EXPERIMENTAL STUDY ON VIBRATION CONTROL OF A BEAM-LIKE FOOTBRIDGE BY TUNED MASS DAMPER

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Footbridges are often designed as slender structures, sensitive to human-induced excitation. In the case where excessive vibration cause discomfort, vibration reduction measures such as tuned mass damper (TMD) are needed. In this paper, a TMD damping system designed to reduce the vibration of the first mode of a flexible beam-like footbridge was concerned. The responses of the footbridge induced by a pedestrian at different step frequencies were measured. The vibration responses before and after the TMD system installed were analysed and compared in both time and frequency domains. The results show that the starting acceleration of the TMD can meet the actual requirements and the structural damping is significantly increased after TMD installed. For flexible structures like beam-like footbridges, the damping effect of TMD system is closely related to the step frequency. When the main harmonic or sub-harmonic component (1.5f_s) of the step frequency is close to the fundamental frequency of the structure, it will cause a larger structural response which is dominated by the first-order modal. The efficiency of the TMD to reduce structural vertical vibration is relatively high, more than 42%. When the main harmonic and sub-harmonic components are quite different from the fundamental frequency of the structure, the structural response is relatively small, and the damping effect of the TMD system is not obvious.

Keywords: TMD, footbridges, vibration reduction, step frequency

1. Introduction

With the increase of span and wide use of new building materials, footbridges, characterized with low frequency and low damping, are susceptible to dynamic loads and will cause significant dynamic responses. The main dynamic load acting on the footbridge is the walking load of pedestrian. The pedestrian load is periodical and often expressed by Fourier series [1-3]. This expression contains the main harmonic and sub harmonic components of step frequency [4-5]. When the walking frequency and its main harmonic component are close to the structural fundamental frequency, walking load will cause resonance or near-resonance, resulting in excessive response. And at the same time, whether sub-harmonic components cause resonance or not are rarely concerned. When the resonance or near-resonance occurs, the additional damping can effectively reduce the structural vibration. TMD is the most widely used additional damping device [6-7]. TMD is used to control the human-induced vibration in many projects since the Millennium Bridge accident on its open day in 2000 [8-11]. Field test shows that TMD can significantly increase the structural damping [12-13]. However, in practical application, manufacturing precision and installation level of TMD will greatly influence the damping effect, so it is necessary to analyse the damping effect of TMD system and its influencing factors through field experiments.

In this paper, the structural response test with or without TMD under different walking frequencies of pedestrian is carried out on a beam-like footbridge. The vibration responses before and after the TMD system installed were analysed and compared in both time and frequency domains. The damping effect of TMD is evaluated according to the test. Before the experiment, the modal identification of the footbridge and the vibration reduction design were carried out. In addition, the starting acceleration of TMD is investigated in this paper.

2. Model test of the beam-like footbridge

In this study, the dynamic characteristics of the footbridge are identified through experimental tests. The footbridge has dimensions of 10.3m in length, 1.0m in width and 0.10m in thickness as shown in Fig. 1. Compared with the actual pedestrian bridge, the footbridge is flexible structure because its line density is 343 kg/m.

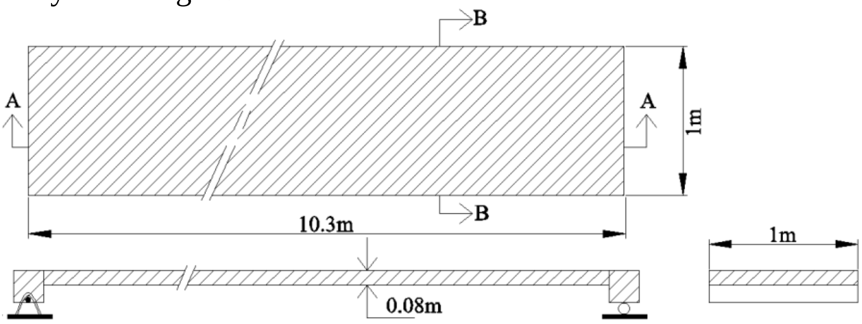


Figure 1: Reinforced concrete beam-like footbridge

The modal parameters of the footbridge are identified by the stochastic subspace method under ambient excitation. For identifying the vibration mode of the structure, 38 measuring points are arranged on the footbridge deck, as shown in Fig 2. Four acceleration sensors were available for response measurements. Due to the limitation of the number of sensors, the test was divided into13 groups. One sensor was kept at TP32 at all times to provide a common reference, while the

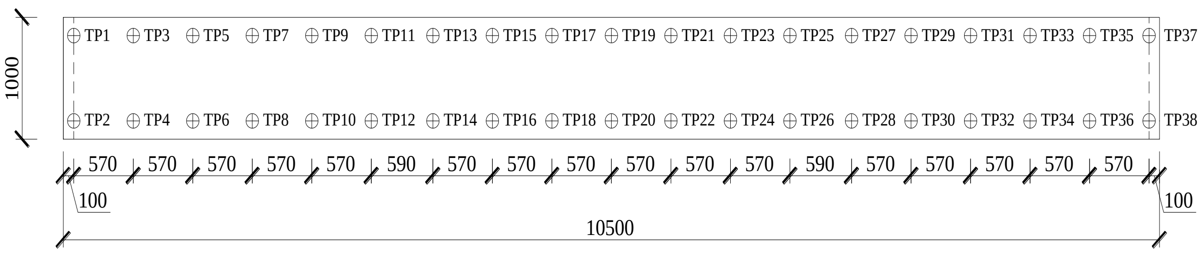


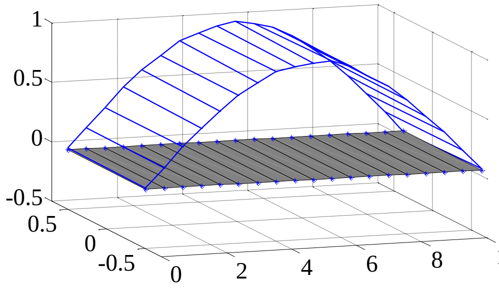
Figure 2: Measuring point arrangement

remaining three acceleration sensors were arranged on the other measuring points in different test groups. The sampling time of each test is 20min and the sampling frequency is 200Hz.

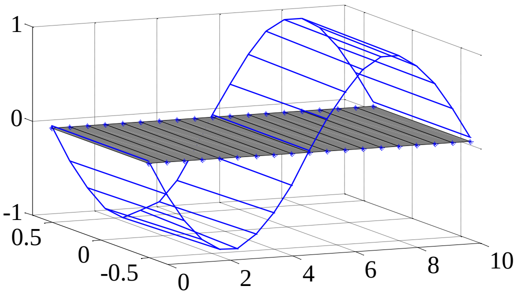
The results of structural modal identification are given in Table 1. Three vibration modes can be identified in the range of 0-20Hz. Two of these modes are vertical bending vibration modes (at 2.83 and 11.08 Hz) while the other mode is torsional mode (at 19.98 Hz). First three vibration modes are shown in Fig. 3. From the results of modal identification, the first modal frequency is close to the walking frequency band (1.5-2.5Hz), which may cause resonance. Therefore, the vibration reduction should be focused on the first order modal.

Table 1: Modal identification results of the beam-like footbridge

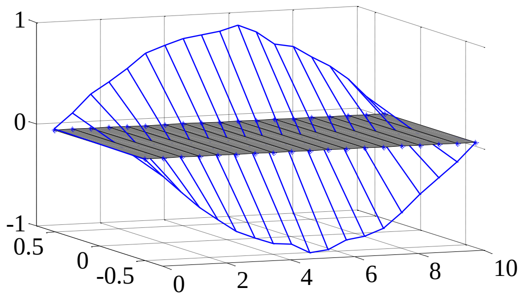
Modal order	Frequency/Hz	Damping ratio/%	Mode
1	2.83	0.23	1st vertical bending
2	11.08	0.60	2nd vertical bending
3	19.98	0.54	1st torsional



(a) f_1=2.83Hz



(b) f_2=11.08Hz



(c) f_3=19.98Hz

Figure 3: First three vibration modes

3. Design on vibration control

Generally speaking, the structure which needs vibration control is a MDOF system with multiple modes, but the overall structural responses only depend on a certain mode. Therefore, in the design of the vibration control, the modal need to be controlled can be represented by a SDOF system. Meanwhile, TMD can also be expressed with a SDOF system which is attached to the main structure. The dynamic equation of the structure-TMD system is

$$\begin{cases} M\ddot{x}_1 + (C+c)\dot{x}_1 + (K+k)x_1 - c\dot{x}_2 - kx_2 = f \\ m\ddot{x}_2 + c\dot{x}_2 + kx_2 - c\dot{x}_1 - kx_1 = 0 \end{cases} \tag{1}$$

where M, K, C, m, k and c are the mass, stiffness, damping coefficient of structure and TMD respectively, and x_1 and x_2 are the displacement of structure and TMD, respectively.

According to the above formula, the ratio of the amplitude of the acceleration response (A_1) to the maximum static displacement (X_{st}) is

$$\frac{A_1}{X_{st}}=\sqrt{\frac{\lambda^4\left[\left(\gamma^2-\lambda^2\right)^2+\left(2\lambda\gamma\xi_2\right)^2\right]}{\left[\left(1-\lambda^2\right)\left(\gamma^2-\lambda^2\right)-\gamma\lambda^2\left(4\xi_1\xi_2+\gamma\mu\right)\right]^2+\left[2\lambda(\xi_2\gamma(1-\lambda^2-\lambda^2\mu)+\xi_1(\gamma^2-\lambda^2))\right]^2}} \quad (2)$$

where ξ_1 and ξ_2 are TMD and structural damping ratio respectively, λ is the ratio of loading frequency to structural frequency, γ is the ratio of TMD frequency to structural frequency, and μ is the ratio of TMD mass to structural mass. The optimal parameters of TMD can be obtained when the peak value of Eq. (1) is the minimum. The designed parameters of TMD when μ =0.05 are given in Table 2.

Table 2: Design parameters of TMD

Name	Mass/kg	Frequency/Hz	Stiffness/(N/m)	Damping ratio	Damping coefficient /(Ns/m)
TMD	80	2.73	11757	0.137	187

4. TMD performance test

4.1 Starting acceleration

Due to the friction force in the guiding systems, TMD can only be started when the structural acceleration is larger than a certain value. Thus even if the TMD is installed, it cannot be started if its starting acceleration is larger than the threshold value of the structural vibration serviceability requirements. The structure may not meet the vibration serviceability requirements in this time. Therefore, the starting acceleration is a very important parameter for TMD products, and it is necessary to evaluate the parameter of actual TMD products. For outdoor footbridge, the limit value of vibration serviceability is generally 0.5m/s^2, so the starting acceleration should be less than 0.5m/s^2.

Experiments were carried out on the footbridge to test the starting acceleration of TMD. One pedestrian pass through the footbridge at different walking frequencies and the acceleration responses of TMD and the structure were measured. The starting acceleration of TMD can be obtained by comparing the two responses.

Table 3 shows the starting acceleration of TMD under different walking frequencies. Fig. 4 gives the response curves of the footbridge and TMD when f_s=2.0Hz (f_s represents walking frequency). As shown in the Table 3, TMD has started when the structural vertical acceleration is about 0.09m/s^2, which is far less than the limit value of vibration serviceability. Thus, the starting acceleration of the vertical TMD system can meet the requirements of vibration reduction for outdoor footbridge.

Table 3: Starting acceleration under different walking frequencies

Walking frequency/Hz	Starting acceleration /(m/s^2)
1.74	0.10
2.0	0.10
2.8	0.08

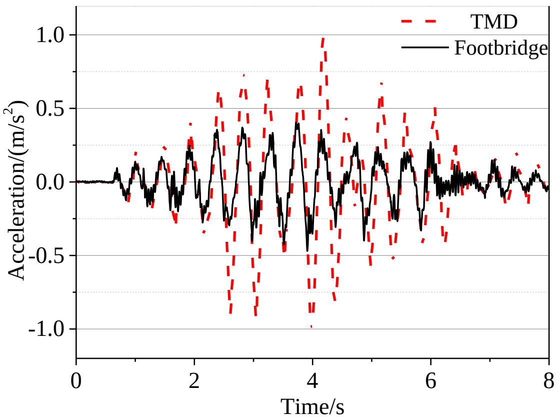


Figure 4: Response curve of structure and TMD when f_s=2.0Hz

4.2 Vibration damping effect

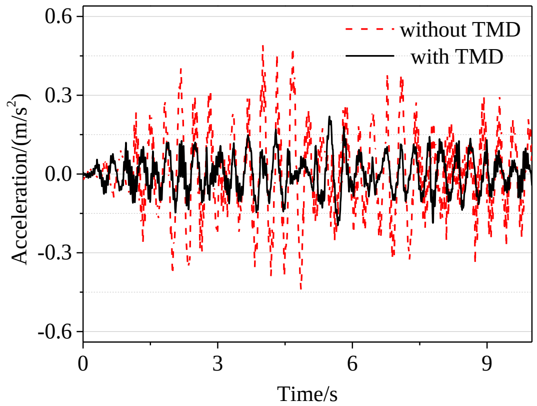
In the experiment, TMD was suspended in the middle span of the footbridge. The structural response tests of footbridge with or without TMD under different walking frequencies were carried out as shown in Fig 5. The walking frequency is controlled by metronome.

Figure 5: Damping effect test

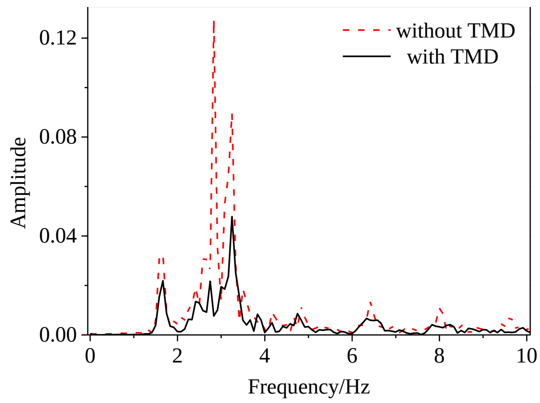
Fig. 6 gives the measured response and spectrum with or without TMD under different walking frequencies. It can be seen from the figure that the structural response of 1.74Hz is dominated by the first-order modal before TMD installed, and the walking frequency and high order modal of structure is small. After installing the TMD, the first order modal response of structure is reduced, and the peak acceleration also decrease in the time domain. The reason for this phenomenon is that the second sub-harmonic component of the walking frequency (1.5f_s) is close to the fundamental frequency of footbridge, which causes near-resonance. At this time, the TMD system which is designed for the first order modal of the structure effectively reduce the structural response and achieve the desired damping effect.

When the walking frequency is 2.2Hz, the structural response is dominated by first order walking frequency before TMD installed. After vibration reduction, although the first order modal component of structure is suppressed, but because of its relatively small, so there is no obvious damping effect in the time domain.

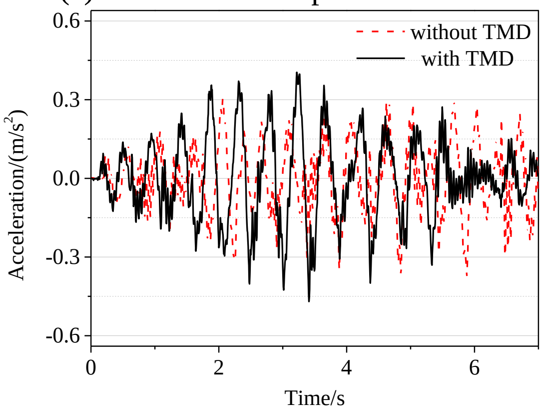
When the walking frequency (2.8Hz) is consistent with the fundamental frequency of structure, the response is very large, and the response only contains the first order modal of the structure. So the vibration control effect of TMD is obvious at this time, and the structural response is greatly reduced.



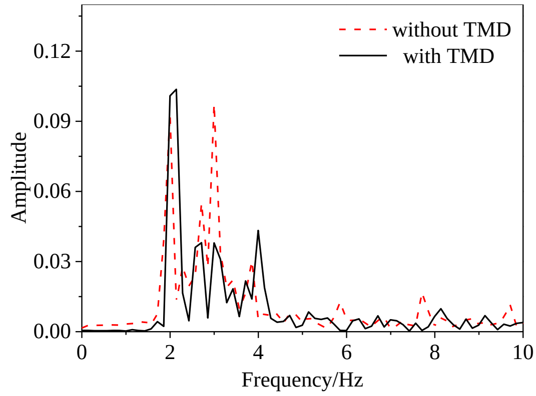
(a) Acceleration response of 1.74Hz



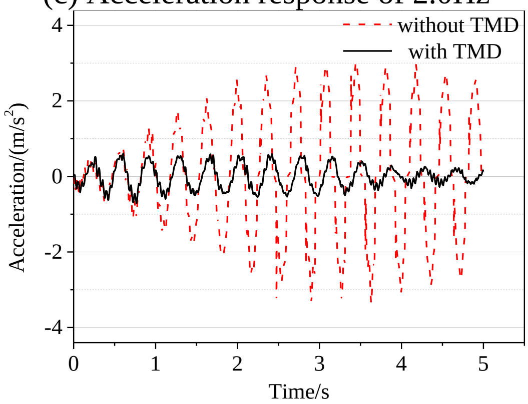
(b) Fourier spectra of 1.74Hz



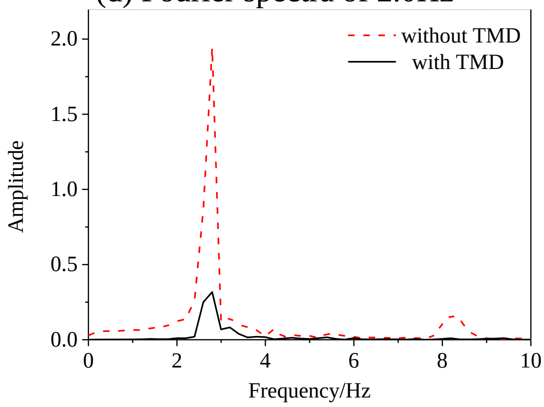
(c) Acceleration response of 2.0Hz



(d) Fourier spectra of 2.0Hz



(e) Acceleration response of 2.8Hz



(f) Fourier spectra of 2.8Hz

Figure 6: Response contrast of middle span with or without TMD

Table 4 gives a comparison of the response before and after vibration reduction. It can be seen that the response of f_s=1.74 is larger than that of f_s=2.0Hz, and the TMD damping rate is 60%. The damping rate is about 80% when f_s=2.8Hz.

Table 4: Measurement of damping effect

Walking frequency /Hz	Peak acceleration/(m/s^2)			R.M.S./(m/s^2)		
	Without TMD	With TMD	Damping rate	Without TMD	With TMD	Damping rate
1.74	52.3	21.9	58%	0.11	0.04	63%
2.0	37.0	46.1	/	0.09	0.08	/
2.8	335	59.2	82%	1.01	0.20	80%

5. Conclusions

The experimental results show that the performance of this TMD is good. The starting acceleration of the TMD is much less than the comfort limit of outdoor pedestrian bridge, which can be used to control the structural vibration responses in time.

For flexible structures like beam-like footbridges, the damping effect of TMD system is closely related to the step frequency. When the sub-harmonic component of the walking frequency ($1.5f_s$) is close to the fundamental frequency of footbridge, the pedestrian loads will cause substantial structural response. The structural response is dominated by the first-order modal in this case, so TMD has remarkable vibration control effect. When the main harmonic or sub-harmonic component are far from the fundamental frequency of structure, the structural response decreases, and the damping effect of the TMD system is not obvious. When the walking frequency is consistent with the fundamental frequency of structure, the response is very large, and the vibration control effect of TMD is the most obvious in all cases.

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