MATEC Web of Conferences **107**, 00009 (2017) DOI: 10.1051/matecconf/201710700009
DYN-WIND'2017

Pedestrian load models of footbridges

Jiří Máca[1,*] and *Jan* Štěpánek[1]

[1]Czech Technical University in Prague, Faculty of Civil Engineering, Department of Mechanics, Thákurova 7, Praha 6, CZ-166 29, Czech Republic

Abstract. The increase of vibration problems in modern footbridges shows that footbridges should no longer be designed for static loads only. Not only natural frequencies but also damping properties and pedestrian loading determine the dynamic response of footbridges and design tools should consider all of these factors. In this paper the pedestrian load models for serviceability verification of footbridges, which are missing in the current European codes, are presented. For simplicity reasons the proposed pedestrian load models are based on stationary pulsating loads instead of moving pulsating loads. It is shown that simplified procedure can be used in verification of the serviceability limit state related to vibration due to pedestrians. Footbridge vibrations don't cause usually structural problems, but if the vibration behaviour does not satisfy the comfort criteria, changes in the design or damping devices could be considered. The most popular external damping devices are viscous dampers and tuned mass dampers (TMD). The efficiency of TMD is demonstrated on the example of a footbridge prone to vibrations induced by pedestrians. It is shown that if the TMD is tuned quite precisely the reduction of accelerations can be very significant.

1 Introduction

Modern footbridges are very often lightweight and flexible structures, where the first natural frequencies of vibration may fall close to dominant frequencies of the dynamic excitation due to walking or running. Such bridges are susceptible to vertical as well as to horizontal vibrations leading to a resonant response characterized by high levels of vibration and a dynamic design is necessary.

In this paper, the different models of dynamic loads caused by pedestrian crossing the bridge, which can be used in serviceability verification, are presented. Although footbridge vibrations do not cause usually structural problems, they can induce some uncomfortable sensation, and so many codes establish maximum acceptable values of acceleration. Provided that the vibration behaviour due to expected pedestrian traffic is checked with dynamic calculations and satisfies the required comfort, any type of footbridge can be designed and constructed. If the vibration behaviour does not satisfy some comfort criteria, changes in the design or damping devices could be considered.

[*] Corresponding author: maca@fsv.cvut.cz

2 Pedestrian loads

In order to verify serviceability limit state related to vibration due to pedestrians it is necessary to define dynamic pedestrian load. Numerous studies deal with determination of human walking, running or jumping force over the years, cf. e.g. [1].

The possible loading scenario can be divided into five categories:
- Single person loading;
- Normal traffic - spatially unrestricted traffic where each individual can move freely without having to change walking pattern to avoid contact with others;
- Crowd loading - spatially restricted traffic where the walking of each individual is restricted due to limited space;
- Group loading - a number of persons is walking closely together;
- Vandal loading - a person, or a group of people, tries to excite the structure by moving in a correlated harmonic way in response-sensitive areas.

In addition to these five groups three different types of human motion are commonly considered to model the dynamic loads applied by pedestrians, namely walking, running and rhythmic jumping. All these load models can often be categorized into deterministic and probabilistic models. In this paper only the deterministic models of a single pedestrian, group and crowd loading will be considered.

Two types of analytical force models can be found in the literature: time-domain models (deterministic and probabilistic force models) and frequency-domain models – for a detailed review cf. [1] and [2]. The suitable model of mutual interaction between human gait and elastic bridge has been developed in [3].

As an example the deterministic force model for walking is given. The vertical force component is greater than the horizontal one, but the lateral and longitudinal horizontal components can also cause vibration related problems of slender bridges. Frequency of lateral movement, which occurs as a result of moving the centre of mass from one foot to the other, is equal to half of the step frequency of vertical or longitudinal movement.

General shapes of the temporal evolution of the pedestrian loads - assuming a perfect periodicity of the force - can be performed using appropriate load-time functions, for a vertical periodic force $F_{p,ver}(t)$, lateral periodic force $F_{p,lat}(t)$ and longitudinal periodic force $F_{p,long}(t)$:

$$F_{p,ver}(t) = G + \sum_{i=1}^{3} G a_i \sin(2\pi\, i\, f_p\, t - \varphi_i) \tag{1}$$

$$F_{p,lat}(t) = 0.05 G \sin 2\pi \frac{f_p}{2} t \tag{2}$$

$$F_{p,long}(t) = 0.20 G \sin 2\pi\, f_p t \tag{3}$$

where G is the weight of the person (usually G = 700 N), f_p is the pacing frequency, a_1 = 0.4, $a_2 = a_3 = 0.1$ are the Fourier coefficients of the i-th harmonic for vertical, lateral and longitudinal forces, $\varphi_1 = 0$ and $\varphi_2 = \varphi_3 = \pi/2$ are the phase shifts of the ith harmonic contributions.

The pacing frequency f_p and the pedestrian forward speed v_p are two parameters that play a fundamental role in terms of the characterisation of the excitation. The corresponding average values are presented in Table 1 for walking and running.

Table 1. Data on walking and running [2].

	Pacing frequency f_p [Hz)	Forward speed v_p [ms^{-1}]	Stride length $L=v_p/f_p$ [m]	Vertical fundamental frequency f_{vert} [Hz]	Horizontal fundamental frequency f_{lat} [Hz]
Slow walk	1.7	1.1	0.65	1.7	0.85
Normal walk	2.0	1.5	0.75	2.0	1.0
Fast walk	2.3	2.2	0.96	2.3	1.15
Slow running (jogging)	2.5	3.3	1.32	2.5	1.25
Fast running (sprinting)	>3.2	5.5	1.72	>3.2	>1.6

A general proposal as to the typical frequency ranges for different human activities is given for walking 1.6-2.4 Hz and 3.5-4.5 Hz (first and second walking harmonics), for running 2.0-3.5 Hz, for jumping 1.8-3.4 Hz and for bouncing 1.5-3.0 Hz. Commonly adopted mean value frequency for running and jumping is 2.5 Hz [10].

3 Proposed load models

The current European standard for determination of traffic loads on bridges [4] does not recommend the load models for serviceability limit verification due to pedestrians. The Guidelines for the design of footbridges [5] gives the certain pedestrian load models. The load models are divided into three categories: Single pedestrian load model (DLM1), Group of pedestrians load model (DLM2) and Continuous pedestrian stream load model (DLM3). Instead of pulsating forces in vertical and lateral direction which move with the speed of 0.9 f_p, the stationary pulsating forces applied at the most adverse position on the bridge are defined.

DLM1 defines vertical $F_{p,v}(t)$ and horizontal (lateral) components $F_{p,h}(t)$ as:

$$F_{p,v}(t) = 180 \sin 2\pi f_v t \quad [\mathrm{N}] \tag{4}$$

$$F_{p,h}(t) = 70 \sin 2\pi f_h t \quad [\mathrm{N}] \tag{5}$$

DLM2 defines the effect of a group of 8 ÷ 15 persons walking across the bridge by vertical $F_{g,v}(t)$ and horizontal components $F_{g,h}(t)$ as:

$$F_{g,v}(t) = 180\, k_v \sin 2\pi f_v t \quad [\mathrm{N}] \tag{6}$$

$$F_{g,h}(t) = 70\, k_h \sin 2\pi f_h t \quad [\mathrm{N}] \tag{7}$$

The effect of synchronisation of step frequencies and the phase shift between pedestrians is taken into account by coefficients k_v and k_h (Fig. 1).

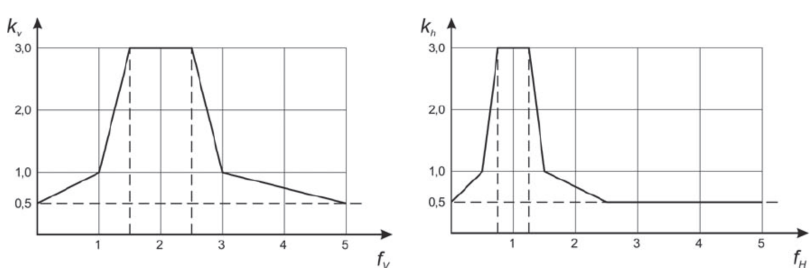

Fig. 1. Coefficients k_v and k_h [5].

 DOI: 10.1051/matecconf/201710700009

DLM3 defines the continuous pedestrian stream is modelled as a uniformly distributed pulsating load with a vertical component $q_{p.v}(t)$ and a lateral component $q_{p,h}(t)$ as:

$$q_{p.v}(t) = 12.6\, k_v \sin 2\pi f_v\, t \quad [\mathrm{Nm}^{-2}] \tag{8}$$

$$q_{p,h}(t) = 3.2\, k_h \sin 2\pi f_h\, t \quad [\mathrm{Nm}^{-2}] \tag{9}$$

The load should be applied in the way to produce the most unfavourable loading case (depending on the mode shape) and a uniformly distributed mass of 400 kN/m^2 (if unfavourable) should be applied at the same location.

4 Example - Footbridge in Čelákovice

The footbridge is a cable-stayed structure with 3 spans 43.0 + 156.0 + 43.0 meters made of Ultra-High Performance Concrete. The height of the steel pylons is 36 meters (Fig. 2 and Fig. 3). Natural frequencies are summarized in Table 2 and important modes of vibration are shown in Fig. 4 to 6.

4.1 Results

Pedestrian loading was modelled using Eq. (6) and Eq. (7) for three principal load cases – a) horizontal excitation with pacing frequency corresponding to the fundamental lateral frequency; b) vertical excitation with pacing frequency corresponding to the fundamental vertical frequency; c) vertical excitation with pacing frequency corresponding to the commonly adopted mean value frequency for walking 2.0 Hz. The results of the analysis are given in Table 3. It can be seen that for the load case c) the accelerations are higher than the limit values taken from Eurocode EN 1990. In such that case the changing of vibration characteristics of the footbridge (natural frequencies) or damping devices should be considered.

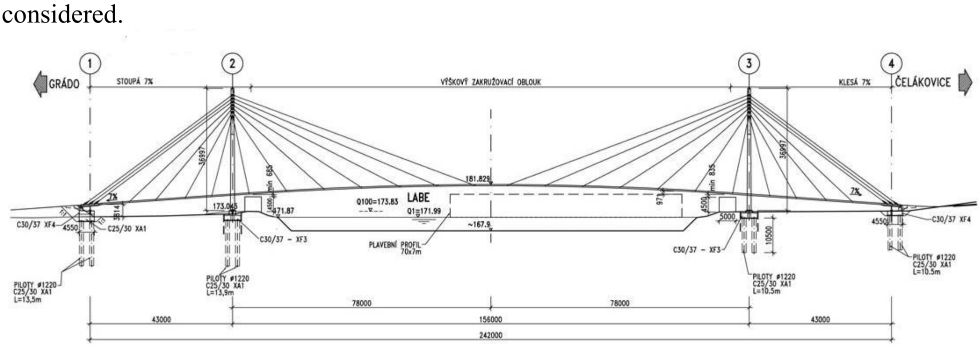

Fig. 2. Footbridge Čelákovice – view [6].

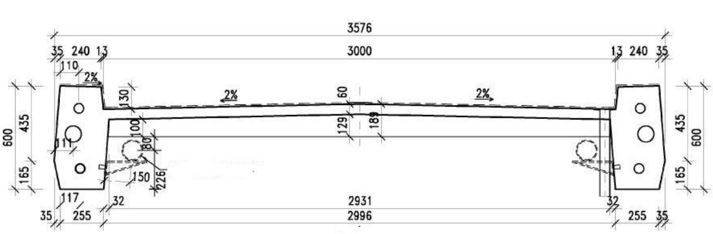

Fig. 3. Footbridge Čelákovice – cross section [6].

Table 2. Footbridge Čelákovice – natural frequencies and modes of vibration.

Mode of vibration	Natural frequency f [Hz]
1 – horizontal bending	0.59
2 – vertical bending	0.63
3 – vertical bending	0.81
4 – vertical bending	1.16
5 – vertical bending	1.44
6 – torsional	1.47
7 – horizontal bending	1.58
8 – vertical bending	1.63
9 – vertical bending	1.72
10 – vertical bending	1.82
11 – pylon	1.87
12 – pylon	1.99
13 – vertical bending	2.04

Table 3. Footbridge Čelákovice – response due to pedestrian loading

Mode of vibration	Pacing frequency f_p [Hz]	Maximum displacement d_{max} [10^{-3} m]	Maximum acceleration a_{max} [ms^{-2}]	Limit acceleration a_{lim} [ms^{-2}]
1 – horizontal bending	0.59	7.0	0.10	0.2
2 – vertical bending	0.63	15.3	0.24	0.7
13 – vertical bending	2.04	4.5	0.74	0.7

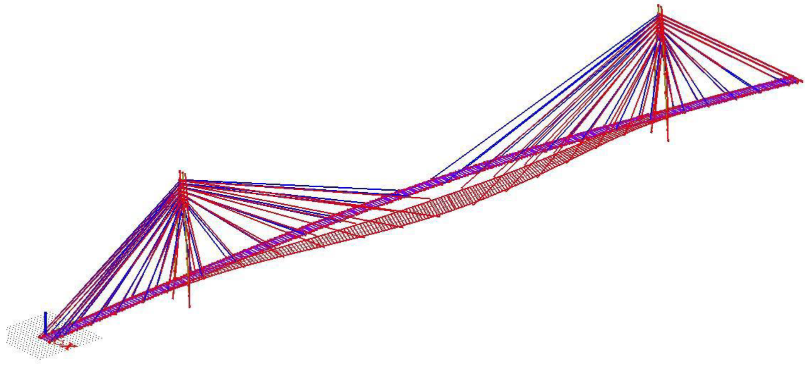

Fig. 4. Footbridge Čelákovice – horizontal bending mode of vibration – f = 0.59 Hz.

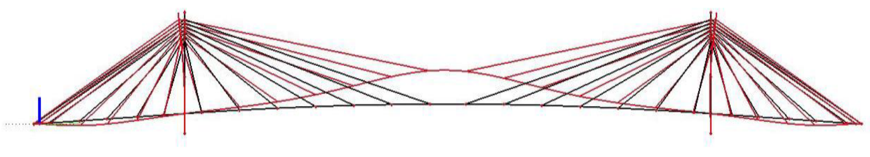

Fig. 5. Footbridge Čelákovice – vertical bending mode of vibration – f = 0.63 Hz.

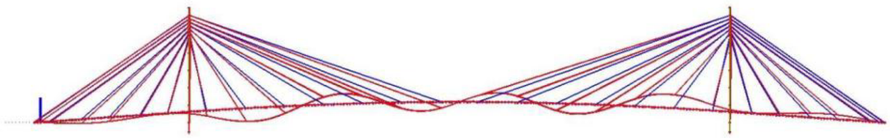

Fig. 6. Footbridge Čelákovice – vertical bending mode of vibration – f = 2.04 Hz.

4.2 Footbridge with TMD

To avoid undesirable vibrations of the structure it is a good idea to install tuned mass dampers (TMDs) on the footbridge to dissipate the energy from one or more modes. A TMD is often a much more lucrative solution when compared to changing the natural frequencies of the structure.

The theory of how a TMD works, and how to determine the optimal characteristics are summarized in [7]. With respect to the antisymmetric shape with natural frequency of vertical bending 2.04 Hz (cf. Fig. 5) two TMDs were mounted at the points with maximum displacements close to the midspan.

Parameters of the footbridge:

Mass m_s = 440 000 kg
Natural frequency f_s = 2.04 Hz

Parameters of the TMD:

Mass m_d = 2 200 kg
Mass ratio $\mu = 2m_d / m_s = 0.01$
Natural frequency $f_d = f_s /(1+ \mu) = 2.02$ Hz
Stiffness $k_d = \left(2\pi f_d\right)^2 m_d = 354$ kN/m

As a result of the increased mass of the footbridge with two TMDs) the corresponding natural frequency changed to the value of 1.83 Hz. The response was calculated for the pacing frequency 1.83 Hz and results are given in Table 4.

Table 4. Footbridge Čelákovice – response due to pedestrian loading

Mode of vibration	Pacing frequency f_p [Hz]	Maximum displacement d_{max} [10^{-3} m]	Maximum acceleration a_{max} [ms^{-2}]	Limit acceleration a_{lim} [ms^{-2}]
vertical bending	2.04	4.5	0.74	0.7
vertical bending with TMDs	1.83	2.2	0.29	0.7

5 Conclusions

In this paper the pedestrian load models for serviceability verification of footbridges, which are missing in the current European codes, are presented. For simplicity reasons the proposed pedestrian load models are based on stationary pulsating loads instead of moving pulsating loads. It is shown that simplified procedure can be used in verification of the serviceability limit state related to vibration due to pedestrians.

Not only natural frequencies but also damping properties and pedestrian loading determine the dynamic response of footbridges and design tools should consider all of these factors. Footbridge vibrations don't cause usually structural problems, but if the vibration behaviour does not satisfy the comfort criteria, changes in the design or damping devices could be considered. The most popular of these are viscous dampers and TMDs. The efficiency of TMD is demonstrated on the example of a footbridge prone to vibrations induced by pedestrians. Is has been shown that if the TMD is tuned quite precisely (especially its frequency) the reduction of accelerations can be very significant.

The authors gratefully acknowledge support from Technology Agency of the Czech Republic (TAČR), project TE01020168 *Centre for Effective and Sustainable Transport Infrastructure* (CESTI) and CTU project SGS17/043/OHK1/1T/11 *Development and application of advanced algorithms for numerical analysis and modeling of structures and materials.*

References

1. S. Živanovič, A. Pavic A, P. Reynolds, J. Sound Vib. **279**, 1-74 (2005)
2. H. Bachman, W. Ammann, *Vibrations in Structures Induced by Man and Machines* (IABSE Structural Engineering Document 3e, 1987)
3. J. Máca, M. Valášek, *8th International Conference on Structural Dynamics EURODYN 2011*, 1083-1089 (2011)
4. *Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges*, (CEN, 2003)
5. *Guidelines for the design of footbridges*, (FIB Bulletin 32, 2005)
6. *Lávka přes Labe - statický výpočet,* (Pontex, 2013)
7. J. Máca, Mater Sci Eng (to be published)