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Control of Vibrations of Common Pedestrian Bridges in Jordan Using Tuned Mass Dampers

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Abstract

Due to their inherent slenderness and lightness, pedestrian bridges are typically subtle to human induced vibrations. This study was conducted to investigate the effect of human induced vibrations on common simply supported steel footbridges in Jordan, especially those with natural frequencies between 2 to 4 Hz. Such fundamental frequency is close to human movement frequency of walking, jumping and running. The ETABS software was utilized to develop a finite element model (FEM) in order to identify the footbridge dynamic properties including frequency, natural period, stiffness and the critical length at which the induced-vibrations become of great effect. The bridge was excited with multiple human walking and running loading scenarios. The response of the footbridge was evaluated and compared with and without integrating tuned mass dampers (TMD) tuned with the fundamental natural frequency of the footbridge in order to optimize appropriate mass, stiffness and damping coefficient. It was observed that after attaching the TMD, the fundamental vibration frequency decreased to stable value less than human excitation frequencies. Also, acceleration, velocity, and displacement responses were decreased significantly to be within acceptable limits. Finally, a recommendation and guidelines are given for considering the induced-vibrations in the design of common footbridges in Jordan.

*Keywords:*Footbridges, TMD, FEM, Vibrations, Dampers.

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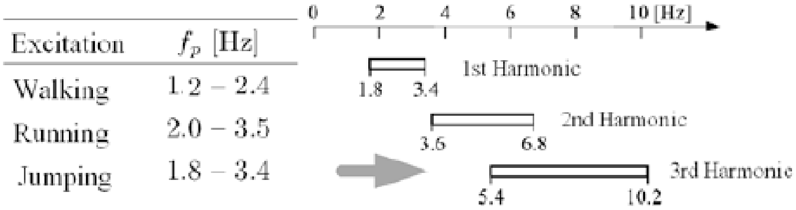
1. Introduction

Pedestrian bridges (also called footbridges) were used hundred years ago, starting from using stones and timber materials until steel structures nowadays. Existence of footbridges provides a safe movement of pedestrians over the urban roads, highways, slopes or rivers [1]. Footbridges are designed and checked based on static analysis according to the applicable load combinations (dead load, live load, seismic, and wind). Also, dynamic load excitation of walking, jumping and running must be considered because lateral and vertical vibrations occur when people cross the footbridges which makes resonance and discomfort as happened in London Millennium Bridge [2] and Solferino footbridge in Paris [3].In some cases, this may cause collapse and consequence human and economic losses. This problem is specifically related to low-frequency footbridges with natural frequency value lower than 4 Hz in the vertical and 2Hz in the lateral direction as specified in design codes ISO/DIS standard 10137[4]. When the footbridge is excited by a group of pedestrians walking at the same speed to maintain the group consistency, synchronization of walking steps makes a walking frequency around 2 Hz which is near to the natural frequency of the bridge [5-7]. Pedestrians load has three components: vertical, lateral and longitudinal. The vertical one is considered as the major component which take up to 40% of the body weight and about 10% of the vertical loading works laterally when people walk [8]. Several studies showed that there are ranges of exciting frequencies induced by human activities depending on the type of movement as shown in Fig. 1[9].



Excitation	f_p [Hz]
Walking	1.2 – 2.4
Running	2.0 – 3.5
Jumping	1.8 – 3.4

Fig. 1. Frequency range for an excitation by human activities on footbridges

Tuned mass dampers (TMD) can be used to increase damping of abridge and to reduce the amplification of bridge excitation. A TMD consist of a vibrating mass (m) that is a percentage of the total bridge mass supported by helical springs having total stiffness (k) equal to the structure stiffness with parallel viscous dampers (c). The mechanism of controlling structural vibrations by attaching a TMD to the structure is to dissipate the structural energy by vibration of the TMD in a certain phase shift relative to the bridge motion. Theoretical studies showed that the efficiency of TMD depends on the ratio between TMD mass and the structure's mass. Experimental results showed that TMDs with appropriate mass reduce bridge excitation and acceleration level [10].

This paper presents a parametric study taken into consideration common pedestrian bridges in Jordan with varying span length to evaluate the change in frequency and control vibrations using TMD. The studied footbridge is a typical simply supported footbridge on Irbid- Amman Highway Preliminary analysis indicated that the bridge first natural frequency is close to the human walking and running frequencies, which dictates the need for taking into consideration the dynamic loading caused by moving pedestrians in the bridge design. The main objective of this study is to provide guidelines for common footbridges in Jordan to avoid collapse and priceless losses using TMD considering different bridge lengths and different loading scenarios.

2. . Static and Modal Analyses

The analysis is done on a typical simply supported footbridge on Irbid- Amman Highway, at the end of Marsa'a Village Rise with 20 m simply supported span length, 2.6 m width and 2.3 m height. The footbridge is made of non-composite concrete deck slab (5 cm thick) supported on steel elements interconnected with each other through bolting system. W-shape sections are used as main and secondary girders in the footbridge, U5x10-section is used to support the top steel deck slab and L5-section is used as a bracing on the top. Table 1 shows the details of the footbridge used sections and Fig.2 shows the 3D view of the ETABS model of the footbridge. Static, modal, and time time-history analyses were conducted on the footbridge. In static analysis, the bridge length is increased from

20 m to 32 m and the structural members were analyzed and checked according to the applicable load combinations (dead load, live load of 4 kN/m^2, and wind load of 80 km/hr (22.35 m/s) in X and Y directions) provided by theASCE7 and the BS Codes [11-12]. All ETABS models showed that the main girders in all cases are adequate in terms of stress limit, and meet deflection criteria under full live loading as shown in Table 2 according to AASHTO [13]. This indicates that the footbridges are designed properly way under static loads.

Modal analysis was then performed to check the natural frequency of the bridge system and to compare it with the expected frequency from human activities. For the 20 m case, it was noticed that the natural frequency of the first lateral vibration mode is 1.852 Hz with a period of 0.54 second, and the vertical vibration mode natural frequency is 6.422 Hz with a period of 0.156 second. These results show that there is no problem in the vertical vibration because the frequency is larger than 4 Hz. But, there is a problem in the lateral vibration because the fundamental natural frequency is less than 2 Hz which falls within the range of concern of pedestrian induced vibrations in the lateral direction according to Rainer et al. [5]. The length of the bridge was then increased until arrived to the critical situation of 28 m length which has a lateral frequency of 1.312 Hz and a vertical frequency of 3.573 Hz which falls within the range of concern of pedestrian induced vibrations; i.e. within 0-4 Hz. The following table shows the analysis results for different bridge lengths cases.

Table 1. Details of the footbridge used sections

Shape	Area	Depth	Web length	Web thickness	Flange thickness	Nominal weight
	cm^2	cm	cm	cm	cm	N/m
W40x601	78.1	40	20	1.2	0.8	601.2
W25x334	43.4	25	12.5	1	0.8	334.2
W19.7x192	25	19.7	10	0.7	0.6	192.3
W18x212	27.5	18	9	0.8	0.8	211.9
W16x189	24.5	16	8.2	0.6	1	189
U5x10	9.50	5	10	0.5	0.5	73.2
L5	3.84	5	5	0.4	0.4	29.6

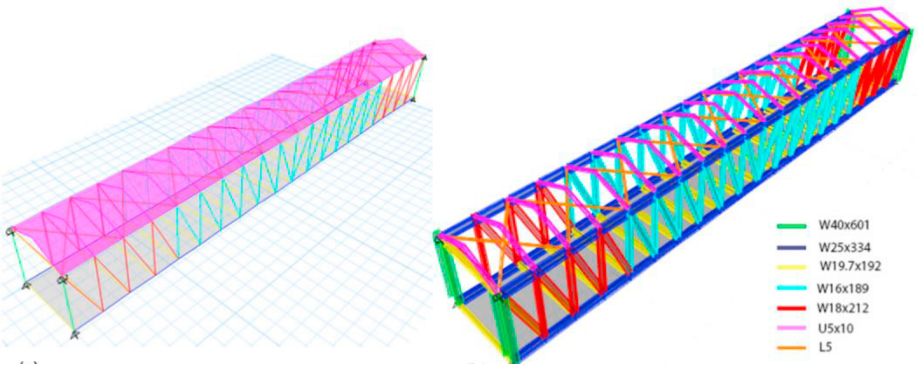


Fig. 2. Footbridge ETABSmodeling

Table 2. Modal analysis results for different cases of the footbridge length

Span Length	Lateral period, sec	Lateral frequency, Hz	Vertical period, sec	Vertical frequency, Hz	Max. live load Deflection, mm	Allowable deflection, mm
20 m	0.54	1.852	0.156	6.422	6.938	40
24 m	0.639	1.566	0.213	4.695	13.05	48
28m	0.762	1.312	0.28	3.573	22.877	56
30m	0.831	1.204	0.317	3.155	28.977	60
31m	0.868	1.152	0.336	2.972	32.705	62
32m	0.906	1.104	0.357	2.805	36.808	64

3. Walking Vibrations and Time History Analysis

The response of pedestrian bridges under the exposure of abnormal pedestrian activities that excite the bridge in a frequency matching its natural frequency of the first mode of vibration must be considered. To do this, time-history analysis was performed assuming eight persons are exciting the bridge at the same time, each weighing 1 kN placed at critical locations near the mid span to maximize the excitation. The loading was amplified by 1.4 times of the pedestrians' weight at the peaks. Fig.3shows the pattern in which the pedestrian loads were distributed. Time history analysis was done assuming two cases of walking and running conditions. To maximize the excitation action, each pedestrian footfall pulse was assumed with a frequency of 3 cycles per second (Hz), which leads to T = 0.333 sec (Fig. 4).The used damping ratio was 0.01 which is recommended for footbridges [14].

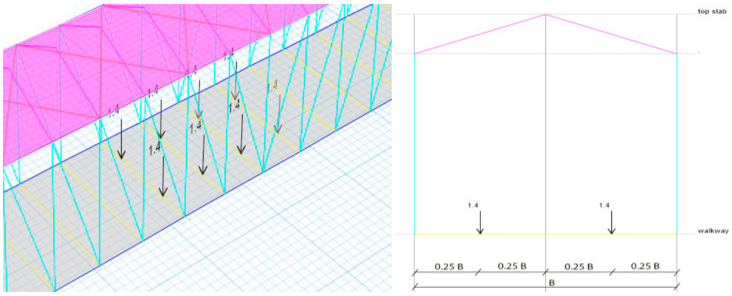
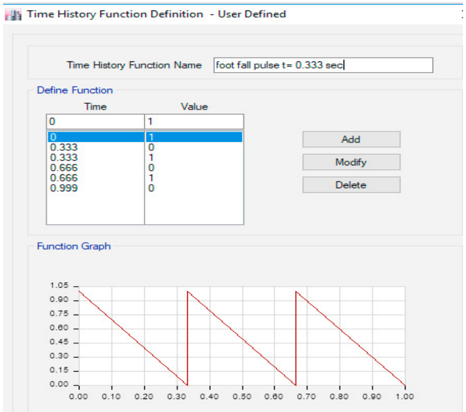


Fig. 3. Pedestrian load distribution on bridge


Time History Function Definition - User Defined

Time History Function Name: foot fall pulse t= 0.333 sec

Define Function

Time	Value
0	1
0	1
0.333	0
0.333	1
0.666	0
0.666	1
0.999	0

Fig.4. Definition of the time-history function.

3.1. Walking excitation

Pedestrian walking is the most common type of human excitation that is applied on footbridges. In the vertical direction, forces are generated by the perpendicular movements of the body with frequency values ranging between 1.2 – 2.4 Hz. Analysis results showed that the footbridge lateral frequency = 1.31 Hz (T = 0.76 sec), which may match the walking action. Therefore, the load case was set in a way to make the excitation for the eight pedestrians pattern at the critical location (middle of the bridge) happens each 0.76 sec together four times (Fig. 5).

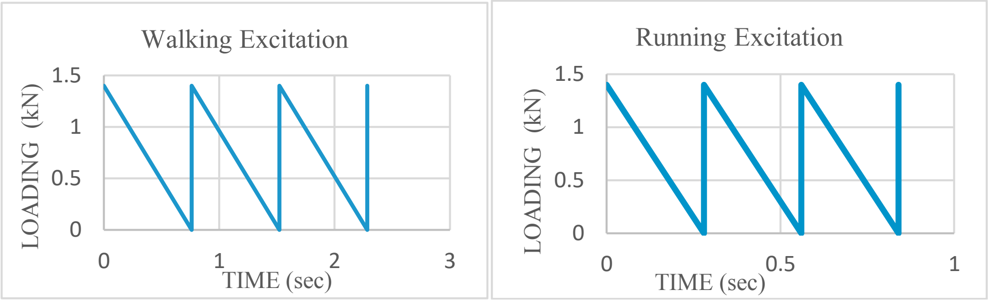


Fig.5. Walking and running excitation

3.2. Running excitation

Using GIS, slope map including the slopes of the bus stops and the slopes of the streets was prepared. In addition to that service area map of the bus stops defined as the area within a radius of 400 m was also prepared. Population and Land use maps were generated using the available collected data. The existence of the shelter and bay areas was done by reconnaissance surveys, based on that tables containing the attributes of the bus stops of the study were prepared.

3.3. Analysis of Existing Bus Stops

Pedestrian running is considered a type of human excitation that is applied on footbridges. In the vertical direction, forces are generated by the perpendicular movements of the body with frequency values ranging between 2 – 3.5 Hz. Analysis results showed that the footbridge vertical frequency is= 3.57Hz (T= 0.28 sec), which may match the running action. Therefore, the load case is set in a way to make the excitation for the eight pedestrians pattern at the critical location (middle of the bridge) happens each 0.28 sec together four times (Fig. 5).

4. Tuning of the TMD

Calculations of the parameters of the TMD were done to find the mass of the damper, the stiffness of the spring elements, the tuning frequency, and damping ratio based on the two degree of freedom model shown in Fig 6. Optimization of the frequency ratio and of the TMD damping was aimed at the minimization of the structural response, through the minimization of the structural dynamic magnification function. One of the most effective methods is the Den Hartog criterion [15], which is based on the analysis of an un-damped structure assuming the structural damping to be zero (Cs = 0), which is acceptable to useas the typical damping ratio ofsteel footbridges is very small (1%).

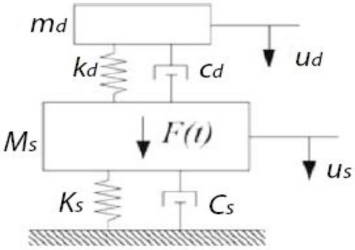


Fig.6. The two mass-damper system

Where, M_s is the system main mass, m_d is the damper mass, K_s is the system stiffness, k_d is the damper stiffness, C_s is the system damping, c_d is the damper damping, U_s is the system displacement, and u_d is the damper displacement Table 3 shows the weights of the footbridge members as well as its mass and the practical mass for the damper.

Table 3. Weight of the footbridge members

Section	Number of frames	Weight (kN)
W40x601	4	5.53
W25x334	4	37.43
W19.7x192	31	15.5
W18x212	28	14.35
W16x189	82	37.21
U5*10	58	5.91
L5	28	2.72
Total weight		118.65 kN
Total mass(M_s) =Total weight/g		12.09 kN.s^2/m =12095 kg
Practical mass for each damper, $m_d = 0.05*M_s$		0.6045 kN.s^2/m =605 kg

Once the practical mass of the damper is determined, the dampers were then tuned to have the same frequency as the natural frequency of the first mode of vibration of the footbridge (1.31 Hz). The circular natural frequency of the system$\omega_s = 2\pi.fs = 2\pi * 1.31 = 8.26rad/s$. The circular natural frequency of the damper$\omega_d = \omega_s$ = 8.26 rad/s. Then the stiffness of the system$Ks = \omega_s^2 .Ms = 8.26^2 * 12095$kg = 824kN/m and the critical damping $Ccr = 2\,md.\omega_d$ = 2* 604.7* 8.26 = 9985N.s/m = 10kN.s/m.μ is the mass ratio = m_d/M_s = 0.05. The optimal damping ratio (ξopt), the damping of the damper (C_d), the optimum value of the frequency ratio (αopt), and the optimal stiffness of the TMD ($kopt$)are calculated as follows:

$$\xi opt = \sqrt{\frac{3\,\mu}{8(\,1+\mu)}} = \sqrt{\frac{3*0.05}{8*(1+0.05)}} = 0.134 \tag{1}$$

$$Cd = \xi opt.Ccr = 0.134*10 = 1.34\text{kN.s/m} \tag{2}$$

$$\alpha opt = \frac{1}{1+\mu} = \frac{1}{1+0.05} = 0.95 \tag{3}$$

$$kopt = \mu.Ks.\alpha opt^2 = 0.05 *824*(0.95)2 = 37.4\text{kN/m} \tag{4}$$

The TMD was simulated as one mass supported on four springs with a damper as shown in Fig. 7. The TMD was assigned in the simulation under the middle span of the bridge.

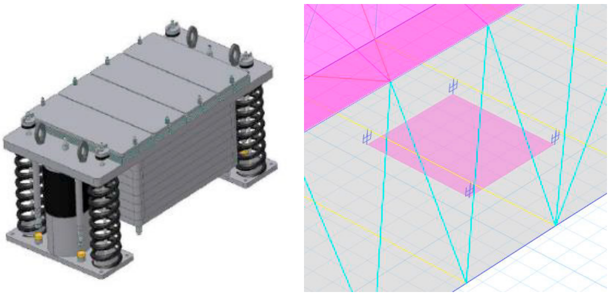


Fig. 7. TMD simulation

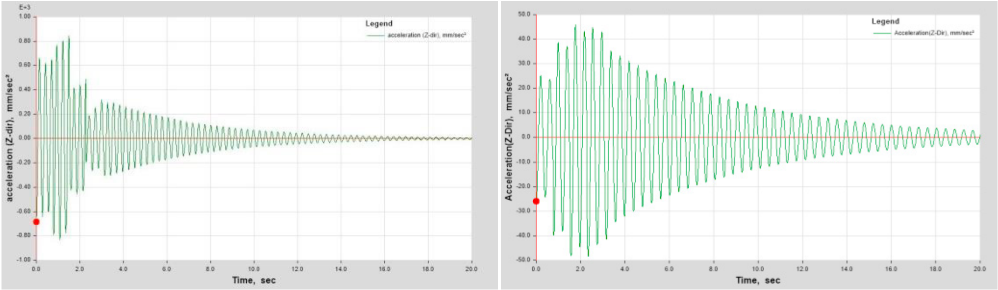


Fig. 8. Walkign excitation, acceleration-time trace without TMD (Max = 0.828 m/s^2) and with TMD (0.0485 m/s^2)

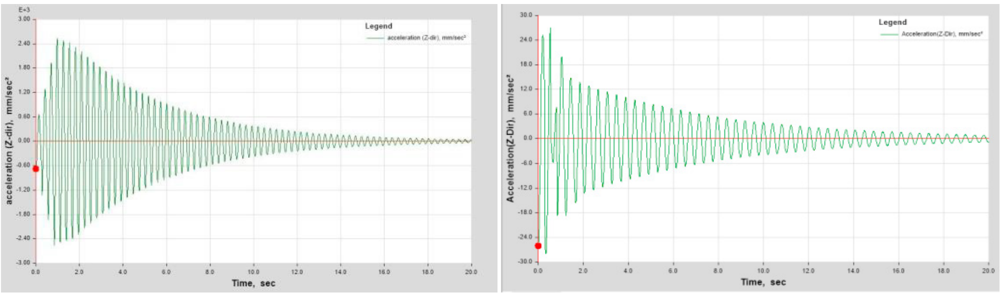


Fig. 9. Walkign excitation, acceleration-time trace without TMD (Max = 2.56 m/s^2) and with TMD (0.028 m/s^2)

5. Discussion of the Results

After attaching the TMD to the footbridge, the fundamental vibration frequency was decreased to 1.146 Hz, which is less than the minimum value of the range of walking frequency (1.2 – 2.4 Hz), and therefore the system can be considered stable. The response (acceleration) of the footbridge at the most critical location (at the center) was obtained before and after incorporating the TMD for the walking and running cases. The results showed that under walking excitation, the maximum acceleration decreased after incorporating the TMD from 829 mm/s^2(8.13%g) to 48.5mm/s^2 (0.48%g), which is way below the recommended maximum limit of 5%g. Also, for the running excitation, the maximum acceleration decreased from 2556 mm/s^2 (25%g) to 28mm/s^2 (0.27%g), which is way below the recommended maximum limit of 5%g according to ISO 10137 [4]. Under walking excitation, the maximum velocity decreased after incorporating the TMD from 37. mm/sto 3. mm/s, which is a 92% reduction. Under running excitation, the maximum velocity decreased from 11 mm/sto 1.78mm/s, which is a 98% reduction. Under walking excitation, the maximum displacement decreased 3.1 mm to 0.3mm, which is a 90% reduction. Under running excitation, the maximum displacement decreased from 9 mm to 0.39mm, which is a 96% reduction. Figs. 9 and 10 show the acceleration-time traces before and after the TMD for the walking and running cases. The traces clearly show that the incorporated TMD were very effective in controlling the vibrations of the footbridge.

6. Conclusions and Recommendations

In general, TMD sare tuned to the fundamental natural frequency of the footbridge and mounted to a specific location in a structure in order to reduce the amplitude of vibration to an acceptable level, increase the structure vibration period, dissipate the input energy caused by vertical and lateral forces, and reduce long-term vibration-induced deteriorations in footbridges. For common footbridges in Jordan, designing footbridges with conservative sections under static loads only is not sufficient. Dynamic load from human excitation of (walking, running, and jumping) must be taken into consideration because they may excite footbridges with frequencies close to the footbridge natural frequency making lateral and vertical vibrations, discomfort of crossing pedestrians and sometimes resonance case. The use of TMDs is the most effective and economical solution to solve this problem and they can be optimized and tuned with frequency equals to the footbridge fundamental natural frequency to absorb all vibrations and dissipate the energy. After designing footbridges on the static loads, a numerical model must be done to analyse the bridge dynamically and obtain the footbridge fundamental frequency and then design TMD if it needed.

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