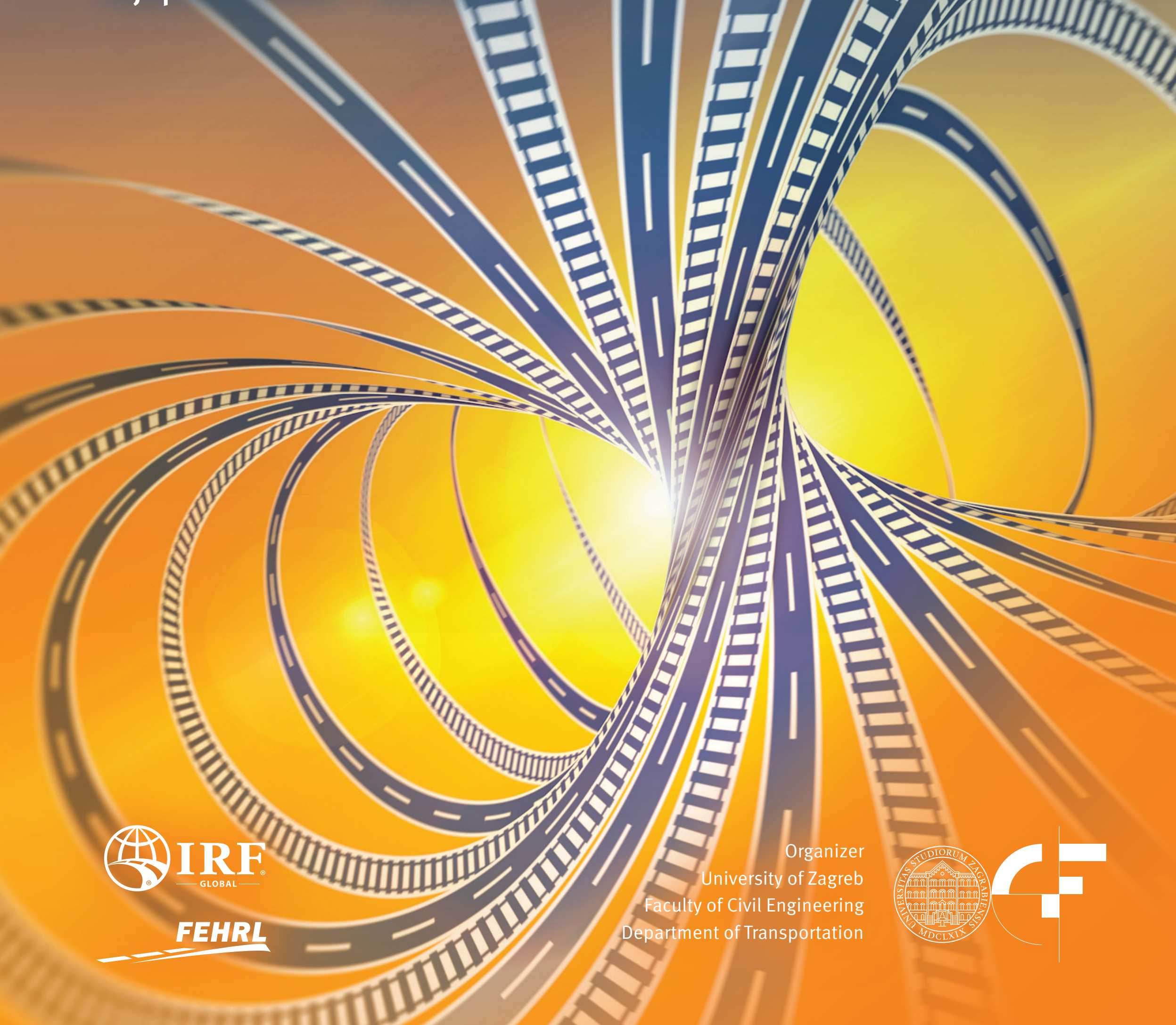
CETRA[2018]

5th International Conference on Road and Rail Infrastructure

17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR



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CETRA[2018]
5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

TITLE
Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY
Stjepan Lakušić

ISSN
1848-9850

ISBN
978-953-8168-25-3

DOI
10.5592/CO/CETRA.2018

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY
"Tiskara Zelina", May 2018

COPIES
500

Zagreb, May 2018.

Proceedings of the
5th International Conference on Road and Rail Infrastructures – CETRA 2018
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Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

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CETRA2018 17–19 May 2018, Zadar, Croatia
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THE ANALYSIS OF VIBRATIONS INDUCED BY PEDESTRIAN TRAFFIC AND THE APPLICATION OF DAMPING SYSTEMS ON FOOTBRIDGES

Petra Mužic, Anđelko Vlašić
University of Zagreb, Faculty of Civil Engineering, Croatia

Abstract

With the fast development of modern materials and the intention to create constructions that are more elegant and architecturally different, pedestrian bridges with slender cross sections and wider spans are build, resulting in reduced mass and stiffness in comparison to older bridges. That leads to increased vertical and horizontal vibrations and low natural frequencies under pedestrian loading which correspond with the frequencies of the human walk and create a very unpleasant occurrence known as resonance. Despite this problem being known from the 1980's, it is a growing concern in pedestrian bridges nowadays. What is more, the current European Norm that determines the traffic load on bridges does not provide any pedestrian load models to check the serviceability limit state. The Eurocode directs engineers to the application of National Annexes from individual countries where the corresponding dynamic models should be defined. In the Croatian National Annex, such dynamic models are still missing. This paper analyses the impact of pedestrian traffic models on the dynamic behaviour of pedestrian bridges, including numerical dynamic analysis confirmed with experimental dynamic tests using the "Time history" method. Increasing the damping by modifying the structure, connections, supports and non-structural elements may be considered, but often considerable practical problems arise. To increase the damping, it is far more effective, and less expensive, to install a damping system. Damping systems increase the amount of energy that is dissipated by the structure. In this paper the performance and optimization of different damping systems will be presented. The analysis will include the application of considered and confirmed pedestrian load models on numerical systems of vibration sensitive footbridges, where the vibrations tend to be decreased using dampers. Moreover, guidelines for the practical treatment of vibration problems in pedestrian bridges using various dampers will be given.

Keywords: bridge vibrations, pedestrians, damping, dynamic models

1 Vibration problems of pedestrian bridges

Vibrations induced by pedestrians can strongly affect the serviceability and in rare cases the fatigue resistance and the safety of a footbridge. If the structure damping is low and natural frequencies of the bridge match the frequency of walking noticeable vibrations can occur. On the other hand, footbridges so rigid that no vibrations are induced have either very short spans or are not particularly elegant or economic structures. The main goal of a structural engineer should not be to stiffen the bridge until all elegance is lost, but to control the vibrations in a targeted way. The vibrations have to move within boundaries in which the structural safety is absolutely guaranteed and the users still feel comfort while crossing the bridge. Therefore, an engineer not only has to know what components influence the vibrations e.g. how to shift

DOI: https://doi.org/10.5592/CO/CETRA.2018.959

the natural frequency of the bridge, where to install vibration dampers, but he also has to know the limits of human acceptance of vibrations.

1.1 Excitation loads of pedestrians

The human body is a complex mechanical system with inherent mass, stiffness and damping properties. When a human being occupies a structure, a combined human-structure system is formed. The term human-structure interaction covers the two-way feedback within the human-structure system [1]. While walking, the body weight is taken over by the vertical standing leg and transferred to the floor causing both vertical, horizontal-lateral and horizontal-longitudinal reaction ground forces (Figure 1). To be able to perform a dynamic analysis of a structure, a mathematical model of the pedestrian dynamic forces is needed. The dynamic character of the walking force can be described as a function of time and space, periodically repeated with regular time intervals according to a person's stepping pace [2]. The step frequency differs from 1,7 Hz (slow walking) to 2,4 Hz (fast walking). Horizontal walking components derive from the continuous horizontal shifting of the body mass center and their frequency equals to half of the step frequency. General shapes for continuous forces in vertical and horizontal directions have been constructed assuming a perfect periodic force. Hence, the periodic components of walking force can be represented by Fourier series [2]:

Vertical walking force: $$F_{p,v}(t) = G + G\sum_{i=1}^{n} \alpha_{i,v} \sin(2\pi \cdot i \cdot f_s \cdot t - \varphi_i) \quad (1)$$

Lateral walking force: $$F_{p,lat}(t) = G\sum_{i=1}^{n} \alpha_{i,lat} \sin(2\pi \cdot i \cdot \frac{f_s}{2} \cdot t - \varphi_i) \quad (2)$$

Longitudinal walking force: $$F_{p,long}(t) = G\sum_{i=1}^{n} \alpha_{i,long} \sin(2\pi \cdot i \cdot f_s \cdot t - \varphi_i) \quad (3)$$

Various Fourier coefficients for the i^{th} harmonic are suggested in [1].

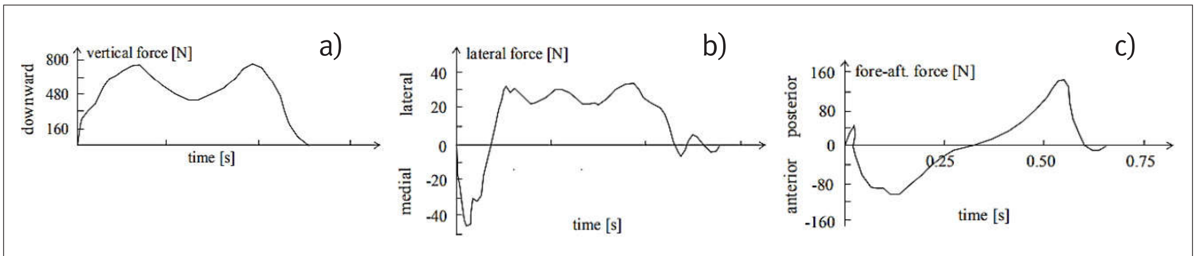


Figure 1 Walking force in (a) vertical, (b) lateral and (c) longitudinal direction [3]

Synchronization of walking pedestrians may also occur, which means pedestrians coordinating their movement with other pedestrians and the bridge both in vertical and lateral direction. Pedestrians are more sensitive to lateral vibrations often causing the problem called "Lock in effect", which describes horizontal lateral synchronization of bridge movement and pedestrians walking. Severity of horizontal movement coordination was witnessed on London Millennium Bridge [4] and the Passarelle Solferino footbridge [5].

1.2 Vibration boundaries in design practice

The measured or calculated dynamic response values of a bridge can be compared and controlled by different guidelines. Guidelines have been made in different design norms about permitted acceleration and bridge frequency, Table 1 and Table 2.

Table 1 Limits for vertical and horizontal accelerations in different norms

Vertical acceleration aV, max [m/s²]		
Eurocode 0, Appendix 2	0,7	for f1 ≤ 5 Hz f1 – fundamental natural frequency
Eurocode 5, Part 2EdeEE	0,7	for f1 ≤ 5 Hz f1 – fundamental natural frequency
DIN – Fachbericht 102	$0{,}5\cdot\sqrt{f_{1,vert}}$	for f1 ≤ 5 Hz f1 – fundamental natural frequency of the unloaded bridge
BS 5400	$0{,}5\sqrt{f_1}$	f1 – fundamental natural frequency
Bachmann	0,5-1,0	–
Lateral acceleration aL, max [m/s²]		
Eurocode 0, Appendix 2	0,2	horizontal vibrations due to normal use
Eurocode 0, Appendix 2	0,4	For exceptional crowd conditions
Eurocode 5 , Part 2	0,2	for f ‹ 2,5 Hz

Table 2 Limits for vertical and horizontal frequencies in different norms

Norm/Standard	**Limit frequency values**	
	Vertical	**Horizontal**
Eurocode 0, Appendix 2	‹ 5 Hz	–
Eurocode 2	1,6 Hz – 2,4Hz, 2,5 Hz – 5Hz	–
Eurocode 5	‹ 5 Hz	0,5Hz-2,5 Hz
DIN-Fachbericht 102	1,6 Hz – 2,4 Hz, 3,5 Hz – 4,5 Hz	–
BS 5400	‹ 5 Hz	–

1.3 Considered load models

The pedestrian load model suggested by Bachmann implies a completely synchronized walk of N pedestrians. The functions mentioned under eqn (1), (2) and (3) are used to determine the motion components. For Bachmann's model Fourier coefficients and phase angles can be found in [1].

For the purpose of this research, after studying the theoretically described dynamic models from various norms and authors, it was decided to use the valid British National Annex to Eurocode 1991-2 for the vertical walking component [6]. In this load model, the design maximum vertical acceleration resulting from a single pedestrian or a pedestrian group should be calculated by assumption that these are represented with a vertical pulsating force F(N) moving across the span of the bridge at a constant speed v_t:

$$F = F_0 \cdot k(f_v) \cdot \sqrt{1+\gamma\cdot(N-1)} \cdot \sin(2\pi \cdot f_v \cdot t) \tag{4}$$

Furthermore, the above listed function combines various parameters to describe the walking process and deliver a more realistic function of walk. For instance; F_0 contains the reference load for walking or running, $k(f_v)$ is the relation between the bridge natural frequency and the pedestrian pacing rate, γ describes the synchronization within a group of pedestrians with consideration of the span length and factor N which is the number of people dependent on the footbridge category. Corresponding charts and tables for factor determination can be found in [6].

2 Calculation model and experimental conformation

2.1 Time history calculation method

The general approach for dynamic response of structures is to use numerical time-stepping methods for integration of the equation of motion. This includes, after the solution is defined at beginning time i.e. $t = 0$, an attempt to satisfy dynamic equilibrium at discrete points in time while the pedestrian load is moved.

2.2 Experimental measurements

Dynamic tests have been conducted on a truss pedestrian bridge which connects the main and backyard building of the Faculty of Civil Engineering in Zagreb (Figure 2). Dynamic tests on the bridge were used to determine its modal parameters and vertical accelerations under various pedestrian loading. A software model was adjusted i.e. calibrated according to the obtained values and pedestrian load was applied. After the analysis both results were compared. Numerical and experimental data are sufficiently matching (Table 3). This confirms the accuracy of the used model of pedestrian movement and time-history analysis model [7].

Table 3 Experimental and numerical results of vertical acceleration [m/s^2]

	Experimentally obtained results	Numerically obtained results
One person	0,062	0,057
Three persons	0,188	0,167
Six persons	0,310	0,296

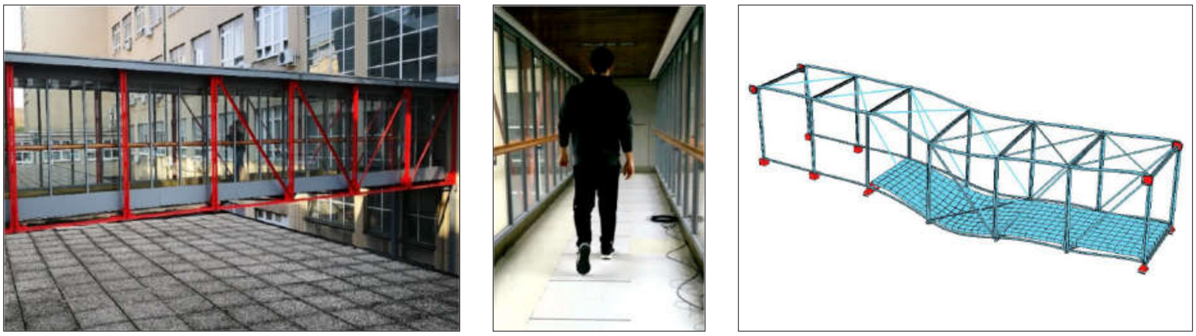


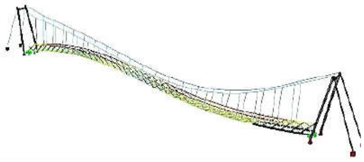
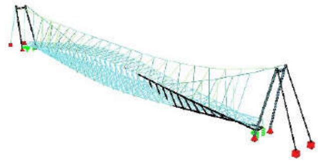
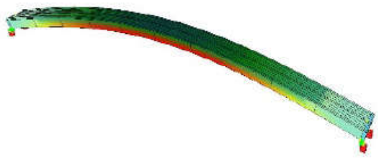
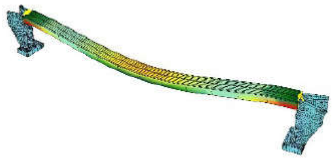
Figure 2 Experimental and numerical determination of accelerations

3 Reduction of vibration acceleration

3.1 Prevention with structural measures

Structural measures include modifying the structure, connections, supports and non-structural elements in the designing phase of a new bridge or on an existing bridge in aim to suppress structural vibrations until reaching acceptable levels. To demonstrate the influence of structural measures two alternatives of the same suspended bridge and a simply supported beam bridge have been dynamically analyzed under pedestrian loading. As it can be seen (Table 4) the variant of the suspended bridge with inclined hangers and the variant of the simply supported beam bridge with rigid supports show notably smaller accelerations for vertical pedestrian loads. More to the research can be found in [7].

Table 4 Dynamic modification as a result of structural measures

	Vertical hangers		Inclined hangers	
Second critical mode				
Mode shape	vertical		torsional	
Relevant critical mode	f = 1,73 Hz; T = 0,578 s		f = 1,94 Hz; T = 0,515 s	
Load model	Bachmann	BS	Bachmann	BS
Walking frequency [Hz]	1,8	1,73	1,94	1,94
Vertical acceleration [m/s^2]	1,85	0,72	1,53	0,66
	Simply supported beam		**Beam with rigid supports**	
First critical mode				
Mode shape	vertical		vertical	
Relevant critical mode	f = 1,82 Hz; T = 0,549 s		f = 2,46 Hz; T = 0,407 s	
Load model	Bachmann	BS	Bachmann	BS
Walking frequency [Hz]	1,82	1,82	2,46	2,46
Vertical acceleration [m/s^2]	2,74	0,56	2,07	0,23

3.2 Use of dampers

To increase the damping or improve existing structures, it is far more effective, and often less expensive, to install tuned vibration absorbers i.e. dampers. Damping systems increase the amount of energy that is dissipated by the structure. External damping devices include tuned mass dampers (TMD), pendulum dampers, tuned liquid dampers (TLD), tuned liquid column dampers (TLCD), viscous dampers and others. Designing guidelines for various dampers are proposed in [1].

3.2.1 Use of TMD-s for suppression of vertical vibration in FE models

A TMD is a single degree of freedom system consisting of a mass mD (fraction of the bridge modal mass), a damping element with the constant dD and a spring with the constant kD whose resonant frequency is adjusted to match the resonant frequency of the bridge. When the bridge oscillates in resonance under pedestrian loading, the damper moves with greater amplitude resulting with energy dissipation and reduction of amplitude at the fixing point. The effect of TMD displacement in relation to the mass ratio μ is shown on a simple beam bridge with rigid supports. Using the TMD vertical accelerations from the first vertical mode can be reduced from 0,62 m/s^2 to 0,14 m/s^2, Table 5. Figure 3. shows that the greatest efficiency differences in the optimal position (Position 1) can be noted in the μ range of from 0,02 to 0,05. The damping efficiency for the mass ratio μ between 0,06 and 0,08 is reduced, meaning that even with more applied mass a linear vibration reduction should not be expected.

Table 5 Accelerations dependent on the mass ratio and the damper position

POSITION 1 – Optimal position	POSITION 2	POSITION 3
		
POSITION 4	**POSITION 5**	**POSITION 6**
		

Mass ratio μ	POS. 1 [m/s²]	POS. 2 [m/s²]	POS. 3 [m/s²]	POS. 4 [m/s²]	POS. 5 [m/s²]	POS. 6 [m/s²]	mD [t]	kD [kN/m]	dD [kNs/m]
No damper	0,62	0,62	0,62	0,62	0,62	0,62	–	–	–
0,01	0,52	0,52	0,54	0,55	0,56	0,56	0,37	525	5
0,02	0,45	0,47	0,50	0,54	0,55	0,56	0,74	1030	15
0,03	0,37	0,40	0,46	0,52	0,55	0,56	1,12	1510	26
0,04	0,30	0,33	0,41	0,50	0,55	0,56	1,49	1983	40
0,05	0,25	0,28	0,37	0,48	0,55	0,56	1,86	2431	54
0,06	0,20	0,23	0,32	0,46	0,54	0,56	2,23	2862	69
0,07	0,17	0,19	0,28	0,44	0,54	0,56	2,61	3277	86
0,08	0,14	0,16	0,25	0,41	0,53	0,56	2,98	3677	102

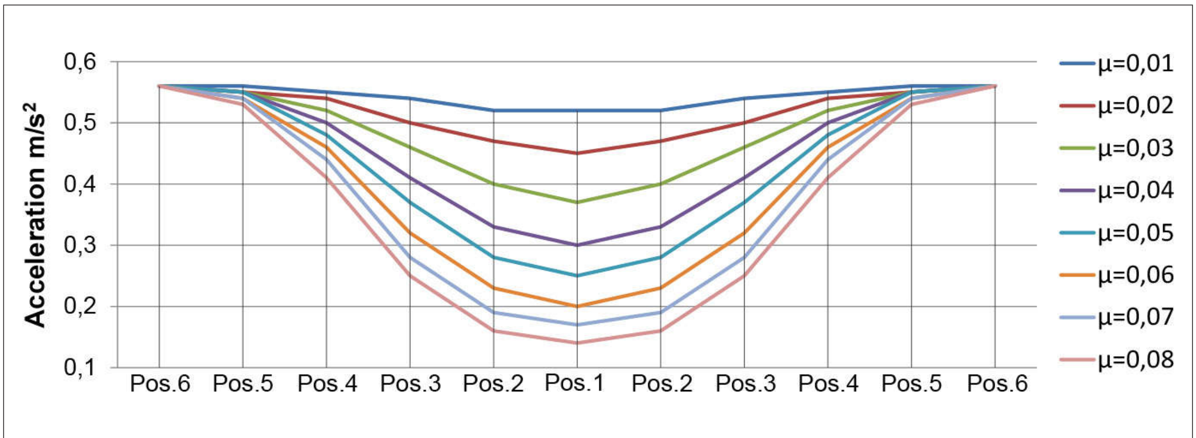


Figure 3 Resulting acceleration in relation to mass ratio and damper position

3.2.2 Use of pendulum dampers for suppression of horizontal vibration in FE models

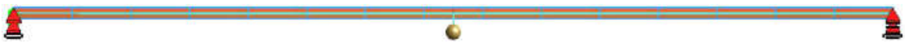
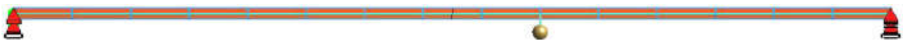
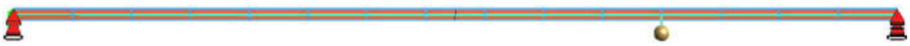
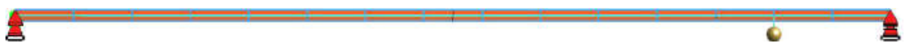
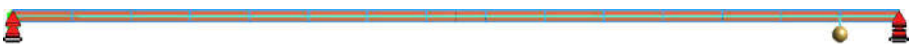
Pendulum dampers are generally intended for reducing lateral vibrations by horizontal translatory motion. To analyze pendulum dampers in numerical models, the construction must be loaded with the horizontal walking force. In this case the previously used norm BS5400 does not provide any specific load model. Therefore, the horizontal load function according to Stráský [8] is used:

$$F_{gp,v}(t) = 70 \cdot k_h(f_h) \cdot \sin(2 \cdot \pi \cdot f_h \cdot t) \tag{5}$$

where factor $k_h(f_h)$ contains the possibility of horizontal synchronization.

Furthermore, the analyzed simple beam model consists of steel welded longitudinal and transverse I profiles and a timber revetment. Using the pendulum damper horizontal accelerations of the first horizontal mode can be reduced from 0,65 m/s^2 to 0,03 m/s^2 (Table 6, Figure 4). Unlike in case of TMD-s where with the increasement of the mass ratio almost linearly increased the efficiency, this does not happen for pendulum dampers, especially at lower mass ratios. As shown in Figure 4. the damper with μ = 0,04 only achieves significant reduction of vibrations at the optimal position (Position 1), in other positions his efficiency is even lower than for the damper with μ = 0,01. Such behavior can be explained by considering the pendulum sensitivity for movement in two horizontal directions. Also, in the numerical analysis, the model of a pendulum damper is extremely demanding and sensible to minor changes in position geometry.

Table 6 Accelerations dependent on the mass ratio and the damper position

	**Position 1 – Optimal**
	**Position 2**
	**Position 3**
	**Position 4**
	**Position 5**
	**Position 6**
	**Position 7**

Mass ratio μ	**POS. 1 [m/s^2]**	**POS. 2 [m/s^2]**	**POS. 3 [m/s^2]**	**POS. 4 [m/s^2]**	**POS. 5 [m/s^2]**	**POS. 6 [m/s^2]**	**POS. 7 [m/s^2]**	**mD [t]**	**dD [kNs/m]**
No damper	0,65	–	–	–	–	–	–	–	–
0,01	0,32	0,32	0,30	0,38	0,28	0,44	0,60	0,1188	0,6157
0,02	0,60	0,12	0,16	0,60	0,25	0,63	0,52	0,2367	0,6249
0,03	0,05	0,05	0,08	0,095	0,15	0,27	0,48	0,3564	0,6341
0,04	0,05	0,38	0,34	0,44	0,65	0,60	0,65	0,4752	0,6433
0,05	0,03	0,05	0,052	0,062	0,082	0,22	0,40	0,594	0,6525

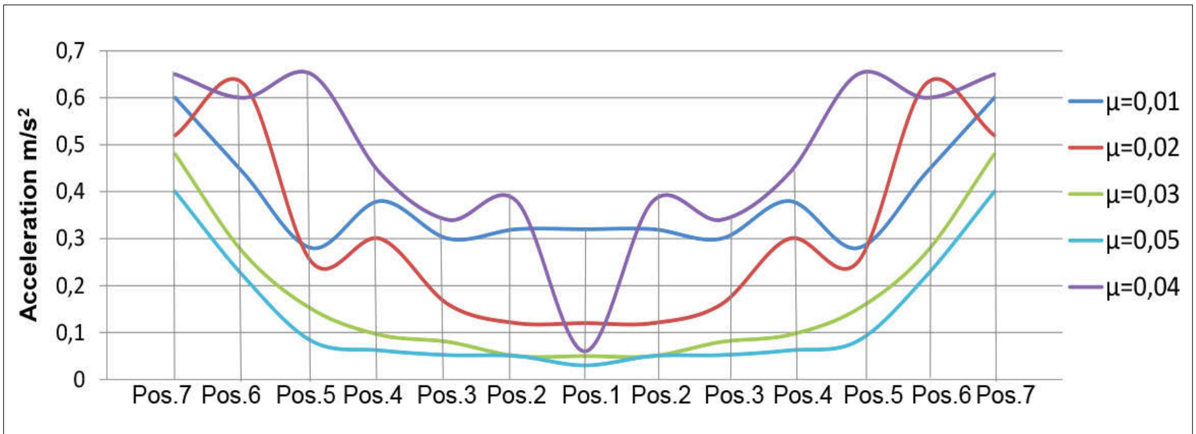


Figure 4 Graphical representation of the mass ratio and damper position

4 Conclusion

Although vibration problems on pedestrian bridges have been known for decades, they have so far been insufficiently regulated by current European norm. The reason for the non-existence of pedestrian models in the norm is a large number of factors that affect human motion. Dynamic properties of the bridge under pedestrian loading often stay unknown until its use, and in many cases they depend on the experience of the designing engineer. Construction measures for vibration reduction at the initial stage of design are the least invasive and often simple ways to achieve significant effect on the dynamic bridge properties. In case where all applied construction measures fail in reducing the acceleration to the level specified in the norm guidelines, or such interventions require a large amount of additional investment, dampers are used. There are many types of dampers and their use depends on the specificity of the vibration that appears on the bridge. The purpose and justification of a dynamic analysis can clearly be seen in shown examples, where the ratio of "invested" mass and "gained" vibration reduction depending on damper type and position is not always linear. Considering the results of this work globally, it is concluded that there are available guidelines for damper design that can accurately estimate their parameters. But only after the dynamic analysis in the numerical model, it can be precisely determined which type, position and parameters of the damper achieve the greatest impact on the bridge.

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