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# **EXPERIMENTAL APPROACH OF** THE SINGLE PEDESTRIAN-INDUCED EXCITATION

## ABSTRACT

Pedestrian-induced vibrations are a criterion for serviceability. This loading is significant for light-weight footbridge structures, but was established as a basic loading for the ceilings of various ordinary buildings. Wide variations of this action exist. To verify the different conclusions of various authors, vertical pressure measurements invoked during walking were performed. In the article the approaches of different design codes are also shown.

#### I. INTRODUCTION

Among different types of human-induced loads on footbridges, walking force caused by a single pedestrian has been 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 by the time or frequency domains) have been developed from an assumption of the 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. As considered in the published literature, in such a situation, walking at

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## **KEY WORDS**

- Serviceability,
- pedestrian action,
- numerical analysis.

a near resonant frequency is expected to generate the highest level of response. However, the walking force is not perfectly periodic, and it could be attenuated due to interaction between the pedestrian and the structure. 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's consistency is a very frequent load type on footbridges in urban areas

The dynamic load impact of a crowd has not been researched very much in the past, especially in relation to pedestrian bridges. Wheeler and Grundmann, et al. [13] are among the handful of researchers who have 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 the synchronization of walking steps between the people in the group. However, there is no group force model which has been generally accepted.

#### **II. DYNAMIC LOADS INDUCED BY PEDESTRIANS**

Pedestrian loading, whether by walking or running, has been studied rather thoroughly and is defined as a point force exerted on the support, as a function of time and the pedestrian's position. Considering that *x* is a pedestrian position in relation to a footbridge's centerline, the load of a pedestrian moving at a constant speed *v* can therefore be represented as the product of a time component F(t) by a space component  $\delta(x - vt)$ ,  $\delta$  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 the 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.

Measurements of continuous walking were also taken. The time histories measured were close to periodic with an average period equal to the frequency of an average step. General shapes for continuous forces in both the vertical and horizontal directions were constructed by assuming a perfect periodicity of the force, see Figure 2: Periodic walking time histories in vertical directions [14]. As mentioned in the previous section, the vertical forcing frequency is generally in the region of 1.4 - 2.4 Hz. 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. 2 General shapes for continuous vertical forces

To verify the various authors' conclusions, vertical pressure measurements invoked during walking were undertaken. Three sensors with a diameter base of 0.20 m were placed on a rigid platform. The distance between the gauge axes in the direction of movement was equal to 0.9 m. The configuration is gauging basis can be seen in Figure 3. In Figure 4, the effects from each gauge (normalized to the static load) are in different colors. In Figure 5 a blue resulting curve is added.

The experiment also examined the force transmission of the step from the heel to the toe (the first gauge for the heel, the second for the toe and the third for the second leg's heel), which can be seen in Figure 6. The results of the measurements for this configuration can be seen in Figure 7. This configuration confirmed the measurement results for the configuration with one sensor for each step. The measurements were also effected for athletic and home footwear; in addition, various mats were placed on surface sensors (e.g. 15 mm of polystyrene). In terms of these variants, a measurable effect on the resulting force record, was not acsertained whether using footwear or an adjustment surface.

This force record was represented as a Fourier series. The step frequency for this record was approximately 1.55 Hz, i.e. a speed of 1.4 m.s<sup>-1</sup>. The dynamic coefficient for the harmonic members ( $\alpha_1 = 0.32$ ,  $\alpha_2 = 0.09$ ,  $\alpha_3 = 0.12$ ,  $\alpha_4 = 0.02$ ) was derived from the graph plotted in Figure 8. The record was normalized to the static weight. The experimentally obtained results agree with the results in Table I.

#### A. Periodic load models

The periodic load models are based on the assumption that all pedestrians produce exactly the same force and that this force is periodic. It is also assumed that the force produced by a single pedestrian is constant over time.

Dynamic loading caused by a moving pedestrian may be considered





Fig. 3 Gauge configuration – variant 1



Fig. 5 Force record from gauge configuration – variant 1

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]:

$$F(t) = G + \sum_{k} \alpha_{n} G \cdot \sin(2\pi f t + \varphi_{n})$$
<sup>(2)</sup>

where G is the pedestrian's weight,  $\alpha_n$  is the load factor of the *n*-th harmonic, f is the frequency of the force,  $\varphi_n$  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.

Several measurements were taken in order to quantify the load factor  $a_{n,}$  which is essential for this load model. The results of such measurements are shown in Table I.

In 1977, Blanchard, et al., [4] proposed a vertical dynamic load



Fig. 4 Force record from gauge configuration – variant 1



Fig. 6 Gauge configuration – variant 2

factor of 0.257. Ten years later, Bachmann and Ammann [2] 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.

The principles of work [15] 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 [8].

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

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**Fig. 7** *Force record from gauge configuration – variant 2* 



Fig. 8 Force-frequency record

Authors [8]	δ	Type of move - force direction	Frequency
Blanchard [4]	$\delta_1 = 0.257$	walk – vertical	4 - 5
Bachmann [2]	$\delta_1 = 0.4 - 0.5, \ \delta_2 = \delta_3 = 0.1$	walk - vertical	2.0 - 2.4
Dallard [5]	$\delta_1 = 0.37,  \delta_2 = 0.1,  \delta_3 = 0.12,  \delta_4 = 0.04,  \delta_5 = 0.08$	walk - vertical	2.0
	$\delta_1 = 0.039, \ \delta_2 = 0.01, \ \delta_3 = 0.043, \ \delta_4 = 0.012, \ \delta_5 = 0.015$	walk - transverse	1.0
	$\delta_{1/2} = 0.037, \ \delta_1 = 0.204, \ \delta_{3/2} = 0.026, \ \delta_2 = 0.083, \ \delta_{5/2} = 0.024$	walk – longitude	2.0
Rainer [11]	$\delta_1, \delta_2, \delta_3, \delta_4$	frequency dependent	
Bachmann [2]	$\delta_1 = 0.4 - 0.5, \ \delta_2 = \delta_3 = 0.1$	walk – vertical	2.0 - 2.4
	$\delta_1 = \delta_3 = 0.1$	walk – transverse	1.0 Hz
	$\delta_{1/2} = 0.1, \ \delta_1 = 0.2, \ \delta_2 = 0.1$	walk – longitude	2.0 Hz
	$\delta_1 = 1.6,  \delta_2 = 0.7,  \delta_3 = 0.2$	run – vertical	2.0-3.0 Hz
Kerr [10]	$\delta_1,  \delta_2 = 0.07,  \delta_3 = 0.06$	walk – vertical	
Young [16]	$\begin{split} \delta_1 &= 0.37(\text{f-}0.95) \leq & 0.5\\ \delta_2 &= 0.054 + 0.0044\text{f}\\ \delta_3 &= 0.026 + 0.0050\text{f}\\ \delta_4 &= 0.010 + 0.0051\text{f} \end{split}$	walk – vertical	average $\delta$
Setra [12]	$\delta_1 = 0.4, \ \delta_2 = \ \delta_3 = 0.1$	walk - vertical	
	$\delta_{1/2} = \delta_{3/2} = 0.05, \ \delta_1 = \delta_2 = 0.01$	walk – transverse	
	$\delta_{1/2} = 0.04, \ \delta_1 = 0.2, \ \delta_{3/2} = 0.03, \ \delta_2 = 0.01$	walk – longitude	
Bachmann [3]	$\delta_1 = 1.8/1.7, \ \delta_2 = 1.3/1.1, \ \delta_3 = 0.7/.5$	jump – vertical	2.0 - 3.0
	$\delta_1 = 1.9/1.8, \ \delta_2 = 1.6/1.3, \ \delta_3 = 1.1/.8$	high jump – vertical	2.0 - 3.0
	$\delta_1 = 0.17/0.38, \ \delta_2 = 0.1/0.12, \ \delta_3 = 0.04/0.02$	bouncing – vertical	1.6 - 2.4
	$\delta_1 = 0.5$	bouncing - transverse	0.6
Yao [15]	$\delta_1 = 0.7,  \delta_2 = 0.25$	bouncing – vertical	2.0

 Tab. 1 Input harmonic member

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#### **III. DESIGN CODE APPROACH**

#### A. British standard

The BD 29/04 states that all footbridges shall satisfy the vibration serviceability requirements set out in BD 37/01: Appendix B5.5 [6]. It states that if the fundamental natural frequency of a vibration exceeds 5 Hz for an unloaded bridge in the vertical direction and 1.5 Hz for a loaded bridge in the horizontal direction, the vibration serviceability requirement is deemed to be satisfied.

On the other hand, if the fundamental frequency of the vertical vibration is less than, or equal to, 5 Hz, the maximum vertical acceleration of any part of the bridge shall be limited to

$$a_{\rm lim} = 0.5\sqrt{f} \tag{3}$$

The maximum vertical acceleration can be calculated either using a simplified method or a general method. The simplified method for deriving the maximum vertical acceleration given in BD 37/01is only valid for a single span, or a two-or-three-span continuous, symmetrical, simply supported superstructure with a constant cross section. For more complex superstructures, the maximum vertical acceleration should be calculated assuming that the dynamic loading applied by a pedestrian can be represented by a pulsating point load *F*, which moves across the main span of a bridge at a constant speed *v*, as follows:

$$F = 180 \sin (2\pi ft)$$
(4)  
$$v_t = 0.9 \cdot f$$

where f is the fundamental natural frequency of the bridge and t is the time. If the fundamental frequency of a horizontal vibration is less than 1.5 Hz, special consideration should be given to the possibility of the excitation of lateral movements of an unacceptable magnitude by pedestrians. Bridges having a low mass and damping, which are expected to be used by crowds of people, are particularly susceptible to such vibrations. The method for deriving the maximum horizontal acceleration is, however, not given [3].

#### B. Eurocode

In EN1990: Basis of Structural Design, it is stated that the pedestrian comfort criteria for serviceability should be defined in terms of the maximum acceptable acceleration of any part of a deck. They recommended maximum values for any part of a deck are also given, see Table II.

The standard Eurocode 1: Part 2, defines the models of traffic loads for the design of road bridges, footbridges and railway bridges. Chapter 5.7 deals with the dynamic models of pedestrian loads. It states that depending on the dynamic characteristics of a structure,

#### Tab. 2 Maximum acceptable acceleration, EN1990.

	Maximum acceleration
Vertical vibrations	0.7 m.s <sup>-2</sup>
Horizontal vib., normal use	0.2 m.s <sup>-2</sup>
Horizontal vibration, crowd	0.4 m.s <sup>-2</sup>

the relevant natural frequencies of the main structure of a bridge deck should be assessed from an appropriate structural model. Further, it states that forces exerted by pedestrians with a frequency identical to one of the natural frequencies of a bridge can result in resonance and need to be taken into account for verifications of the limit state in relation to the vibrations. Finally, Eurocode 1 states that an appropriate dynamic model of a pedestrian load as well as the comfort criteria should be defined. The methods for modeling pedestrian loads are, however, left to the designer.

Eurocode 5, Part 2, [7] contains information relevant to the design of timber bridges. It requires the calculation of the acceleration response of a bridge caused by small groups and streams of pedestrians in both vertical and lateral directions. The acceptable acceleration is the same as in EN1990, i.e., 0.7 and 0.2 m.s<sup>-2</sup> in the vertical and the horizontal directions, respectively. A verification of these comfort criteria should be performed for bridges with natural frequencies lower than 5 Hz for the vertical modes and below 2.5 Hz for the horizontal modes. A simplified method for calculating the vibrations caused by pedestrians on simply supported beams is given in Eurocode 5: Annex B. The load models and analysis methods for more complex structures are, on the other hand, left to the designer. In Eurocode 5, it is also stated that the data used in the calculations, and therefore, the results, are subject to very high degrees of uncertainty. Therefore, if the comfort criteria are not satisfied with a significant margin, it may be necessary to make provision in the design for the possible installation of dampers in the structure after its completion.

#### C. ISO 10137

The ISO 10137 guidelines [9] were developed by the International Organization for Standardization with the objective of presenting the principles for predicting vibrations at the design stage and also to assess the acceptability of vibrations in structures.

ISO 10137 defines the vibration source, path and receiver as three key issues which require consideration when dealing with the vibration serviceability of structures.

The vibration source (pedestrians) produces dynamic forces or actions. The medium of the structure between the source and receiver (the bridge) constitutes the transmission path. The receiver of the vibrations is then again the pedestrians on the bridge. According to ISO 10137, an analysis of the response requires



a calculation model that incorporates the characteristics of the source and the transmission path and which is then solved for the vibration response of the receiver.

ISO 10137 states that the designer should decide on the serviceability criterion and its variability. Further, ISO 10137 states that pedestrian bridges should be designed so that vibration amplitudes from applicable vibration sources do not alarm potential users. In Annex C, examples of vibration criteria for pedestrian bridges are given. It suggests using the base curves for any vibrations in both the vertical and horizontal directions given in ISO 2631-2, multiplied by a factor of 60, except where one or more persons are standing still on the bridge, in which case a factor of 30 should be applicable. This is due to the fact that a standing person is more sensitive to vibrations than a walking one.

However, according to Zivanovic [8], these recommendations are not based on published research pertinent to footbridge vibrations. According to ISO 10137, the dynamic actions of one or more persons can be presented as force-time histories. This action varies over time and positions as the persons traverse the supporting structure.

The design situation should be selected depending on the pedestrian traffic to be admitted on the footbridge during its lifetime. It is recommended the following scenarios be considered:

- One person walking across the bridge
- An average pedestrian flow (group size of 8 to 15 people)
- Streams of pedestrians (significantly more than 15 persons)
- Occasional festive choreographic events (when relevant)

According to ISO 10137: Annex A, the dynamic force F(t) produced by a person walking over a bridge can be expressed in the frequency domain as a Fourier series [8].

#### **IV. CONCLUSION**

Pedestrian - induced vibrations are a criterion for serviceability. It has therefore been assumed that structures respond linearly to pedestrian loads applied and that the dynamic response can be found by solving an equation of motion.

To verify the various authors' conclusions, the vertical pressure measurements invoked during walking were performed.

The British standard BS 5400 [13] requires a check of vibration serviceability in both vertical and horizontal directions. However, it only proposes a load model and design criteria for vertical vibrations. The load modeling and the evaluation of the design criteria for horizontal vibrations are left to the designer.

The standard ISO 10137 proposes load models for calculating the vertical and horizontal vibrations caused by one pedestrian. It also proposes design criteria for vertical and horizontal vibrations.

The Eurocode only proposes load models for both vertical and horizontal loads for simplified structures. For more complex structures, the modeling of pedestrian loads is left to the designer. The Eurocode proposes frequency-independent maximum acceleration limits both for vertical and horizontal vibrations. The load models proposed by the above-mentioned standards are all based on the assumption that pedestrian loads can be approximated as periodic loads. They also seem to be incapable of predicting structure sensitivity to excessive horizontal vibrations caused by a crowd of pedestrians.

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