Vibration comfort criteria assessment for pedestrians and cyclist footbridge with a span of 50 m

Introduction

The footbridges are the structures, whose primary task is to carry pedestrians over a physical impediment [13]. Currently, in addition to the safe conduct of traffic on the other side of the obstacle pedestrian bridges are for their users a kind of opportunity to enjoy the advantages of the environment with which they are associated.

Pedestrian bridges should be designed according to recommendations of the standards which require an analysis of the superstructure in the two limit states: ultimate limit state (ULS) and serviceability limit state (SLS).

The requirements of the ultimate limit state include: exhaustion of the bearing capacity for critical cross sections of the structure; loss of stability of elements or the whole structure; material fatigue in elements or connections. The requirements of the serviceability limit state include: checking of the span deflection and vibration of the structure [3]. In addition, the objects in public space such as footbridges, should meet the requirements of Regulations of the Minister of Transport and Maritime Economy [14, 15].

Dynamic analysis of existing or planned pedestrian bridge is a complicated process, which primary objective is to obtain the desired results. The course can be divided into following phases [4]: physical modeling (physical model), computational modeling (computational model – discrete or continuous), mathematical modeling (mathematical model), analysis of the mathematical model, model verification (verifying that the results of calculations are correct).

The dynamics of footbridges – basic issues

During the design of the footbridge in addition to the static analysis a dynamic analysis is also required. Primary objective of the dynamic analysis is to determine the effect of dynamic loads on the structure dynamic response and its influence on users. Making dynamic analysis, it should be verified that the proposed design provides a sufficiently high comfort of use. Dynamic calculations of civil engineering structures are carried out usually at discrete model of the real system (model with lumped masses). The equation of motion hasthe form [5]:

\[ M\ddot{q}(t) + C\dot{q}(t) + Kq(t) = P(t) \]  

where:

- \( M, C, K \) – successively: mass matrix, damping matrix and stiffness matrix,
- \( q(t) \) – displacement vector,
- \( P(t) \) – dynamic load vector (external force).

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An important stage in the dynamic analysis of the structure is modal analysis [6] that is, calculation of the mode shapes and natural vibration frequency of the structure. In modal analysis the system of equations for the free non-damped oscillatory motion should be solved [5]:

$$Mq(t) + Kq(t) = 0$$  \hspace{1cm} (2)

Next, based on the results of preliminary analysis, it is necessary to analyze the possibility of occurrence of the resonance vibrations. In case of pedestrian bridges the critical natural frequencies are within the ranges: 1.3 Hz \( \leq f_i \leq 2.3 \) Hz (in case of vertical vibration); 0.5 Hz \( \leq f_i \leq 1.2 \) Hz (in case of horizontal vibration).

**The effects of vibration on the human body**

The footbridges significantly differ from the conventional bridges in how they influence the users. The footbridges users are located directly on the object deck, staying there longer than during traveling by car across the bridge and directly feels its behavior. Users are exposed to a greater feeling of structural behavior. At the design stage the footbridges require more attention to ensure the proper functional features and comfortable use.

To determine the effect of vibration to the human body (frequency range 1 to 80 Hz) should take into account the main factors that affect the quality of perception oscillation. Effects oscillation at frequencies less than 1 Hz is a separate issue vibro-ecology. Exposure of humans to vibration in this area may be the cause of seasickness symptoms appear gradually (paleness, dizziness, nausea, vomiting, sweating, drowsiness, complete loss of ability to work).

The main factors determining the human sensitivity to vibration are [6]: position of the body, direction of propagation of oscillation (relative to spine), manner of human activity on the object, age, sex, incidence of oscillation, time of day, nature of the oscillation, predictability of the vibrations, “domestication” of oscillation.

The human exposure to the impact of vibrations from each frequency ranges can cause different reactions [6]:

- 0.1–0.8 Hz: seasickness;
- 0.8–10.0 Hz: harmful effects on the eyes and the deterioration of the quality of work;
- 0.9–3.0 Hz, 5.0–8.0 Hz, 9.0–10.0 Hz: fundamental resonance of the human body;
- 1.0–1.5 Hz: disordered breathing;
- 1.5–4.0 Hz: lack of coordination of the limbs;
- 5.0–10.0 Hz: adverse effects on the cardiovascular system.

Commonly, the following factors determining the impact oscillation on humans: oscillation spectrum, level of amplitude or rms value of displacement, velocity or acceleration of vibration, the direction of oscillation, repeatability of the vibrations, time impact oscillation on the human.

<table>
<thead>
<tr>
<th>Description</th>
<th>The range of frequency 1-10Hz</th>
<th>The range of frequency 10-100Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The maximum vibration acceleration [m/s²]</td>
<td>The maximum vibration velocity [mm/s]</td>
</tr>
<tr>
<td>Slightly felt</td>
<td>0.034</td>
<td>0.500</td>
</tr>
<tr>
<td>Clearly felt</td>
<td>0.100</td>
<td>1.300</td>
</tr>
<tr>
<td>Unpleasant</td>
<td>0.550</td>
<td>6.800</td>
</tr>
<tr>
<td>Intolerable</td>
<td>1.800</td>
<td>13.800</td>
</tr>
</tbody>
</table>

*Source: [6]*
To properly determine the impact oscillation on people an appropriate parameter should be chosen (representative of a specific frequency range). In the frequency range 1–10 Hz perception oscillation is proportional to the acceleration and in the range of 10–100 Hz to the vibration speed. However, it should be noted that this breakdown may change depending on the source and nature of the oscillations. In Table 1 are shown the human perception threshold.

An important document used to determine the effect of vibration on the human is the international standard ISO 2631/2 (1989). Vibration frequency range in covered by the ISO 2631/2 (1989) is: 1–80 Hz. It is used for daily vibration and incidental vibration, taking into account the horizontal and vertical direction. The document defines three levels of human discomfort: limit reduced comfort (discomfort during eating, reading or writing); limit reduced ability to work due to tiredness; exposure limit (the maximum tolerable level vibration due to the safety of life and health).

To assess the impact of vibration on people staying in the building and receiving vibrations in a passive way may be used the recommendations of the Polish standard PN-88/B-02171 (1988). The document defines the limit values of the vibration in order to preserve comfort in the 1–80 Hz the frequency band. Criteria perceptibility of vibration by workers are also in the recommendations VDI 2057 (1987) [6].

The paper [1] was given an acceptable vibration amplitudes (speed and acceleration) according to the environment of origin (Table 2). They have been collected and described on the basis experience of authors and present in the literature comfort criteria.

<table>
<thead>
<tr>
<th>The environment of receiving oscillation</th>
<th>The acceptable level of oscillation</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structures for pedestrians</td>
<td>$a \leq 5 \pm 10%$ g</td>
<td>A lower level of acceleration does not cause discomfort.</td>
</tr>
<tr>
<td>Office buildings</td>
<td>$a \leq 2%$ g</td>
<td>The Regulations (DIN 4150 and BS 6472) provide different values</td>
</tr>
<tr>
<td>Sports halls</td>
<td>$a \leq 5 \pm 10%$ g</td>
<td>Higher values are admissible in the case: sound effects are small; apply to apply to participants of the events on vibrating floors or around.</td>
</tr>
<tr>
<td>Concert halls, discotheques</td>
<td>$a \leq 5 \pm 10%$ g</td>
<td>As described above.</td>
</tr>
<tr>
<td>Floors in manufacturing plants</td>
<td>$v \leq 10$ mm/s</td>
<td>The factory precision work requires more stringent criteria.</td>
</tr>
</tbody>
</table>

Source: [1]

The vibration comfort criteria for bridges and footbridges are greater than the requirements posed mode of transport and physical workplaces (industrial). However, they are less than the criteria posed living homes and intellectual workplaces. For bridges and footbridges perception of vibration depends on the way activity of the user object. Very thorough review of the criteria of comfort for bridges and footbridges include works: [6] and [9]. In this paper there are direct connections to this.

**The vibration comfort criteria assessment for the pedestrians and cyclists footbridge a span of 50m**

The analyzed object is footbridge KP-214A (above the highway A1 in Poland). The construction was designed in accordance with the Regulations of the Minister of Transport and Maritime Economy [14][15]. It was assumed load a crowd of pedestrians $q = 4.0 [\text{kN/m}^2]$ (PN-85/S-10030). Supporting structures is a single-span bridge. Bridge is connected to the two steel arches by hangers (M56). Superstructure was designed with pre-stressed concrete B45. The footbridge supports have been realized as a longwall, founded on piles CFA. The supports are made of concrete B35 [8]. The basic technical parameters...
of the footbridge are [8]: the theoretical span of the structure is 50.00 m; the span of the curves is 46.716 m; the length of the footbridge is 51.60 m; the usable width of footbridge is 3.00 m; the overall width of the footbridge is 4.50 m; the overall height is 0.60 m; were applied elastomeric Bearings. Dimensions of the footbridge and the precise parameters of the supporting structure were adopted under the [8].

The dynamic analysis was performed numerically. The numerical calculations were performed using the plate-rod, three dimensional computational model. The model was prepared on the basis of footbridge construction project [8]. In the first part was performed calculation of the mode shapes (Fig. 2) and natural vibration frequency of the structure (Tab. 3).

In the second part of the dynamic analysis was calculated dynamic response of footbridge loaded pedestrian walkway. Initial calculations of the dynamic revealed vibration modes and frequencies belonging to the frequency range of the dynamic excitations coming from the pedestrians (1.4–3.4 Hz). The frequencies, together with the corresponding modes of vibration are illustrated in Figure 2.

Dynamic load caused by man, is periodic. The function describing this kind of impact can be represented as a Fourier series [3, 10]:

\[
F_i(t) = G + \sum_{i=1}^{n} G\alpha_i \sin(2\pi f_i t - \varphi_i)
\]

where:

\(G\) – the person’s weight (N),

\(\alpha_i\) – the Fourier’s coefficient of the i th harmonic, i.e. dynamic load factor (DLF),

\(f_i\) – the frequency of the i th harmonic,

\(\varphi_i\) – the phase angle of the i th harmonic.
\( f_k \) – the activity rate (Hz),

\( \varphi_i \) – the phase shift of the \( i \)th harmonic,

\( i \) – the order number of the harmonic,

\( n \) – the total number of contributing harmonics,

\( t \) – the time step.

In equation (6) vertical force is decomposed into part of the corresponding to the static weight of the pedestrian \((G)\) and a dynamic part which is a sum of harmonics pedestrian action of a frequency equal to an integer multiple of the frequency walk. In the calculations it is assumed that pedestrian, who is represented by the force \( F_z (t) \) moves on footbridge at a speed of:

\[
v_p = l_k f_k \tag{4}\]

where:

\( l_k \) – the pedestrian stride length.

The numerical analysis were adopted the following motion parameters: \( L_t = 50.00 \text{ m} \) (the length of the footbridge), \( l_{k1} = 50.00 \text{ cm} \), \( l_{k2} = 175.00 \text{ cm} \) (the pedestrian stride length: \( l_{k1} \) for \( f_1 \) and \( l_{k2} \) for \( f_2 \)), \( G = 700 \text{ N} \) (the weight of pedestrian), \( t_{k1} = 0.0137 \text{ s} \), \( t_{k2} = 0.0063 \text{ s} \) (the time step), \( \alpha_i \) and \( \varphi_i \) were assumed with Table 1 from [10]. Calculation of the dynamic response of the object (for extortion in the form of pedestrian traffic) was made using the Autodesk Algor Simulation. The Rayleigh model of damping was introduced in calculation. Rayleigh damping coefficients were determined based on [8]: \( \alpha = 0.0589; \beta = 0.00032 \). The values of the Rayleigh damping coefficients and the level of the acceleration of the footbridge caused by a single pedestrian crossing is shown in Table 4.

Table 3. The Rayleigh damping coefficients and the maximum vibration acceleration of footbridge

<table>
<thead>
<tr>
<th>The frequency of the impact of pedestrian [Hz]</th>
<th>The weight [N]</th>
<th>The damping</th>
<th>The acceleration, [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.46</td>
<td>700</td>
<td>0.0589</td>
<td>0.00032</td>
</tr>
<tr>
<td>3.19</td>
<td>700</td>
<td>0.0589</td>
<td>0.00032</td>
</tr>
</tbody>
</table>

Source: The Author’s material

In order to determine the dynamic influence of more than one pedestrian on the dynamic behavior of the footbridge the results obtained for a single user \( a_{1max} \) should be multiplied by an increasing factor of \( M \). The value of \( M \) factor depends on the type of vibration excitation and size of the pedestrians group \( N_g \): synchronized group of the footbridge users walking, running or jumping: \( M = N_g \); random impact of free stream of pedestrians: \( M = \sqrt{N_g} \). The acceleration for the different cases are summarized in Table 5.
### Table 4. The extrapolated value of vibration acceleration with a larger number of pedestrians

<table>
<thead>
<tr>
<th>The size of the pedestrians group</th>
<th>The acceleration [m/s²]</th>
<th>Synchronized group of the footbridge users</th>
<th>Random impact of free stream of pedestrians</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.16</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.24</td>
<td>0.75</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.64</td>
<td>2.00</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.72</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Source: The Author’s material.

### The vibration comfort criteria assessment

Taking into account the results of numerical analysis were checked the criteria vibration of comfort for the footbridge (during a single pedestrian crossing and a larger group of pedestrians at crossings synchronized and in the absence of synchronization). The results are summarized in the Table 6, and compared with the selected of comfort criteria (according to the literature).

In situations where on the footbridge will be located a larger group of users comfort may be disturbed in the case of moving at least a three synchronized group of pedestrians or a group of pedestrians not synchronized with the number of at least 8 persons (Table 5).

### Table 5. Analysis of comfort of use of the footbridge (single pedestrian)

<table>
<thead>
<tr>
<th>The standard</th>
<th>The acceptable acceleration [m/s²]</th>
<th>The maximum acceleration [m/s²]</th>
<th>f₁ =1.46 Hz</th>
<th>f₂ =3.19 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 5400 [11]</td>
<td>0.63</td>
<td>complied</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td>The paper [1]</td>
<td>0.70 – 1.0</td>
<td>complied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The paper [9]</td>
<td>0.65</td>
<td>complied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SETRA [16]</td>
<td>0.50</td>
<td>complied</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PN-EN 1990/A1 [12]</td>
<td>0.70</td>
<td>complied</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: The Author’s material

### Conclusions

The analysis results were obtained in a numerical way. This approach led to the conclusions:
- the numerical analyzes have shown that the footbridge will be used with the requirements for vibration comfort (for a single pedestrian);
- in situations when on the footbridge will be located a larger group of users comfort may be disturbed in the case of moving at least a three synchronized group of pedestrians or a group of pedestrians not synchronized with the number of at least 8 persons.

### Abstract

The paper is dedicated to issues related with the dynamics of footbridges. It includes basic information about dynamic characteristics of pedestrian bridges and vibration comfort criteria for this structures. An essential part of the work is dynamic analysis pedestrians and cyclists footbridge with a span of 50m.
The analysis was completed on basis of a numerical model in Autodesk Algor Simulation 2011 (Student Version) package.

**Keywords:** footbridge, dynamics, footbridge vibration, communication load

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**ANALIZA KRYTERIÓW KOMFORTU WIBRACYJNEGO KŁADKI DLA PIESZYCH I ROZPIĘTOŚCI 50 M**

**Streszczenie**

Praca poświęcona jest zagadnieniom związanym z komfortem wibracyjnym kładek dla pieszych. W pierwszej części zostały omówione zagadnienia związane z definicją i wymaganiami stawianymi kładkami dla pieszych, ich dynamiką oraz percepcją wibracji przez ludzi. W referacie został dokonany również przegląd dokumentów określających kryteria komfortu wibracyjnego. Druga część prezentowanej pracy to analiza komfortu wibracyjnego łukowej kładki dla pieszych o rozpiętości 50 m. Model obiektu został wykonany w programie Algor Simulation 2011 (wersja edukacyjna).

**Słowa kluczowe:** komfort wibracyjny, kładka dla pieszych, analiza dynamiczna

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**References**


[14] Regulation of the Minister of Transport and Maritime Economy of the technical conditions which should be fulfilled by public roads and their location 2.03.1999, (Dz.U. nr 43 poz. 430), 1999.

[15] Regulation of the Minister of Transport and Maritime Economy of the technical conditions which should be fulfilled by road engineering objects and their location 30.05.2000, (Dz.U. nr 63 poz. 735), 2000.
