Technical Sciences, 2018, 21(3), 233–246

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

Quarterly peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: www.uwm.edu.pl/techsci/

ASSESSMENT OF COMFORT OF USE OF FOOTBRIDGES

Marek Pańtak, Kinga Marecik

Chair of Bridges and Tunnels Construction
Institute of Building Materials and Structures
Faculty of Civil Engineering
Cracow University of Technology

Received 5 May 2017, accepted 30 September 2018, available online 8 October 2018.

Key words: comfort, footbridges, vibrations, dynamics, serviceability limit state.

Abstract

To assess the comfort of use of the structures designed for human use during its vibrations it is necessary to know the requirement of the comfort criteria for the specific type of the structure. In the paper the issue of evaluation of the footbridges vibrations acceptability along with proposal of comfort criteria for the footbridges elaborated on the basis of survey researches were presented. The proposal of the vibration comfort criteria taking into account frequency of vibrations occurrence (frequent, rare and exceptional events) were characterized and compared with propositions of other authors, standards and recommendations.

Introduction

Constant progress in material engineering affects the design principles of building structures. The structural materials getting better resistance parameters enable to design a new structures with greater spans and smaller dimensions of cross sections of the structural elements. The contemporary footbridges become lighter and longer than older one. They have smaller vertical and horizontal stiffness, smaller mass and lower values of damping parameters. Because of that they can be susceptible to different dynamic actions. An important type

Correspondence: Marek Pańtak, Katedra Budowy Mostów i Tuneli, Wydział Inżynierii Lądowej, Politechnika Krakowska im. Tadeusza Kościuszki, ul. Warszawska 24, 31-155 Kraków, e-mail: mpantak@pk.edu.pl

of dynamic loads of footbridges are loads generated during human movement. These dynamic loads may have various sources of origin e.g. forces generated during walking, running, jumps, squats or other rhythmic and choreographic activities. Fundamental vibration frequencies of the light-weight footbridges are often in the frequency range of human action 1.4–3.4 Hz (BACHMANN, AMMANN 1987, PAŃTAK 2007).

Dynamic response of these footbridges, correctly designed for variable actions accepted in accordance with PN-EN 1991-2:2007 (2007) i.e. uniformly distributed crowd loading including the dynamic amplification effects and treated in design as a static load, can exceed established vibrations limits during vibrations caused by dynamic loads generated by moving users of the footbridge (i.e. changing in time ground reaction forces) especially in the case of occurrence of resonant vibrations of the structure. It should be clearly noted that variable action of the crowd including dynamic amplification effects used as a static load cannot be assumed as a substitute of pedestrian dynamic actions (see PN-EN 1991-2:2007 2007, Chapter 5.1 (4) and 5.7). The static load does not allow to determine vibration amplitudes defined as a vibration acceleration and should not be treated as a guarantor of fulfilment of the requirement of vibration comfort criteria.

In the case of high dynamic susceptibility of the footbridge, users can experience unpleasant vibrations of the structure (especially in cases of light-weight steel footbridges with small damping). It should be noted that vibrations are an important limit state in the design of footbridges.

In order to check the requirements of limit state of vibrations the amplitudes of the forced vibrations of the structure should be calculated and compared with permissible vibrations amplitudes specified in the comfort criteria. The comfort criteria should be developed taking into account a number of parameters affecting the human perception of vibrations.

The main parameters determining the human sensitivity to vibrations are: position of the body (sitting, standing, lying), direction of transmission of the vibrations onto the human spine (vertical, horizontal), frequency response of the vibrations, human activity (resting, walking, running), age and sex, time of the day (day, night), duration of the vibrations, frequency of occurrence and nature of the vibrations (continuous, intermittent, impulse) as well as predictability of the vibrations and degree of habituation to the vibrations (BACHMANN, AMMANN 1987, FLAGA 2002).

Fundamental parameters determining the intensity of human perception of vibrations are: vibrations amplitude, frequency response of the vibrations, direction of the vibrations, vibrations impact time (exposure time), repeatability of the vibrations (FLAGA 2002).

The limit values of vibrations are often defined as a value of accepted acceleration of vibrations in function of frequency and duration of the vibrations for three orthogonal directions. In the case of stochastic vibrations the limit value of acceleration of vibrations is assumed as a root-mean-square (*rms*) value of acceleration of vibrations a_{rms} calculated for defined averaging time. For harmonic vibrations the limit value of acceleration of vibrations is assumed as a peak value of acceleration of vibrations $a_{\max}$ (without averaging of the value of acceleration).

Comfort criteria for footbridges – review of recommendations

Different recommendations of comfort criteria for the assessment of comfort of use of the footbridges can be found in several documents: ISO 10137... (2007), PN-EN 1990:2004/A1 (2008), *Footbridges – Assessment of vibrational behaviour...* (2006) and in older ones: *Steel, Concrete and Composite...* (1978), BACHMANN, AMMANN (1987), GRUNDMANN et. al. (1993), PAŃTAK (2007), PAŃTAK et. al. (2012).

The comfort criteria presented in ISO 10137... (2007) were established with two assumptions: minimum adverse comments of the population subjected to vibrations, vibrations do not unduly alarm of the footbridge users. The criteria were defined in the form of two base curves with appropriate multipliers depending on the type of the structure. The base curves were defined for two direction of the vibration: vertical and horizontal.

According to ISO 10137... (2007) the acceptable acceleration of vibrations for footbridges in vertical direction should not exceed levels obtained by multiplying the base curve for the vertical direction by factor of 60, except situations where one or more persons standing still on the walkway, in these cases a multiplier of 30 should be applicable (Fig. 1*a*). In cases of horizontal vibrations level of vibrations should not exceed 60 times the base curve for the horizontal direction (Fig. 1*b*). Limit values of vibrations were defined in terms of root-mean-square (*rms*) value of acceleration. For the calculation of (*rms*) values of the acceleration an averaging time of 1 s is recommended.

Another document containing recommendations for assessing of comfort of use of the footbridges is a design standard (PN-EN 1990:2004/A1 2008). The comfort criteria presented in PN-EN 1990:2004/A1 (2008) are defined in terms of maximum acceptable acceleration $a_{\max}$ (peak acceleration of vibrations). The recommended acceptable maxima of acceleration $a_{\max}$ are: $a_{\max,v} = 0.7$ m/s^2 for vertical vibrations, $a_{\max,h} = 0.2$ m/s^2 for horizontal vibrations due to normal use and $a_{\max,h} = 0.4$ m/s^2 for horizontal vibrations in case of vibration induced during exceptional crowd conditions. It was pointed out that other criteria may be defined as appropriate in the National Annex.

Based on dynamic investigations and analyses of numerous footbridges in *Steel, Concrete and Composite...* (1978) the upper limit of tolerable acceleration for footbridges with natural vertical vibration frequency $f \leq 5.0$ Hz

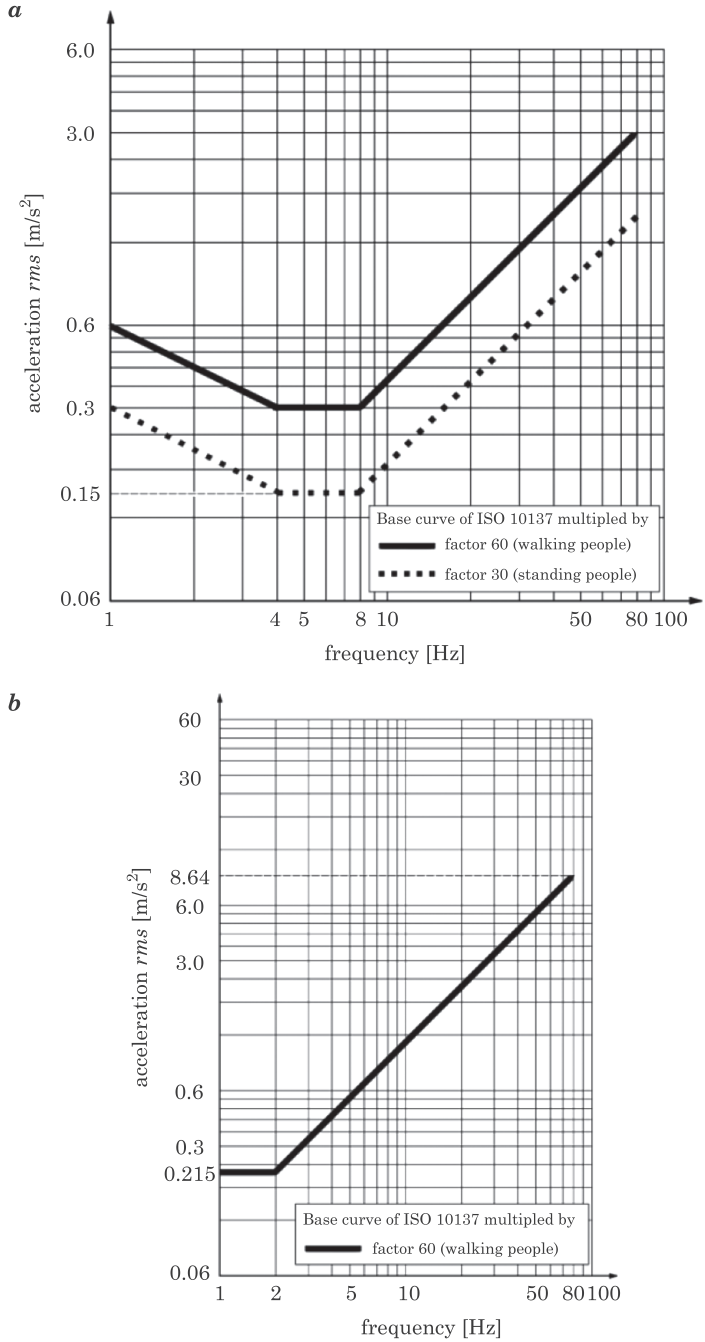


Fig. 1. The comfort criteria for footbridges according to ISO 10137 (2007) for: *a* – vertical vibrations, *b* – horizontal vibrations (side to side and forward to reverse)
Source: own elaboration.

was specified as $a_{max} = 0.5 \cdot f^{0.5}$ m/s^2 (where f – vibration frequency of the structure). For instance, during vertical vibrations of the structure with frequency $f = 1.7–2.3$ Hz the range of tolerable acceleration of vibrations is $a_{max} = 0.65–0.75$ m/s^2. In *Steel, Concrete and Composite...* (1978) there are no any recommendations for acceptable level of acceleration of horizontal vibrations.

Taking into account own experiences (BACHMANN, AMMANN 1987) proposed the permissible levels of peak acceleration of vibrations for pedestrian structures a_{max} in the range of 0.5–1.0 m/s^2 for vertical vibrations and 0.1–0.2 m/s^2 for horizontal vibrations.

In the opinion of GRUNDMANN et al. (1993), considering the result of the study of LEONARD (1966), the maximum value of acceleration of vertical vibrations should not exceed the value defined in *Steel, Concrete and Composite...* (1978) and the maximum value of acceleration of horizontal vibrations should not exceed $^1/_5$ value of tolerable acceleration of vertical vibrations ($a_{max,h} \leq 0.2 a_{max,v} = 0.1 \cdot f^{0.5}$ m/s^2).

Different way of evaluation of comfort criteria was presented in *Footbridges – Assessment of vibrational behaviour...* (2006). In these recommendations three levels of comfort (maximum, mean and minimum) were defined. In the case of vertical vibrations maximum comfort is ensured if $a_{max,v} \leq 0.5$ m/s^2 (vibrations of the structure are practically imperceptible to the users), average comfort is ensured if $a_{max,v} = 0.50–1.00$ m/s^2 (vibrations of the structure are barely perceptible to the users), minimum comfort is ensured if $a_{max,v} = 1.0–2.5$ m/s^2 (allowed for seldom occurring dynamic loads, accelerations undergone by the structure are perceived by the users, but do not become intolerable). For horizontal vibrations: maximum comfort is ensured if $a_{max,h} \leq 0.15$ m/s^2, average comfort is ensured if $a_{max,h} = 0.15–0.3$ m/s^2, minimum comfort is ensured if $a_{max,h} = 0.3–0.8$ m/s^2. Moreover, in the cases of horizontal vibrations when the "lock-in" effect may occur (the effect of synchronization of the pedestrians with the frequency and phase of the horizontal vibrations) in order to avoid the "lock-in" effect the acceleration of the vibrations of the footbridge deck should be limited to $a_{max,h} = 0.1$ m/s^2. The forth range of acceleration of vibrations is also pointed out in the recommendations defining uncomfortable (unacceptable) vibrations. Vibrations with acceleration $a_{max,v} \geq 2.5$ m/s^2 are unacceptable in the case of vertical vibrations and vibrations with acceleration $a_{max,h} \geq 0.8$ m/s^2 are unacceptable in the case of horizontal vibrations

Furthermore, in *Footbridges – Assessment of vibrational behaviour...* (2006) noted that choice of comfort level is normally influenced by the population using the footbridge and by the level of importance of the structure depending on the location of the footbridge. It is possible to be more demanding on behalf of particularly sensitive users (schoolchildren, elderly or disabled people), and more tolerant in case of short footbridges (short transit times, seldom used footbridge, built to link sparsely populated areas). The footbridge owner should define the class of the footbridge as a function of the level of traffic intensity and should determine a comfort requirement level to fulfil. Moreover, according to *Footbridges – Assessment of vibrational behaviour…* (2006) in cases of footbridges for which the risk of excitation of resonant vibration is small (when the natural vibration frequencies of the structure are out of the frequency range of human activity i.e. walking, running etc.), comfort level is automatically considered to be ensured.

Proposal of comfort criteria for footbridges

On the basis of series of in situ experimental investigations performed by Pańtak in 2004–2006 on over 30 footbridges of different structural schemes new proposals of vibration comfort criteria for footbridges were elaborated by Flaga and Pańtak (Pańtak 2007, Flaga, Pańtak 2003, 2008). The elaborated proposals are presented in Figure 2.

Proposed comfort criteria taking into account courses of the comfort criteria curves defined in ISO 2636… (1989) and PN-B-02171 (1988) and can be characterized as follows: the criteria are related to the vibrations induced by man, the criteria define the comfort levels in case of vibrations sensed by walking users, the criteria taking into account short duration of stay of the pedestrians on vibrating footbridge, the criteria are related separately to vibrations in vertical and horizontal direction, the criteria are related to peak acceleration ($a_{\max}$) as a function of vibrations frequency, the criteria taking into account frequency of vibrations occurrence: frequent events (base curve M1), rare events (curve M1.7) and exceptional events e.g. vandal actions (curve M10).

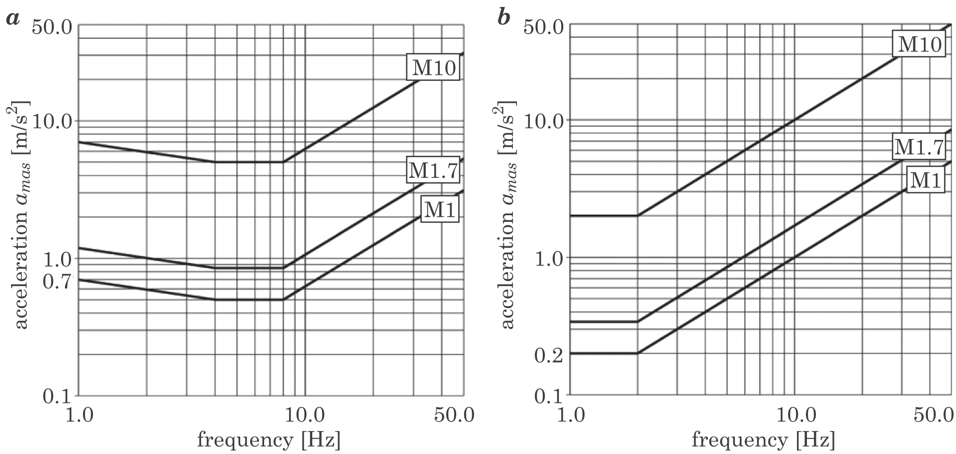


Fig. 2. Proposals of vibration comfort criteria for footbridges:
a – vertical vibrations, *b* – horizontal vibrations
Source: based on Flaga, Pańtak (2008).

The base curve M1 for vertical vibrations in frequency range 1.0–8.0 Hz were verified during in situ tests. During the tests, the members of the research team induced the vibrations of the tested footbridges by the rhythmic squats, running or jumping. Pedestrians passing through the footbridge (casual passers-by and other members of the research team) were asked to express their opinion about the vibrations: whether the vibrations were imperceptible or lightly, clearly, very strongly perceptible during the walk, whether the vibrations prevented them from walking and whether they could adjust to vibrations. The vibrations of the structure were acquired using the set of accelerometers. Moreover the time of reaching the vibration measurement point by survey's respondents was measured using stopwatch.

The curve M1 is the base curve corresponding to the following vibration comfort criterion: among surveyed pedestrians walking through the footbridge at most 10% of pedestrians expressed opinion that vibrations were slightly felt or perceptible and did not disturb walking. This curve is proposed in case of frequent event, i.e. vibrations of daily nature occurring once a day or more frequently and not rarely than once a week.

The curve M1.7 is created by multiplying the accelerations defined by curve M1 by multiplier 1.7. Multiplier 1.7 was established to determine the vibrations level at which at least 10% of pedestrians going over the footbridge expressed opinion, that the vibrations were clearly felt (fully perceptible), making slight difficulty in walking or clearly disturb walking. This curve is proposed in case of rare events, i.e. vibrations occurring more rarely than once a week.

The curve M10 is created by multiplying the accelerations defined by curve M1 by multiplier 10. The curve M10 is a curve related to so called vandal intentional actions on a footbridges in a form of e.g. rhythmical jumping on the spot, rhythmical horizontal body movements of a single person or a group of people, rhythmical squats etc. Multiplier 10 was assumed to protect pedestrians against body injuries (mainly legs) caused by vibrations characterised by high acceleration values. It should be emphasized that for the vibrations levels determined by curve M10, comfort of use of the structure is strongly disturbed (free walking is impossible, standing or running is difficult and strongly disturbed).

In the proposed comfort criteria the acceptable value of acceleration of vertical vibrations in frequency range 1.0–4.0 Hz changes from 0.7 m/s^2 to 0.5 m/s^2 according to the equation $a_{\max,v} = 0.7 \cdot f^{-0.24}$ m/s^2 (where f in [Hz] is the vibration frequency of the footbridge with high probability of excitation by footbridge users during walking, running, etc. It can be a fundamental or higher vibration frequency of the footbridge). In frequency range 4.0–8.0 Hz the permissible acceleration is constant and equals 0.5 m/s^2. In the case of vertical vibration with frequency $f > 8.0$ Hz the comfort criteria were not verified during in situ tests. The acceptable values of acceleration of vertical vibrations were adopted in accordance of the courses of the comfort criteria curves defined in ISO 2636… (1989) and PN-B-02171 (1988). The course of this comfort curve changes according to the equation $a_{max,v} = 0.0625 \cdot f$ m/s^2 (where f is as previous).

In the case of horizontal vibrations the base curve M1 was not verified during in situ tests because of lack of the horizontal mode shapes in tested footbridges. The curve M1 for horizontal vibrations was proposed taking into account comfort criteria curves occurring in ISO 2636… (1989) assuming the value of $a_{max,h} = 0.2$ m/s^2 as the acceptable value of acceleration in frequency range 1.0–2.0 Hz and acceptable acceleration levels $a_{max,h} = 0.1 \cdot f$ for vibrations with frequencies $f > 2.0$ Hz.

It is worth noting that assessment of the comfort of use of the footbridge using proposed comfort criteria curves is not dependent on the density of the crowd. The proposed comfort criteria curves applies both the assessment of vibrations caused by one person and by a dense crowd. Amplitudes of vibrations must not exceed vibration acceleration levels considered acceptable both during the dynamic action of one person and a dense crowd.

Comparisons and discussion

Because of many parameters influencing the human sensitivity to vibrations the vibration comfort criteria must represent the average values of permissible vibrations (FLAGA 2002). It should be remembered that characterised comfort criteria proposed by different authors present averaged values of acceptable acceleration of vibrations. It should be also noted that most of these criteria apply to the situations in which vibrations are received by walking persons. Only proposals of ISO 10137… (2007) present the comfort criteria taking into account the footbridge users standing still on the footbridge deck. In the cases of the footbridges located in a place of great cultural, recreational or touristic importance it may be necessary to reduce the vibrations of the structure to values not disturbing standing still users. Despite the opinion of LEONARD (1966) who claimed that it was both uneconomic and unnecessary to design footbridges where standing people will not feel vibrations. Nowadays, such a need arises especially in the case of footbridges designed as a resting places with viewing points and resting regions with places to sit (e.g. benches). The reduction of vibrations of these structure to acceptable values can be realized (if necessary) by means of tuned vibration dampers.

For proper assessment of the comfort of use of the footbridge it is necessary to understand the vibration influence on footbridge users. In Figure 3 the results of research carried out by PAŃTAK (2007) in relation to the comfort criteria proposed by Flaga and Pańtak are presented. This comparison explains the meaning of defined permissible values of acceleration of vibrations.

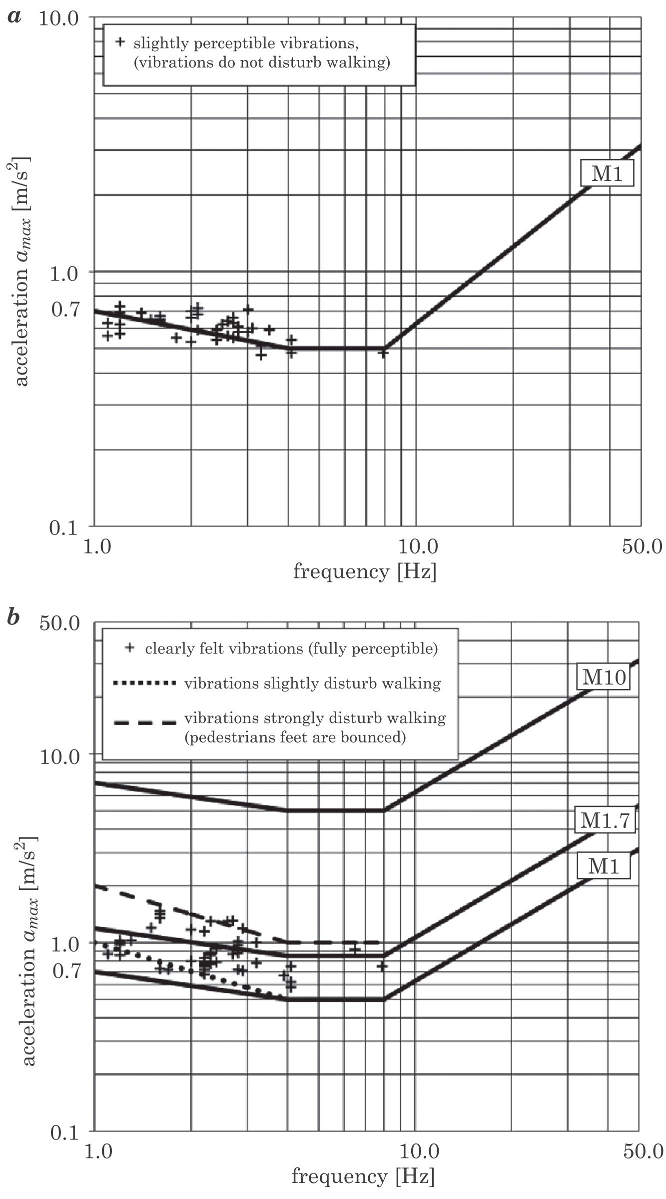


Fig. 3. The comfort criteria proposed by Flaga and Pańtak for vertical vibrations in relation to experimental results: *a* – vibrations slightly perceptible and do not disturbing of walking, *b* – vibrations clearly felt (fully perceptible) and clearly disturbing of walking
Source: based on FLAGA, PAŃTAK (2008), PAŃTAK (2007).

It can be seen that in the case of the vertical vibrations the vibrations slightly perceptible and do not disturbing walking are the vibrations with acceleration $a_{\max,v}$=0.5–0.7 m/s^2 (Fig. 3*a*). Moreover, vibrations with acceleration $a_{\max,v}$=0.7–1.0 m/s^2 are the vibrations clearly felt and slightly disturbing walking. The vibrations with acceleration $a_{\max,v}$ > 1.0 m/s^2 are clearly felt and clearly disturbing walking (pedestrians feet are bounced off the footbridge deck). In the case of $a_{\max,v}$ > 1.5 m/s^2 the vibrations are unpleasant and walking is strongly disturbed.

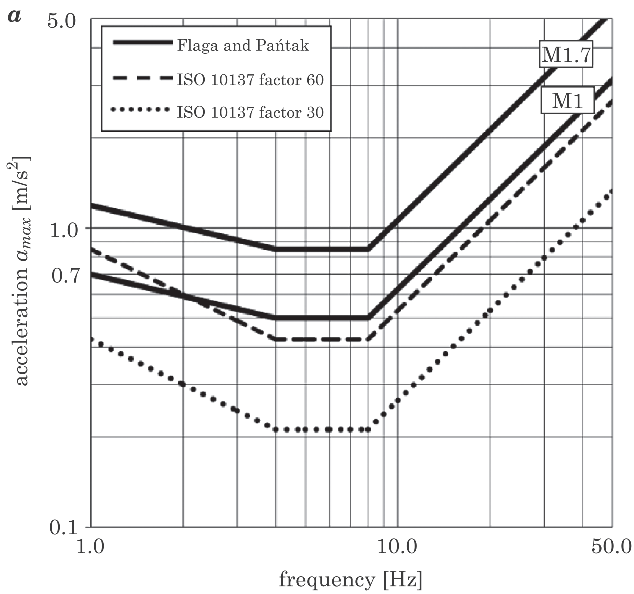
Having regard to the above conclusions it is possible to assess the comfort criteria presented in all standards and recommendations cited in the paper.

Evaluating the recommendations presented in ISO 10137… (2007) it is important to remember that the comfort criteria presented in ISO 10137… (2007) are defined in terms of root-mean-square (*rms*) value of acceleration. To compare the criteria ISO 10137… (2007) with other recommendations the value of acceleration a_{rms} need to be converted to the peak value $a_{\max}$, proper for harmonic vibrations, by multiplying values of a_{rms} by the factor $\sqrt{2}$. In Figure 4 the comparisons of the comfort criteria ISO 10137… (2007) converted to peak acceleration a_{max} with the criteria proposed by FLAGA and PAŃTAK (2008) are presented.

It can be seen that in the case of vertical vibration both base curve M1 and curve (ISO 10137… 2007) with multiplier 60 (converted to $a_{\max}$) define the similar values of permissible peak acceleration of vibrations. In the case of horizontal vibrations the ISO 10137… (2007) curve (converted to $a_{\max}$) is located much higher than base curve M1 proposed by FLAGA and PAŃTAK (2008). Comparison of the requirement of ISO 10137… (2007) for horizontal vibrations with recommendations of other author ($a_{\max,h}$=0.1–0.2 m/s^2) also indicate that requirement of ISO 10137… (2007) is gentler and probably should be verified. Using multiplier from the range 20 to 40 instead of 60 recommended in ISO 10137… (2007) allows to achieve the value of permissible acceleration of the horizontal vibrations $a_{\max,h}$=0.1 – 0.2 m/s^2.

The limit values of the vertical vibrations acceleration assumed in the comfort criteria proposed by FLAGA and PAŃTAK (2008) correspond to the comfort threshold for vibrations sensed by walking users. For standing users permissible values of vibrations accelerations are lower and can be determined using a reduction factor 0.30–0.35 for the M1 curve.

The comfort criteria defined in *Footbridges – Assessment of vibrational behaviour…* (2006) present a comprehensive approach to assessment of the comfort of use of the vibrating footbridges. The three levels of comfort of use of the footbridge defined in recommendations together with additional assessment of importance of the structure depending on its location and traffic intensity allow to assume appropriate comfort criterion by the designer and the owner of the footbridge. The levels of vibrations acceleration defined in *Footbridges – Assessment of vibrational behaviour…* (2006) recommendations for maximum



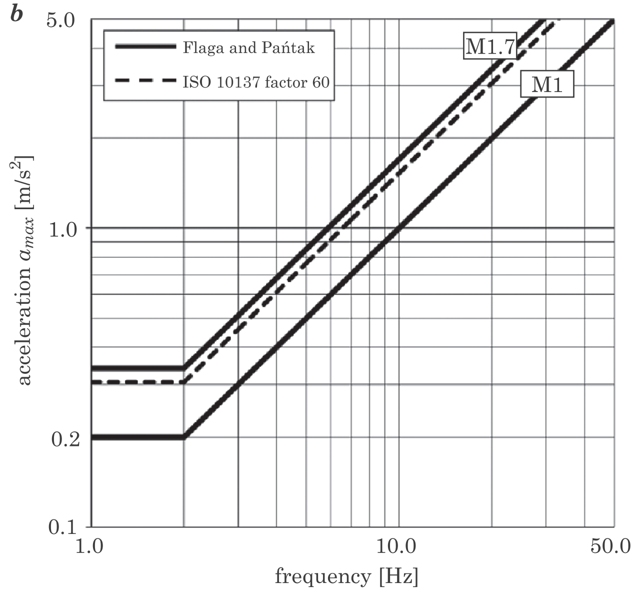


Fig. 4. Comparison of comfort criteria (dotted and dashed lines) converted to peak acceleration of vibrations $a_{\max}$ with criteria proposed by Flaga and Pańtak (solid bold line marked with M1 and M1.7 tags): *a* – vertical vibrations, *b* – horizontal vibrations
Source: based on ISO 10137… (2007), PAŃTAK (2007), FLAGA, PAŃTAK (2008).

and mean comfort are in line with the proposals of other authors. In the case of minimum comfort the upper bound of acceleration of vertical vibrations seems to be too high ($a_{\max,v}=2.5$ m/s^2). Although this large value of acceleration of vibrations according to *Footbridges – Assessment of vibrational behavior…* (2006) is allowed only in the case of seldom occurring vibrations it is important to remember that vibrations with $a_{\max,v} > 1.5$ m/s^2 are unpleasant and walking is strongly disturbed (PAŃTAK 2007).

The comfort criteria recommended by *Steel, Concrete and Composite…* (1978), BACHMANN, AMMANN (1987), GRUNDMANN et. al. (1993) are appropriate recommendations in frequency range of 1.0–8.0 Hz for vertical vibrations and 1.0–2.0 Hz for horizontal vibrations. Nevertheless a more accurate determination of the permissible value of acceleration of vibrations for a given frequency of vibration is possible using comfort criteria defined in ISO 10137… (2007) or by FLAGA and PAŃTAK (2008).

In the light of the above considerations the comfort criteria presented in PN-EN 1990:2004/A1 (2008) can be considered as a simply rules for preliminary assessment of the comfort of use of the vibrating footbridges. It should be noted that in the case of vertical vibrations of the footbridge deck with frequency $f > 1.0$ Hz the vibrations of the structure reaching the value of acceleration of vibrations $a_{\max,v}=0.7$ m/s^2 will be slightly perceptible by the users. The value of permissible acceleration $a_{\max,v}=0.7$ m/s^2 recommended in PN-EN 1990:2004/A1 (2008) is in the range of the medium (mean) comfort of use of the structure defined in *Footbridges – Assessment of vibrational behaviour…* (2006). The requirements for horizontal vibrations defined in PN-EN 1990:2004/A1 (2008) are in good agreement with numerous recommendations of other authors.

More comprehensive methodology of assessment of the comfort of use of the footbridges taking into account frequency of vibrations occurrence (frequent events, rare events, exceptional events) and different levels of comfort of use in a function of location of the footbridge and forecasted traffic intensity seems to be appropriate and should be elaborated in National Annex of the standard PN-EN 1990:2004/A1 (2008). It is important to elaborate and consider in analyses the comfort criteria taking into account the probability of occurrence of resonant vibrations in a function of location of the footbridge (compare recommendations presented in *Footbridges – Assessment of vibrational behaviour…* (2006). Occurrence of some type of vibration excitation on footbridges can be unlikely in different locations as well as occurrence of footbridge vibrations can be acceptable or unacceptable depending on its location. For example: vibration with a maximum acceleration amplitude e.g. 1.5 m/s^2 (i.e. vibrations clearly disturbing walking) excited by e.g. twelve jumping people can be considered as unlikely and generated vibrations can be acknowledged as acceptable even in the case of footbridge located in the busy city centre due to their rare occurrence, while the same vibration with a maximum amplitude 1.5 m/s^2 excited by one jumping person should be considered as a case characterized by a high probability of occurrence and unacceptable in the case of footbridge located in the busy city centre but acceptable in the case of footbridge located in the rural area due to their rare occurrence. The influence of the location of the footbridge on the comfort criteria is an important issue and requires further research and analyses. Nevertheless it should be remembered that assessment of the comfort of use of the footbridges performed on the basis of the results obtained for resonant excitations without knowing the probability of occurrence of the resonance effects during the everyday operation of the structure is an irrational and incorrect procedure.

It should be also noted that all comfort criteria characterised in this paper do not present a proposal of acceptable level of acceleration for running users and cyclists. The runners are less sensitive to vibrations than walking pedestrians (in other words evaluation of comfort of use of the footbridge during vibrations sensed by walking users is more severe restriction) but in some cases evaluation of the comfort of use of the footbridges during vibrations induced and sensed by running users can be important (e.g. occasional sport events, marathons etc.).

The next important and particular type of the footbridges users are the cyclists. The cyclists are the next type of "vibration receiver". They receiving the vibrations in particular way. They sitting on a bicycle saddle and receiving vibrations through the hands, feet and buttocks. Because of that the cyclists become more sensitive to vibrations. It can be important to assess the comfort of use of the structure by cyclists especially in cases of long span footbridges located in popular recreational areas and used by cyclists, pedestrians and runners.

Summary

Comfort of use of the footbridges is a serious problem in case of slender and lightweight structures. The vibrations are important limit state in footbridges design. Dynamic analysis is indispensable step in the design of modern footbridges. Static analyses are insufficient to verify all important requirements of serviceability limit state.

To assess the comfort of use of the footbridges it is important both to know the acceptable value of acceleration of vibrations as well as the frequency of occurrence of the vibrations. It is advisable to specify and take into account the different levels of comfort of use of the footbridges and consider the importance of the structure depending on the place of its location. It seems important to elaborate the methodology of assessment of the comfort of use of the footbridges taking into account the probability of occurrence of the resonant excitation for different types of dynamic impact (walking, running, jumping, squats etc.) and different frequencies of excitation of the vibrations in a function of location of the footbridge.

References

BACHMANN H., AMMANN W. 1987. *Vibration in structures induced by man and machine*. International Association of Bridge and Structural Engineering (IABSE), Zurich.

FLAGA A. 2002. *Problems of vibrations effects on people on bridges*. Inżynieria i Budownictwo, 3–4: 182–187.

FLAGA A., PAŃTAK M. 2003. *The Comfort criteria in the design of footbridges*. Proc. of Sem. Design, construction and aesthetics of pedestrian bridges, Cracow University of Technology, p. 7–27.

FLAGA A., PAŃTAK M. 2008. *Vibration comfort criteria for pedestrians on footbridges*. Proc. Third Inter. Conf. Footbridges, Faculdade de Engenharia Universidade do Porto, Porto.

Footbridges – Assessment of vibrational behaviour of footbridges under pedestrian loading – Practical Guidelines. 2006. Technical Department for Transport, Roads and Bridges Engineering and Road Safety (Service d'études techniques des routes et autoroutes – SÉTRA), Paris.

GRUNDMANN H., KREUZINGER H., SCHNEIDER M. 1993. *Schwingungsuntersuchungen für Fußgängerbrücken*. Springer-Verlag, Bauingenieur, 68: 215–225.

ISO 10137:2007. *Bases for Design of Structures. Serviceability of buildings and walkways against vibrations*. 2007. International Organization for Standardization, Geneva.

ISO 2631:2–1989. *Mechanical vibration and shock. Evaluation of human exposure to whole-body vibration*. Part 2. *Continuous and shock-induced vibration in buildings (1 to 80 Hz)*. 1989. International Standardization Organization, Geneva.

LEONARD D.R. 1966. *Human tolerance levels for bridge vibrations*. RRL, Report No. 34, Harmondsworth.

PAŃTAK M. 2007. *Analysis of vibration comfort criteria for steel footbridges susceptible to dynamic actions*. PhD Thesis, Cracow University of Technology, Cracow.

PAŃTAK M. 2012. *Application of EN 1990/A1 vibration serviceability limit state requirements for steel footbridges*. Procedia Engineering, 40: 345 – 350.

PN-B-02171. *Evaluation of the impact of vibrations on people in buildings*. 1988. PKN, Warszawa.

PN-EN 1990:2004/A1. *Eurocode – Basis of structural design*. 2008. Chapter A2.4. PKN, Warszawa.

PN-EN 1991-2:2007. *Eurocode 1: Actions on structures*. Part 2. *Traffic loads on bridges*. 2007. Chapter 5.1(4). PKN, Warszawa.

Steel, Concrete and Composite Bridges. Part 2. *Specification for Loads*. 1978. BS 5400-2:1978. British Standards Association, London.