the toe-lift off contact. The amplitude of the second peak is 1.4 kN, which models the running characteristics of a person with a gravity of around 0.7 kN (Ohlsson, 1982). The running rate is 3.5 Hz which is within the common range of human running (Rainer et al., 1988, Thelandersson and Larsen, 2003).

The loading protocol shown in Figure 7 (b) was input into OPENSEES for each point step by step, and the acceleration of the centroid point on the timber floor was measured for 5 seconds. The testing sequence is shown in Table 6. Initially, the TMD was nearly-optimally designed, and the system was tested under running-induced vibration in Test No. 21. Subsequently, the off-tuning condition was induced by varying the mass added onto the timber floor in Test No. 22 and 24. In Test No. 23 and 25, the retuning effects by cooling and heating were assessed under running excitations, respectively.

Table 6 Testing sequences for footfall-induced vibration on timber floor-TMD system and the corresponding dynamic parameters

Excitation			Main structure			TMD		
Test No.	Type	Excitation Frequency (Hz)	m_1 (kg)[(1)]	f_1 (Hz)[(2)]	T (°C)[(3)]	f_T (Hz)[(4)]	m_T (kg)[(5)]	c_T (%)[(6)]
21	Footfall	3.5	6603	8.00	21	8.38	110	10.9
22	Footfall	3.5	6603+850	7.53	21	8.38	110	10.9
23	Footfall	3.5	6603+850	7.53	11	7.88	110	10.9
24	Footfall	3.5	6603-150	8.09	21	8.38	110	10.9
25	Footfall	3.5	6603-150	8.09	120	8.56	110	10.9

(1) total mass of the timber floor system
(2) natural frequency of the main structure
(3) working temperature of the SMA beam
(4) natural frequency of one SMA cantilever beam
(5) mass attached to the SMA cantilever beam
(6) equivalent viscous damping ratio of the SMA cantilever beam

3.2 Results and discussion

Figure 8 shows the time history of the timber floor response under running excitations. Figure 8 (a) and (c) present a comparison of the structural responses under tuned and off-tuned conditions. It can be seen that excessive vibration increased when the floor functioned with an off-tuned TMD. Table 7 presents the maximum acceleration in time history and the RMS acceleration of each test. Increasing the structural mass by 850 kg can lead to an increase of 11.3% in maximum acceleration and 24.0% in RMS acceleration. As shown in Figure 8 (b) and Table 7, the structural response can be effectively reduced by cooling the SMA, in which case the maximum and RMS acceleration decreased by 24.6% and 42.1%, respectively.

Off-tuning by reducing the structural mass can cause an increase in the structural response, as seen in Figure 8 (c). In the retuning process in Figure 8 (d), the SMA heating is limited, as the maximum and RMS accelerations increase by 1.4% and 1.0%, respectively. This can be explained through the analysis of the input signal in the frequency domain. Figure 9 shows the FFT results of the input running footstep time history. The first three dominant frequencies are 3.51, 7.02 and

10.53 Hz. According to Figure 4, 5 and 6, the acceleration amplitudes of the floor-TMD system at approximately 3.5 and 10.5 Hz are significantly lower in contrast with those around approximately 7 Hz. For this timber floor-TMD system, retuning by cooling the SMA can effectively lower the structural response at approximately 7 Hz when the extra load of 850 kg is added (Figure 5). However, heating provides less effect, as seen in Figure 6, and only the amplitude in the second mode can be reduced.

Regarding the results, when the TMD is off-tuned, the higher dominant frequencies of the running footsteps could result in a significant increase. In other words, running involves a broad range of frequencies, and the higher dominant frequencies associated with running could significantly increase the excessive vibration in off-tuning, particularly if there is resonance. Therefore, it is important to retune the TMD for the timber floor system in order to lower the overall response at a wide range of frequencies, so as to attenuate the vibration effectively. This system has the significant potential to be utilised in sports centres, gymnasiums and dancing halls. In terms of the limitation of heating SMAs, an adaptive damping device can be applied to control the overall amplitude, according to Den Hartog (1956)'s theory. Thus, the collaboration between the adaptive damping device and the frequency-shifting semi-active TMD should be investigated.

Table 7 Maximum acceleration in time history and RMS acceleration of each test; Reduction percentage in off-tuning and retuning

Test No.	Tuning condition	Maximum acceleration in time history (m/s^2)	Reduction percentage (from Test No. # to *)	RMS acceleration (gal)	Reduction percentage (from Test No. # to *)
21	Nearly optimal tuned	0.651	-	1.977	-
22	Off-tuned	0.725	-11.3% (from 21 to 22)	2.451	-24.0% (from 21 to 22)
23	Retuned	0.547	24.6% (from 22 to 23)	1.725	42.1% (from 22 to 23)
21	Nearly optimal tuned	0.651	-	1.977	-
24	Off-tuned	0.852	-30.9% (from 21 to 24)	2.485	-25.7% (from 21 to 24)
25	Retuned	0.864	-1.4% (from 24 to 25)	2.509	-1.0% (from 24 to 25)

3.3 Summary

In this section, the footfall of running was input to excite a timber floor-TMD system modelled on OPENSEES. The vibrations of the system with a nearly-optimally tuned, off-tuned and retuned TMD were assessed under running footfall excitations. When the TMD is off-tuned by varying structural mass, the structural response increases. To retune a system in which the structural mass is increased, the structural response can be effectively reduced by cooling the SMA. However, the effectiveness of retuning by heating the SMA is limited for the off-tuning condition in which the mass is reduced. By FFT analysis of the input, the higher dominant frequencies of running could resonate with the structural natural frequency and consequently increase the structural response when the TMD is off-tuned. Therefore, it is important to conduct retuning in order to reduce the overall vibration amplitude in a wide frequency range. In terms of the limitations of heating, an adaptive damping approach should be studied in the future to assess its feasibility for use with a frequency-shifting semi-active TMD.

4. Conclusion

In this study, a pre-stressed SMA was applied to a timber floor system for semi-actively control of the TMD. The study was conducted by simulation on OPENSEES software. By analysing the free vibration in the frequency domain, it was determined that the off-tuning caused by varying the main structural mass can lead to an increase in the structural response. By retuning the natural frequencies using temperature control on the SMA, the vibration amplitude can be reduced by up to 26% at a wide range of frequencies.

Footfall excitation caused by human running involves a wide range of frequencies, where the higher dominant frequencies could cause resonance and increase the structural response when the TMD is off-tuned. Therefore, retuning of the floor system is essential in order to reduce the overall amplitude in a broad frequency range. The results show that an SMA with temperature control can effectively retune the natural frequency and reduce vibration. Under heating of the SMA, the effectiveness is limited, and a device with a variable damping coefficient should be studied further to assess the applicability of collaboration with the SMA. Moreover, the variance of the mechanical properties of SMAs while heating should be larger, and the SMAs with higher phase transformations should be studied further.

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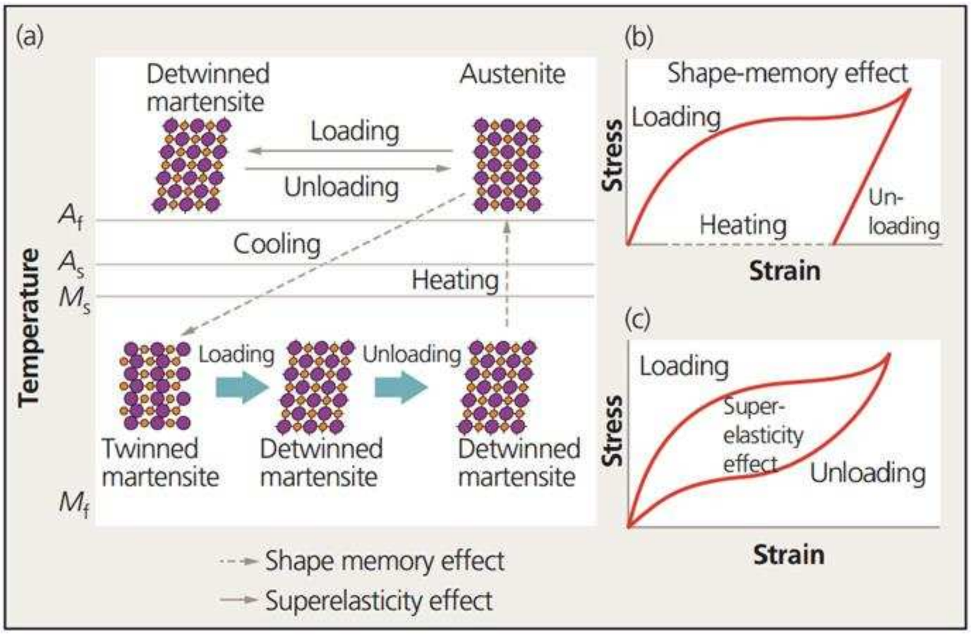


Figure 1 Different phases of SMA at various temperatures and stress-strain curve demonstrating the (b) shape memory effect; (c) superelasticity (Chang and Araki, 2016)

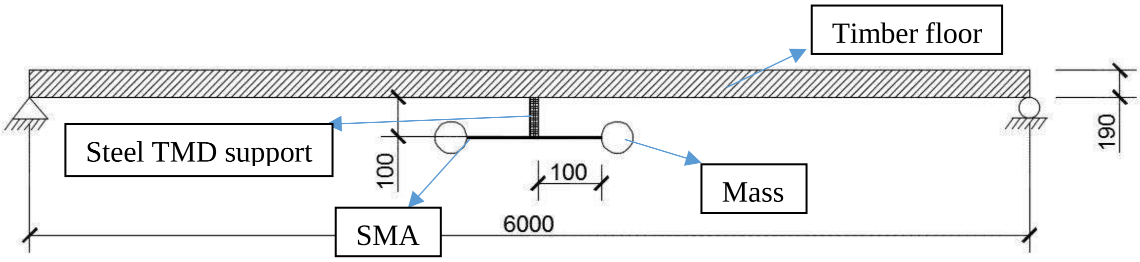


Figure 2 Timber floor using tuned mass damper by bending SMA (unit: mm)

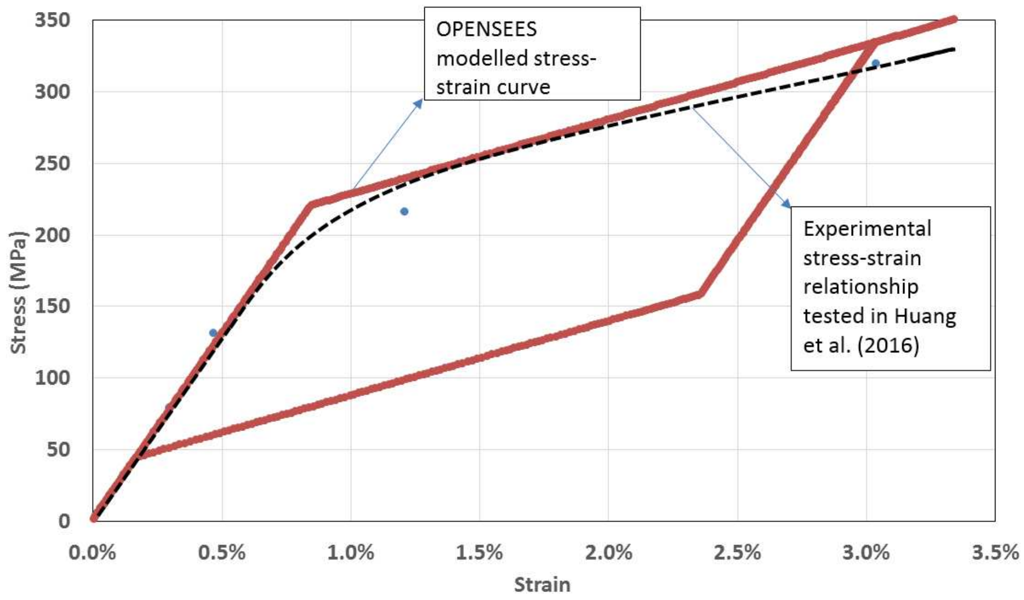


Figure 3 Experimental stress-strain curve tested in Huang et al. (2016) (black dot curve) and OPENSEES modelled stress-strain curve (red curve)

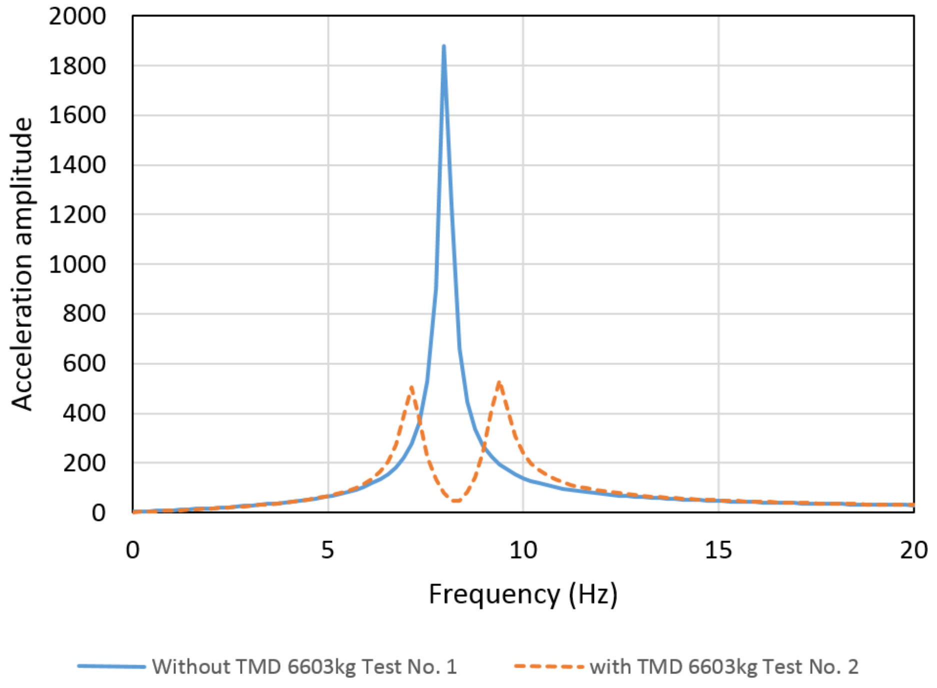


Figure 4 Frequency response of timber floor system with and without a TMD (m_1=6603 kg)

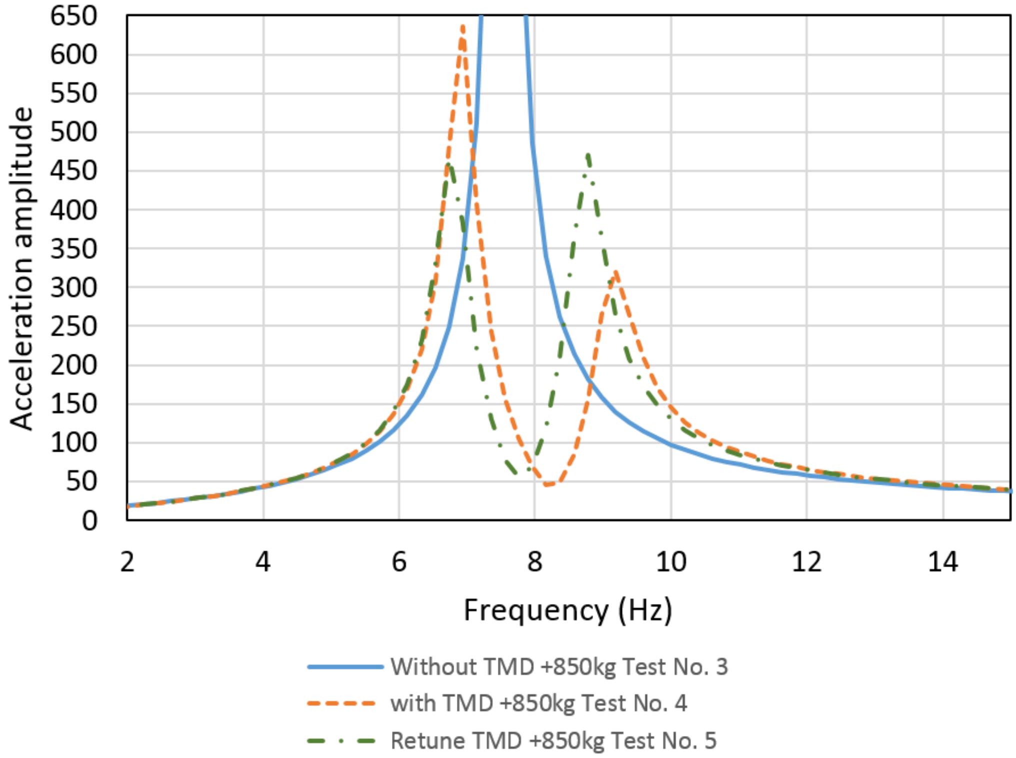


Figure 5 Frequency response of a timber floor system without TMD, with off-tuned TMD and with retuned TMD (m_1=6603+850 kg)

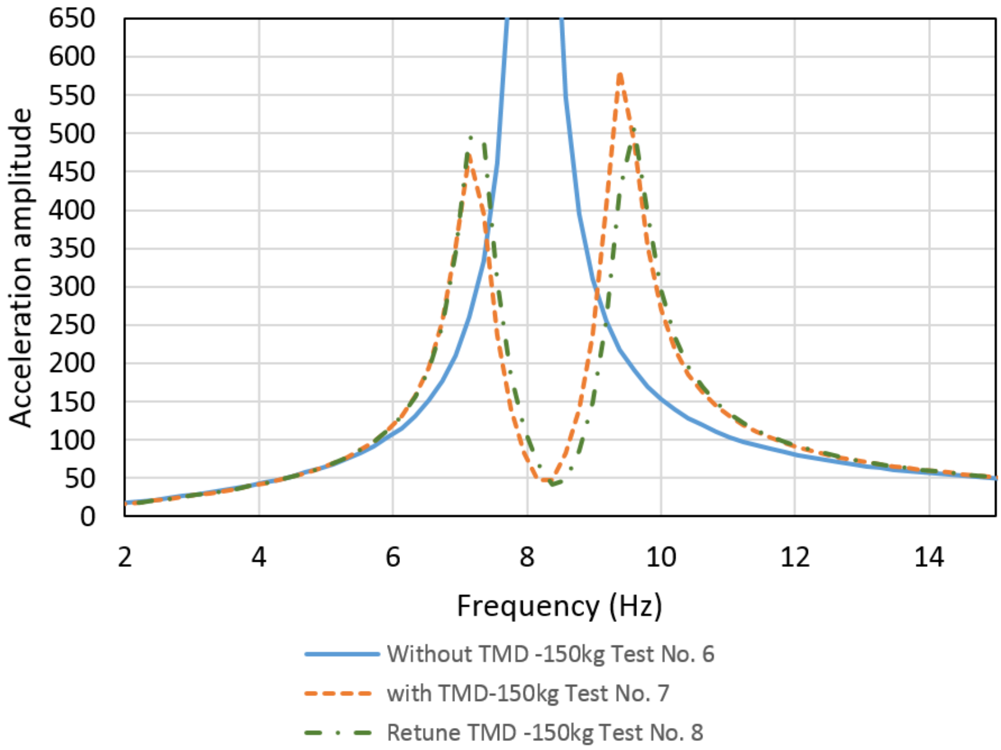
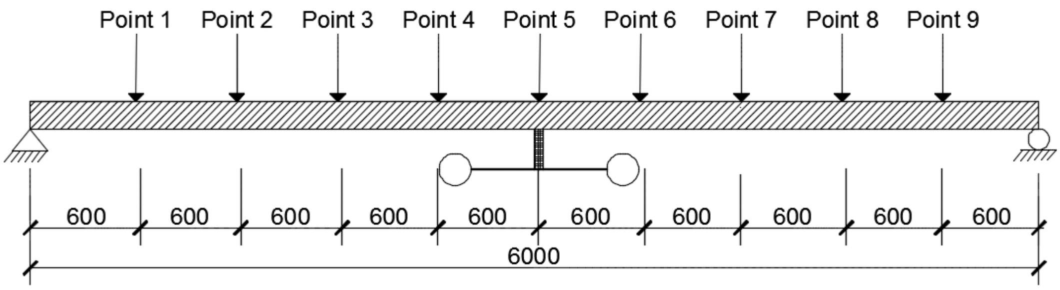
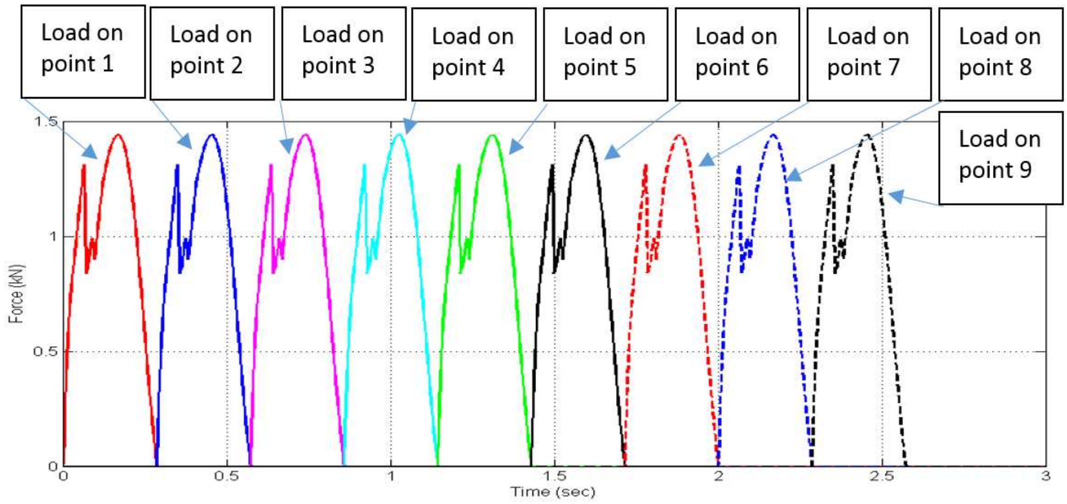


Figure 6 Frequency response of a timber floor system without TMD, with off-tuned TMD and with retuned TMD (m_1=6603-150 kg)

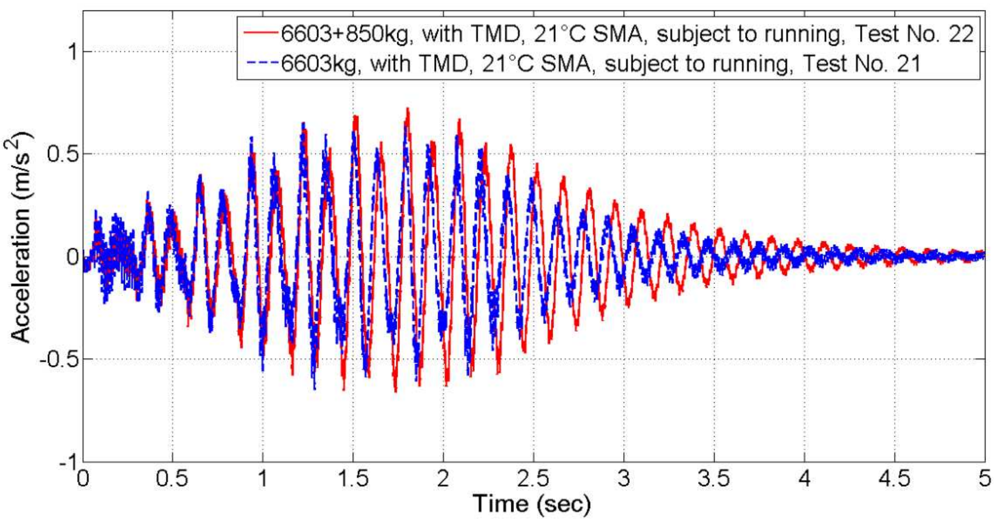


(a)

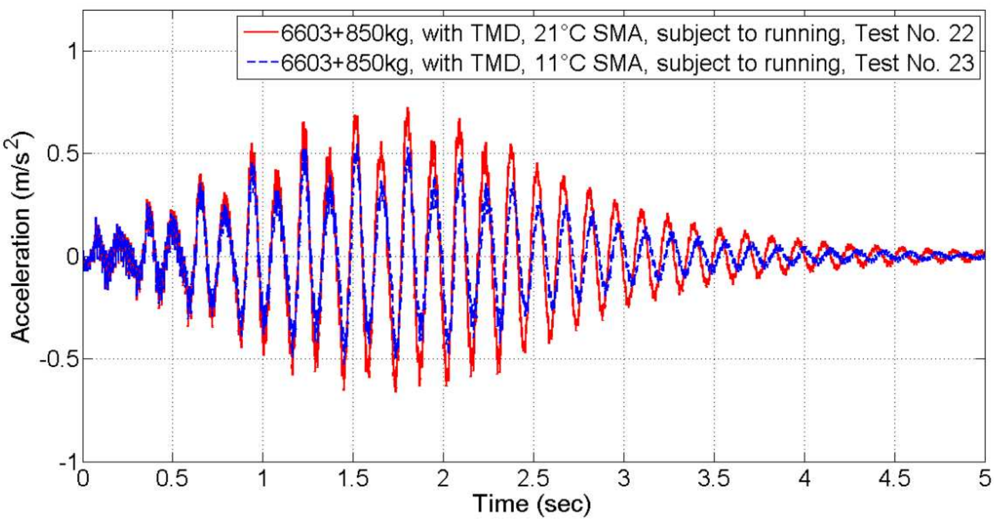


(b)

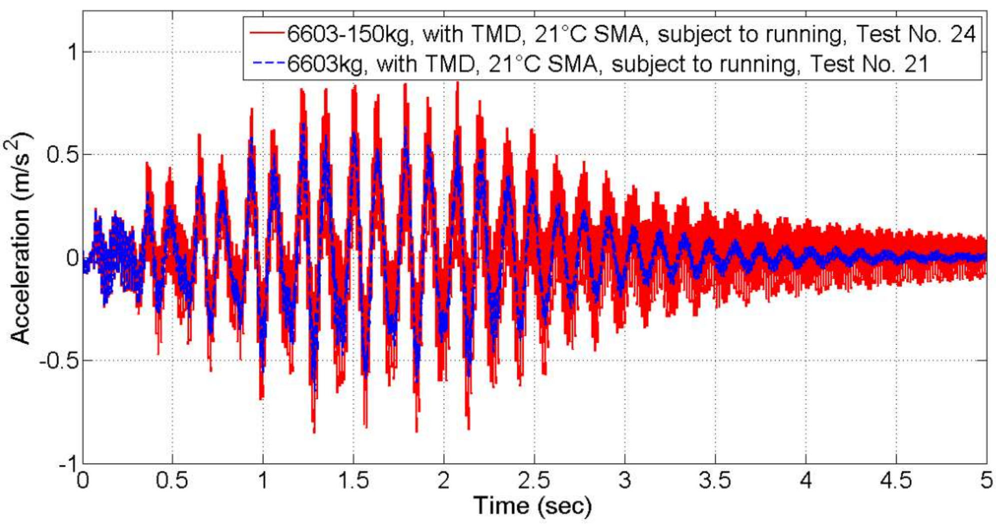
Figure 7 (a) Footfall loading positions (unit: mm); (b) Footfall loading protocol


6603+850kg, with TMD, 21°C SMA, subject to running, Test No. 22
6603kg, with TMD, 21°C SMA, subject to running, Test No. 21
Acceleration (m/s^2)
Time (sec)
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

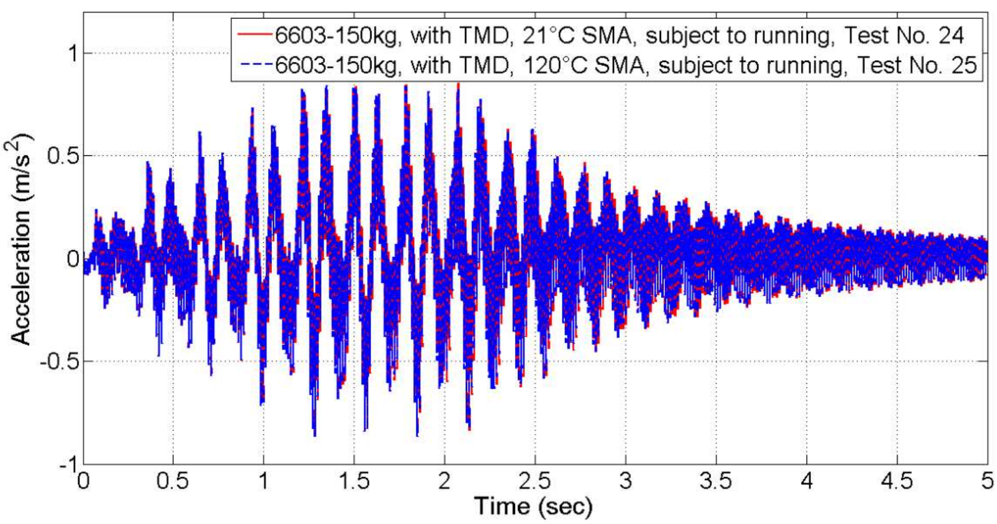
(a)


6603+850kg, with TMD, 21°C SMA, subject to running, Test No. 22
6603+850kg, with TMD, 11°C SMA, subject to running, Test No. 23
Acceleration (m/s^2)
Time (sec)
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

(b)



(c)



(d)

Figure 8 Time history of the structural response (a) off-tuning caused by increasing the structural mass; (b) retuning by SMA cooling; (c) off-tuning caused by decreasing the structural mass; (d) retuning by SMA heating

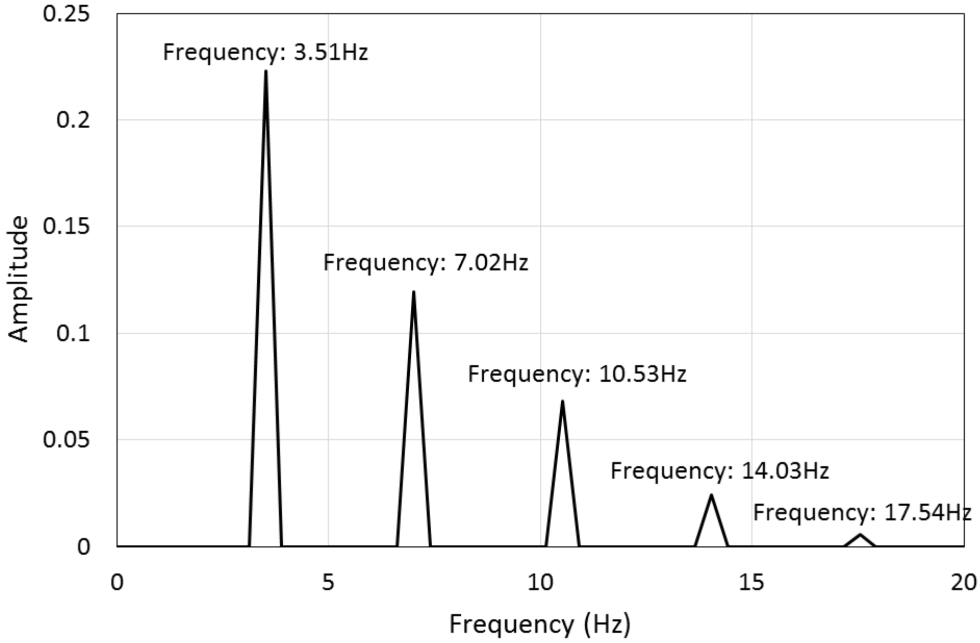


Figure 9 FFT analysis of footstep input signal by running

Figure captions

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Table captions

Table 1 Nearly-optimally designed dynamic parameters for main structure and TMD

Table 2 Testing sequences for the timber floor-TMD system and the corresponding dynamic parameters

Table 3 Comparison between Test No. 1 and Test No. 2 in terms of maximum acceleration amplitude in frequency domain, R factor and RMS acceleration in the first five seconds in the time domain

Table 4 Comparison between Test No. 4 and Test No. 5 in terms of maximum acceleration amplitude in the frequency domain, R factor and RMS acceleration in the first 5 seconds in the time domain

Table 5 Comparison between Test No. 7 and Test No. 8 in terms of maximum acceleration amplitude in frequency domain, R factor and RMS acceleration in the first 5 seconds in the time domain

Table 6 Testing sequences for footfall-induced vibration on timber floor-TMD system and the corresponding dynamic parameters

Table 7 Maximum acceleration in time history and RMS acceleration of each test; Reduction percentage in off-tuning and retuning