Dynamic Action Induced By Walking Pedestrian

J. Kala, V. Salajka and P. Hradil

Abstract**—**The main focus of this paper is on the human induced forces. Almost all existing force models for this type of load (defined either in the time or frequency domain) are developed from the assumption of perfect periodicity of the force and are based on force measurements conducted on rigid (i.e. high frequency) surfaces. To verify the different authors conclusions the vertical pressure measurements invoked during the walking was performed, using pressure gauges in various configurations. The obtained forces are analyzed using Fourier transformation. This load is often decisive in the design of footbridges. Design criteria and load models proposed by widely used standards and other researchers were introduced and a comparison was made.

Keywords**—**Pedestrian action, Experimental analysis, Fourier series, serviceability, cycle loading.

I. Introduction

AMONG different types of human-induced loads on footbridges, walking force caused by a single pedestrian was established in the past as the most important load type because of its most frequent occurrence. Also, almost all existing force models for this type of load (defined either in the time or frequency domain) are developed from the assumption of perfect periodicity of the force and are based on force measurements conducted on rigid (i.e. high frequency) surfaces. However, footbridges which exhibit vibration serviceability problems are low-frequency flexible structures with natural frequencies within the normal walking frequency range. In such a situation, walking at a near resonant frequency is expected to generate the highest level of response as considered in the published literature. However, the walking force is not perfectly periodic [4] and it could be attenuated due to interaction between the pedestrian and the structure [9]. These two facts deserve more attention in future force modeling. Apart from a single person walking, a group of pedestrians walking at the same speed to maintain the group consistency are a very frequent load type on footbridges in urban areas.

These forces are for people walking on stationary pavements, but it is noted by Bachmann and Ammann that “pedestrians walking initially with individual pace on a footbridge will try to adjust their step subconsciously to any vibration of the pavement. This phenomenon of feedback and synchronization becomes more pronounced with larger vibration of the structure.” Also, for vertical vibration, the authors note that displacements of the order of 10-20 mm have to occur for the phenomenon to be noticeable, although they say that it is more pronounced for lateral vibrations. “Presumably, the pedestrian, having noticed the lateral sway, attempts to reestablish his balance by moving his body in the opposite direction; the load he thereby exerts on the pavement, however, is directed so as to enhance the structural vibration.”

Dynamic load impact by crowd was not researched much in the past, especially in relation to pedestrian bridges. Wheeler [12] and Grundmann et al. [7] were among a handful of researchers who investigated this issue. They found that, under this type of load, footbridges with a natural frequency of around 2 Hz are prone to experience vibrations at a higher level than those induced by a single pedestrian because of synchronization of walking steps between people in the group. However, there is no group force model which is generally accepted.

Measured values of pedestrian lateral dynamic force/static weight as a function of pavement amplitude Dalart [2] with data by Bachmann [1] and Fujino [7] added, see figure 1. The platform in these experiments was 7.3 m long and 0.6 m wide with a handrail along one side. The amplitude of the fundamental component of lateral force is plotted after dividing by the subject’s weight. Arup’s data is for two different frequencies of pavement oscillation: 0.75 and 0.95 Hz. It appears that subjects walked at a comfortable speed with a walking pace not intentionally “tuned” to the pavement frequency. Fujino’s figure is estimated force amplitude from observations of people walking on a bridge with a 1 Hz lateral mode at amplitude of about 10 mm. The three added lines (drawn for comparison), are for moving a rigid mass at frequencies of .75 Hz (bottom line), .85 Hz (middle), .95 Hz (top) through an amplitude of 15 mm (at the left) to 35 mm (at the right).

However walkers were not asked to try to intentionally “tune” their step to the platform’s motion; instead they were asked to walk comfortably for the 7 or 8 paces required to pass over the platform.

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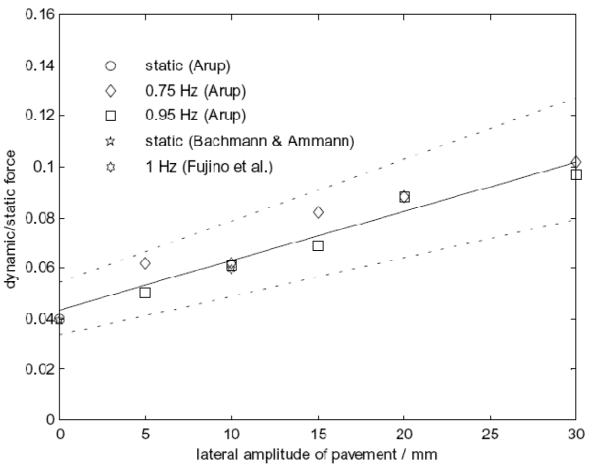

Fig. 1 Dynamic load on moving platform

II. Dynamic Loads Induced by Pedestrians

Pedestrian loading, whether walking or running, was studied rather thoroughly and is translated as a point force exerted on the support, as a function of time and pedestrian position. Considering that *x* is the pedestrian position in relation to the footbridge centerline, the load of a pedestrian moving at constant speed *v* can therefore be represented as the product of a time component $F(t)$ by a space component $\delta(x - vt)$, δ being the Dirac operator, that is:

$$P(x,t) = F(t)\,\delta\,(x - vt) \tag{1}$$

In common design practice, only $F(t)$ is taken into consideration.

A. Vertical Loads

Several measurements were conducted to quantify vertical loads imposed by pedestrians on structures. Most measurements indicate that the shape of the vertical force produced by one person taking one step is of the kind shown in Fig. 1.

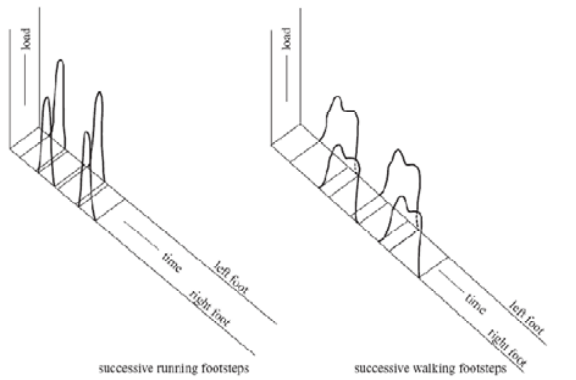

Fig. 2 shape of the vertical force produced by one person taking one step [15]

Measurements of continuous walking were also done. The measured time histories were near periodic with an average period equal to the average step frequency. General shapes for continuous forces in both vertical and horizontal directions were constructed assuming a perfect periodicity of the force, see Figure 3: Periodic walking time histories in vertical directions [16]. As mentioned in the previous section, the vertical forcing frequency is generally in the region of 1.4 – 2.4 Hz [2]. This was confirmed by several experiments, for example by Matsumoto, who investigated a sample of 505 persons. He concluded that the pacing frequencies followed a normal distribution with a mean of 2.0 Hz and a standard deviation of 0.173 Hz.

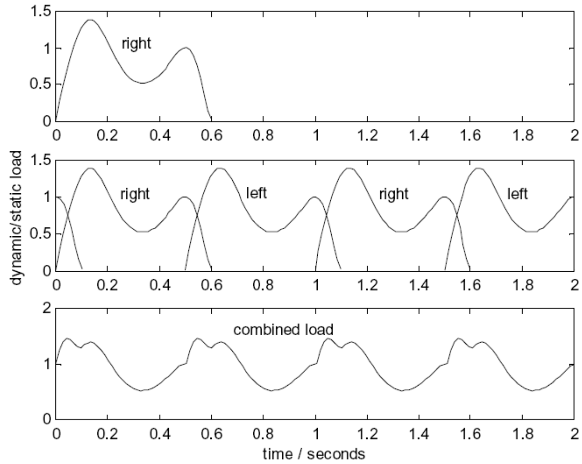

Fig. 3 General shapes for continuous vertical forces [1]

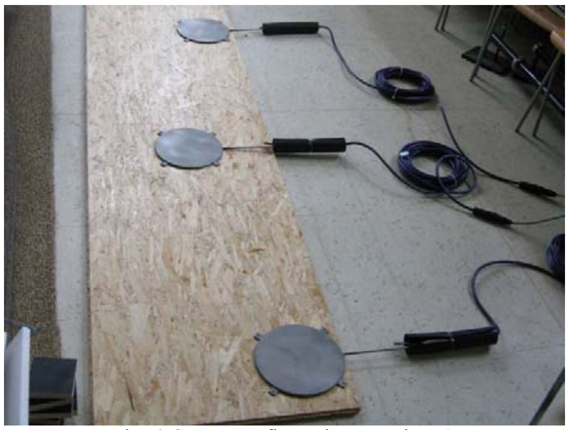

Fig. 4 Gauge configuration – variant 1

To verify the different authors conclusions the vertical pressure measurements invoked during the walking was performed. Three sensors with average base 0.20 m placed on rigid platform were used. Distance between the gauge axes in the direction of movement was equal to 0.9 m. Configuration gauging basis can be seen on Figure 4. In Figure 5 are in different color the effects from each gauge (normalized to static load). In Figure 6 is added blue resulting curve.

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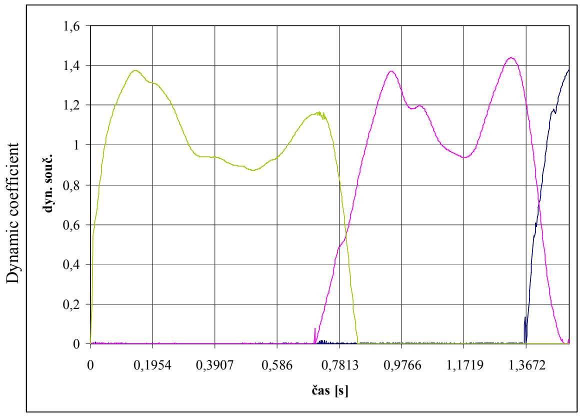

Fig. 5 Force record from gauge configuration – variant 1

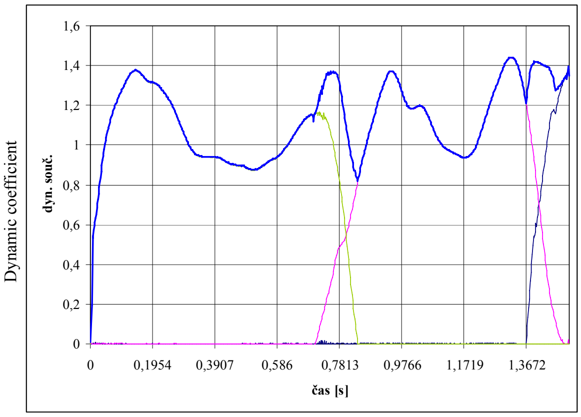

Fig. 6 Force record from gauge configuration – variant 1

In terms of the experiment was examined also the force transmission at the step from heel to the toe (one gauge for heel, second for toe, third for second legs heels) what can be seen in figure 7. Measurements results for this configuration can be seen in figure 8. This configuration confirmed measurements results for the configuration with one sensor for each step. Measurements were effected in sports also with home footwear, in addition was placed on surface sensors various mats (e.g . 15 mm of polystyrene). In terms of these variants there wasn't ascertained the measurable influence neither using footwear nor adjustment surface on resulting force record.

This force record was represented as a Fourier series. The step frequency for this record was approximately 1.55 Hz, i. e. the speed 1.4 m.s^{-1}. Dynamic coefficient for harmonics members (α_1 = 0.32, α_2 = 0.09, α_3 = 0.12, α_4 =0.02) were derived from the graph 9. The record is normalized to the static weight. Experimentally Obtained results are agreement with results in Table I.

Fig. 7 Gauge configuration – variant 2

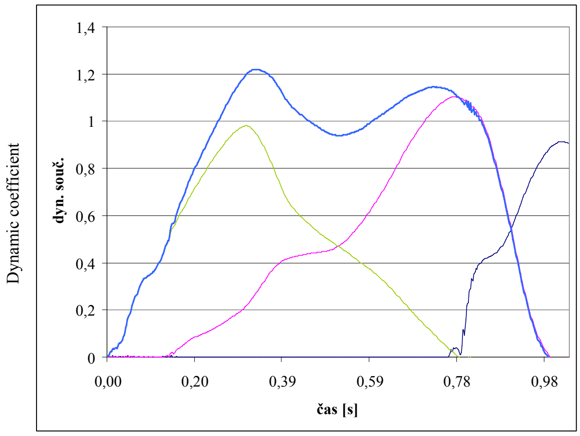

Fig. 8 Force record from gauge configuration – variant 2

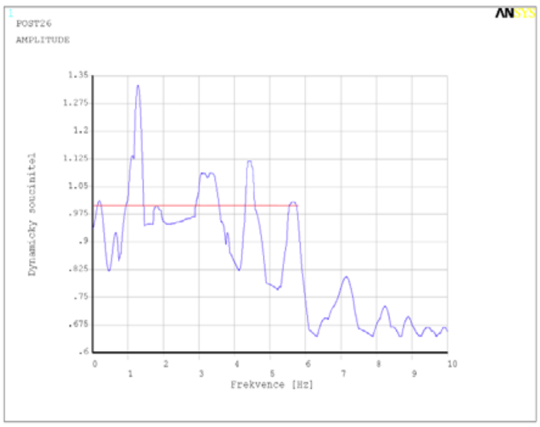

Fig. 9 Force-frequency record

B. *Periodic Load Models*

Periodic load models are based on an assumption that all pedestrians produce exactly the same force and that this force is periodic [11]. It is also assumed that the force produced by a single pedestrian is constant in time.

Dynamic loading caused by a moving pedestrian may be considered a periodic force. This force $F(t)$ can be represented as a Fourier series in which the fundamental harmonic has a frequency equal to the pacing rate [1]:

$$F(t) = G + \sum_{k} \alpha_n G \cdot \sin(2\pi f t + \varphi_n) \qquad (2)$$

where G is the pedestrian's weight, α_n is the load factor of the n-th harmonic, f is the frequency of the force, φ_n is the phase shift of the n-th harmonic, n is the number of the harmonic and k is the total number of contributing harmonics [13].

Several measurements were made in order to quantify the load factor α_n which is essential for this load model. The results of such measurements are shown in Table I.

In 1977, proposed a vertical dynamic load factor of 0.257. Ten years later, Bachmann and Ammann reported the first five harmonics of the vertical as well as the horizontal force. They found the first harmonic of the vertical dynamic load to be 37% of the vertical static load and the first harmonic of the horizontal dynamic load to be 3,9% of the vertical static load.

TABLE I
INPUT RANDOM QUANTITIES

Author	α		Freq.
Young [11]	$\alpha_1 = 0.37(f\text{-}0.95) \leq 0.5$ $\alpha_2 = 0.054+0.0044f$ $\alpha_3 = 0.026+0.0050f$ $\alpha_4 = 0.010+0.0051f$	walk – vertical	average α
Setra [10]	$\alpha_1 = 0.4.\ \delta_2 = \delta_3 = 0.1$	walk – vertical	
	$\alpha_{1/2} = \delta_{3/2} = 0.05,\ \delta_1 = \delta_2 = 0.01$	walk – transverse	
	$\alpha_{1/2} = 0.04,\ \alpha_1 = 0.2,\ \alpha_{3/2} = 0.03,\ \alpha_2 = 0.01$	walk – longitudal	
Bachmann [1]	$\alpha_1 = 1.8/1.7,\ \alpha_2 = 1.3/1.1,\ \alpha_3 = 0.7/.5$	normal jump	2.0 - 3.0
	$\alpha_1 = 1.9/1.8,\ \alpha_2 = 1.6/1.3,\ \alpha_3 = 1.1/.8$	high jump	2.0 - 3.0
	$\alpha_1 = 0.17/0.38,\ \alpha_2 = 0.1/0.12,\ \alpha_3 = 0.04/0.02$	swaying	1.6 – 2.4
	$\alpha_1 = 0.5$	swaying - standing	0.6

In 2001, a year after the opening of the Millennium Bridge, Young presented the work of several researchers. The principles of this work are now used by Arup Consulting Engineers when modeling walking forces and the corresponding structural responses. Young proposed the first four harmonics of the vertical force as a function of the walking frequency f, see Table I [18].

All these tests, performed in order to quantify the load factors, were carried out by direct or indirect force measurements on rigid surfaces [17]. It has already been stated that horizontal movements of the surface seem to increase the horizontal pedestrian force.

III. CONCLUSION

To verify the different authors conclusions the vertical pressure measurements invoked during the walking was performed.

In terms of the experiment was examined also the force transmission at the step from heel to the toe (one gauge for heel, second for toe, third for second legs heels).

Measurements were effected in sports also with home footwear, in addition was placed on surface sensors various mats (e.g . 15 mm of polystyrene). In terms of these variants there wasn't ascertained the measurable influence neither using footwear nor adjustment surface on resulting force record.

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REFERENCES

[1] H. Bachmann, Lively Footbridges a Real Challenge. *Proceedings of the International Conference on the Design and Dynamic Behaviour of Footbridges*, Paris, France, November 20-22, 2002, pages 18-30.

[2] P. Dallard, T. Fitzpatrick, A. Flint, A. Low, R. Ridsdill Smith, M. Willford and M. Roche, *London Millennium Bridge: Pedestrian-Induced Lateral Vibration.* ASCE

[3] Design Manual for Road and Bridges: Loads for Highway Bridges: BD 37/01, Highway Agency, London, February, 2002.

[4] P. E. Eriksson, *Vibration of Low-Frequency Floors—Dynamic Forces and Response Prediction*, PhD Thesis, Unit for Dynamics in Design, Chalmers University of Technology, Goteborg, Sweden, 1994.

[5] Eurocode, Basis of Structural Design - prAnnex A2. EN1990: 2002. European Committee for Standardization, Brussels, Belgium 2002.

[6] Eurocode 5, Design of Timber Structures Part 2: Bridges, EN1995- 2: 2004, European Committee for Standardization, Brussels, Belgium 2004.

[7] Y. Fujino, B. Pacheco, S. Nakamura, P. Warnitchai, Synchronization of Human Walking Observed during Lateral Vibration of a Congested Pedestrian Bridge, Earthquake Engineering and Structural Dynamics, 22, 741-758 (1993).

[8] H. Grundmann, H. Kreuzinger, M. Schneider, *Dynamic calculations of footbridges,* Bauingenieur 68 (1993) 215–225

[9] P. Hradil , J. Kala, V. Salajka, P. Vymlátil, *The application of concrete nonlinear model exposed to impact load*, Recent Researches in Automatic Control - 13th WSEAS International Conference on Automatic Control, Modelling and Simulation, ACMOS'11, 2011, Lanzarote, Spain, Pages 283-286, ISBN: 978-161804004-6.

[10] ISO, *Bases for design of structures Serviceability of buildings and pedestrian walkways against vibration*, ISO/CD 10137, International Stadardization Organization, Geneva, Switzerland, 2005.

[11] J. Kala, V. Salajka, P. Hradil, *Calculation of timber outlook tower with influence of behavior of "steel-timber" connection*, Advanced Materials Research, Volume 428, 2012, Pages 165-168, ISSN: 10226680 ISBN: 978-303785302-3, DOI: 10.4028/www.scientific.net/AMR.428.165

[12] Z. Kala, Thin-Walled Structures 49, 645-651 (2011).

[13] Z. Kala, Engineering Structures 33, 2342-2349 (2011).

[14] Z. Kala, Journal of Civil Engineering and Management 18, 81-90 (2012).

[15] J. Králik, J. Králik,jr.: Probability and Sensitivity Analysis of Machine Foundation and Soil Interaction. Applied and Computational Mechanics. ZCU Plzen. ISSN 1802-680X, 2009, Vol.3, No.1.

[16] S. V. Ohlsson, *Floor Vibration and Human Discomfort*, PhD Thesis, Chalmers University of Technology, Goteborg, Sweden, 1982 (in English).

[17] SETRA, Footbridges, Assessment of vibrational behaviour of footbridges under pedestrian loading, *Technical guide SETRA*, Paris, France 2006.

[18] P. Young, *Improved floor vibration prediction methodologies*, ARUP Vibration Seminar, October 4, 2001.

[19] J. E. Wheeler, Prediction and control of pedestrian induced vibration in footbridges, *ASCE Journal of the Structural Division 108* (ST9) (1982) 2045–2065.

[20] S. Zivanovic, A. Pavic, and P. Reynolds, Vibration serviceability of footbridges under human-induced excitation: a literature review. *Journal og Sound and Vibration 279* (2005).