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РЕЗИМЕ

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DESIGN RECOMMENDATIONS OF FLOOR VIBRATIONS INDUCED BY HUMAN ACTIVITIES

SUMMARY

Structural engineers are now facing with new demands towards long spans, lightweight floors in steel-concrete composite construction and big open interiors. These new design trends are leading to the extensive problems related to the serviceability limit state, especially problems with unwanted floor vibrations. Annoying vibrations caused by human activities are an important serviceability problem, which can significantly affect the comfort of people, quality of life and structure's functionality. Over past years many design recommendations of floor vibrations induced by human activities have been published. This paper presents a short overview of dynamic loads modeling and design recommendations of floor vibrations induced by human activities.

Key words: serviceability limit state, floor vibrations, dynamic loads, acceptance criteria

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1. INTRODUCTION

The current design requirements in the field of building construction are mainly reflected in the design of slender structures, with long spans, large open interiors, unconventional shapes and structural solutions with lightweight composite steel-concrete floors. Also, structural engineers are now facing with increasing demands for buildings that are fast to construct, with the possibility of subsequent reuse of the space for other purposes in relation to those originally envisaged by project. These new design trends are leading to the extensive problems related to the serviceability limit state, especially problems with unwanted floor vibrations, because of lower natural frequencies and lower natural damping of structures.

The term of vibration implies the occurrence of the oscillatory movement of individual structural parts, such as floors, with certain amplitude and frequency of oscillation. The most usual and most important internal source of vibrations is human activity. Human perception and uncompromised functionality of object are two most important acceptability criteria for design of floor vibrations. Once constructed, it is difficult to modify existing construction to reduce its susceptibility to vibrations. It is therefore very important that the acceptability criteria of floor vibrations, depending of the structure purpose, are defined at the early stage of design. Over past years many design recommendations of floor vibrations induced by human activities have been published. This paper presents a short overview of dynamic loads modeling and design recommendations of floor vibrations induced by human activities.

2. DYNAMIC LOADS INDUCED BY HUMAN ACTIVITIES

A major part of the loads encountered in the civil engineering can be defined as dynamic loads, because their intensities vary with time. According to their time functions they can be categorized as: harmonic, periodic, stochastic and impulsive. The most usual and most important internal source of structure's vibrations is human activity. Dynamic loads induced by human activities can be categorized as periodic (such as walking, jumping, dancing and skipping) and stochastic represented as a single impulse to a floor structure (such as take off from the diving platform or landing on a floor after jumping from an evaluated position) (Bachmann and Ammann 1987).

According to the site of action, dynamic loads induced by human activities can be classified in two categories: in situ (periodic jumping to music and sudden standing of a crowd) and moving loads (walking, marching, and running are examples of moving activities) (Ebrahimpour and Sack 2005; ISO Standard 10137 2007).

According to Lim (1991) and Smith et al. (2009), floor vibrations induced by human activities can be classified in two categories: continuous and transient. Continuous vibrations of floor constructions arise from periodic dynamic forces lasting significant period of time such as dancing of people. This kind of excitation can produce resonance of the floor when the frequency of the dynamic force coincides with one of the natural frequencies of the floor structure. Transient vibrations are caused by single impulse or series of impulses. Walking with certain velocity is a main example of series of impulses which cause transient vibrations. Transient vibrations are rather annoying for people than structurally damaging. But in environments such as offices, shopping centers and residential buildings, where human activities represent main type of imposed loads, walking is considered as a source of continuous vibrations.

Dynamic response of the structure depends on structure dynamic characteristics such as: mass of the construction, structure's stiffness, damping ratio, structure's natural frequency and period of oscillation. Resonance is a phenomenon that consists of a given system to oscillate with greater amplitude at some preferential frequencies when it is driven by external forces to oscillate. Frequencies at which the response amplitude is a relative maximum are known as the system's resonant frequencies. Historically, many designers have used natural frequency of the floor structure as a measure of acceptable performance of the structure due to the vibrations. Sufficiently high natural frequency of floor structure means that a floor is out of the frequency range of the first harmonic component of the walking activity (Smith et al. 2009). Resonant response can cause significant increase of the effects of vibrations.

3. MODELING OF DYNAMIC LOADS INDUCED BY HUMAN ACTIVITIES

Modeling of dynamic loads induced by human activities presents the first step in dynamic analysis of structures. Modeling of this type of dynamic loads is extremely complex and dynamic response of structure is usually presented in large number of different mode shapes each with its own natural frequency. Those different mode shapes need to be superimposed in order to find an actual displacement of a structure at any given time (Smith et al. 2009). Actual displacement of a structure exposed to the dynamic force represented with single sinusoidal function of frequency *f* (Hz) is given in Eq. (1):

$$w_n(x,t) = \sum_{n=1}^{\infty} u_n \sin(2\pi f t + \varphi_n)\sin(\frac{n\pi x}{L}) \tag{1}$$

where:

$w_n(x,t)$ is the displacement (m) at a position x along the beam at time t;
t is the time (s);
f is the frequency (Hz) of the forcing function;
u_n is the maximum amplitude (m) of the mode n;
φ_n is the phase angle of the mode n.

Eq. (1) is only appropriate for dynamic force represented with single sinusoidal function and it is quite unlikely that such a simple forcing function will occur in practice. Therefore, more complicated continuous function which is likely to occur in practice can be broken down into a series of sinusoidal functions. Each sinusoidal function is a harmonic of the forcing function and each harmonic has its own amplitude and phase shift. Set of harmonics are known as a Fourier series (Fig. 1). The amplitude of each subsequent harmonic is lower, which represents that most of the energy goes into the first few harmonics. Next chapters represent modeling of dynamic forces induced by human activities according to different standards and publications, mainly based on the Fourier transformation explained earlier.

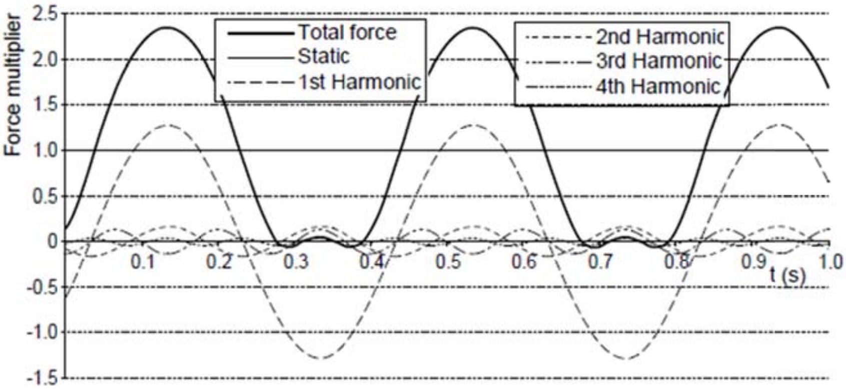


Fig. 1. Fourier series for low impact aerobics

3.1. Modeling of continuous dynamic force

Walking, exercising, dancing and other rhythmic activities are classified as continuous dynamic loads on supporting construction and this type of activities can be represented through a combination of harmonic forces, whose frequency *f* (Hz) are multiples of harmonics of the basic frequency of the dynamic force using Fourier series. In general way, different load models were developed in different standards, design recommendations and research works. The most usual load models of continuous dynamic excitation induced by human activities can be presented with Eq. (2) and Eq. (3), as shown in Fig. 3 and Fig. 2, respectively (Smith et al. 2009; Murray et al.2003):

$$F(t) = P\alpha_i \cos(2\pi i f_s t) \tag{2}$$

$$F(t) = P\left[1 + \sum \alpha_i \cos(2\pi i f_s t + \varphi_i)\right] \tag{3}$$

where:

P is the person's weight (0.7kN);
t is the time (s);
i is the number of harmonics;
f_s is the frequency (Hz) of the forcing function;
α_i is the dynamic load factor for the ith harmonic;
φ_i is the phase angle for the ith harmonic.

This load models were used in many research works (Da Silva et al. 2006; Costa-Neves et al. 2014). Continuous dynamic force (Fig. 3) can be represented by the first four harmonic components using Fourier analysis. As a general rule, the magnitude of the dynamic coefficient α_i decreases with increasing of the harmonics.

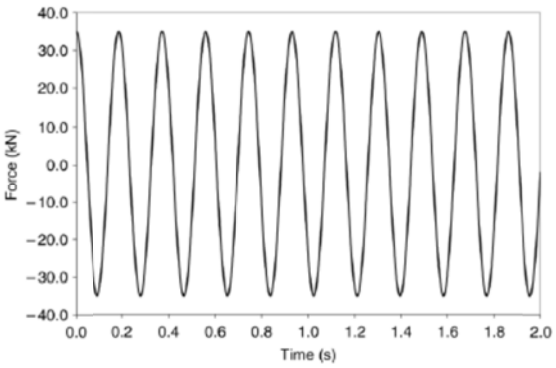


Fig. 2. Dynamic load represented with only one resonant harmonic

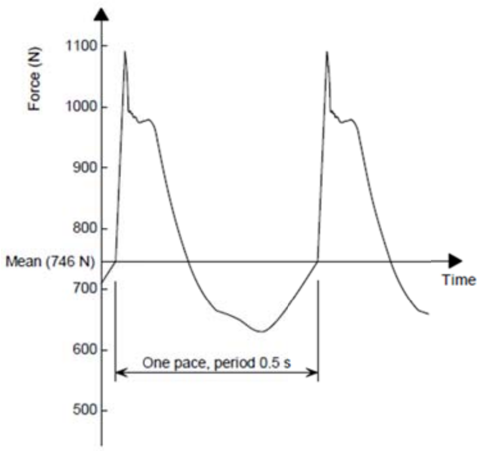


Fig. 3. Dynamic load represented by the first four harmonics

The amplitude of the harmonic force for each harmonic can be calculated using Eq. (4):

$$F_i = \alpha_i P \tag{4}$$

and parameters used in this equation have the same definitions as in Eq. (2) and Eq. (3). Excitation frequency range and design value of coefficient α_i for each harmonic, for different types of human activities, according to Smith et al. (2009) and Murray et al.(2003), are presented in Table 1.

	Walking				Exercising		Dancing	
	SCI		AISC		AISC		AISC	
Harmonic i	f_s (Hz)	α_i	f_s (Hz)	α_i	f_s (Hz)	α_i	f_s (Hz)	α_i
1	1,8-2,2	$0{,}436(if_s-0{,}95)$	1,6-2,2	0,5	2,0-2,75	1,5	1,5-3,0	0,5
2	3,6-4,4	$0{,}006(if_s+12{,}3)$	3,2-4,4	0,2	4,0-5,5	0,6	-	-
3	5,4-6,6	$0{,}007(if_s+5{,}2)$	4,8-6,6	0,1	6,0-8,25	0,1	-	-
4	7,2-8,8	$0{,}007(if_s+2{,}0)$	6,4-8,8	0,05	-	-	-	-

Table 1. Design Fourier coefficients for different human activities.

National Annex to BS EN 1991-2:2003 (2008), defines dynamic load models for pedestrian actions on footbridges. Actions that result from single pedestrian or pedestrian groups can be presented by application of a vertical pulsating force F (N), moving across the span of the bridge at a constant speed v_t, as shown in Eq. (5):

$$F = F_0 k(f_v)\sqrt{1+\gamma(N-1)}\sin(2\pi f_v t) \tag{5}$$

where:

N is the number of pedestrians in the group;
F_0 is the reference amplitude of the applied fluctuating force (N);
f_v is the natural frequency (Hz) of the vertical mode under consideration;
$k(f_v)$ is a combined factor;
t is the elapsed time (s);
γ is a reduction factor;
S_{eff} is an effective span length (m);
S is the span of the bridge (m).

Definitions of all parameters shown in Eq. (5) are given in NA to BS EN 1991-2:2003 (2008). Effective span length can be calculated according to definition given in Fig. 4, and values of amplitude of the applied force and moving speed are given in Table 2.

Load parameters	Walking	Jogging
Reference load, F_0 (N)	280	910
Pedestrian crossing speed, v_t (m/s)	1,7	3

Table 2. Parameters for calculation of pedestrian response.

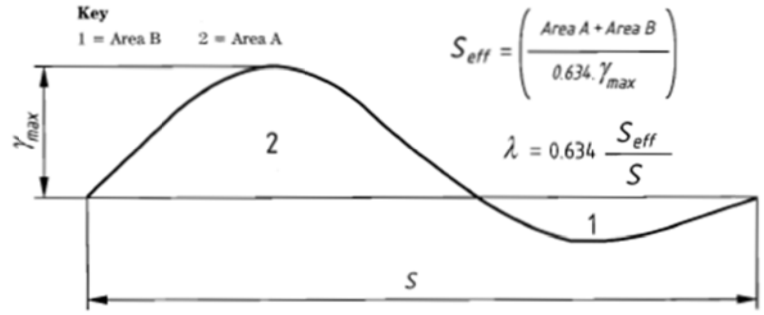
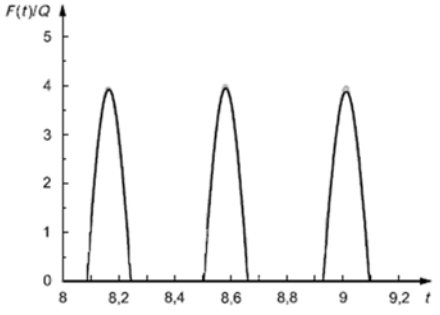


Fig. 4. Effective span calculation



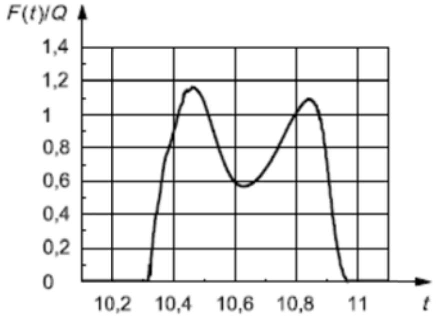


Fig. 5. Vertical force for one person jumping continuously

Fig. 6. Vertical force for one walking step by one person

According to ISO Standard 10137- Annex A (2007), the dynamic force induced by a person of weight *Q*, caring out repetitive coordinative activity such as jumping can be represented as a function of time *t* with a sequence of pulses (Fig. 5). One walking step by one person as a function of time is represented in Fig. 6. ISO Standard 10137- Annex A (2007), defines vertical and horizontal dynamic force on supporting construction, induced by different continuous human activities, as a combination of harmonic forces, using Fourier series, represented with Eq. (6) and Eq. (7):

$$F_v(t) = P\left[1 + \sum \alpha_{i,v} \sin(2\pi i f_s t + \varphi_{i,v})\right] \tag{6}$$

$$F_h(t) = P\left[1 + \sum \alpha_{i,h} \sin(2\pi i f_s t + \varphi_{i,h})\right] \tag{7}$$

where:

P	is the person's weight (0.7kN);
t	is the time (s);
i	is the number of harmonics;
f_s	is the frequency (Hz) of the forcing function;
$\alpha_{i,v}$	is the dynamic load factor for vertical direction;
$\alpha_{i,h}$	is the dynamic load factor for horizontal direction;
$\varphi_{i,v}$	is the phase angle of *i*th harmonic for vertical direction;
$\varphi_{i,h}$	is the phase angle of *i*th harmonic for horizontal direction.

Excitation frequency range and design value of coefficient α_i for each harmonic, for different types of human activities, according to ISO Standard 10137- Annex A (2007) are presented in Table 3.

Activity	Harmonic	Common range of forcing frequency	Numerical coefficient for vertical direction	Numerical coefficient for horizontal direction
	i	if_s (Hz)	$\alpha_{i,v}$	$\alpha_{i,h}$
Walking	1	1,2-2,4	0,37(f_s-1,0)	0,1
	2	2,4-4,8	0,1	
	3	3,6-7,2	0,06	
	4^a	4,8-9,6	0,06	
	5^a	6,0-12,0	0,06	
Running	1	2,0-4,0	1,4	0,2
	2	4,0-8,0	0,4	
	3	6,0-12,0	0,1	

[a] These higher harmonics is rarely significant when human perception is of concern, but may be important for more sensitive building occupancies such as vibration-sensitive instrumentation.

Table 3. Design parameters for moving forces due to one person.

4. DETERMINATION OF DYNAMIC PROPERTIES OF FLOOR STRUCTURES

Determination of dynamic properties of structures can be performed using FEM analysis or using simple calculation formulas for different construction types. The method for determination of dynamic properties of structures should not be disproportionately more refined than the method for the vibration analysis. Various programs can perform dynamic analysis of structures and also offer tools for the determination of natural frequencies and modal masses of structures under consideration.

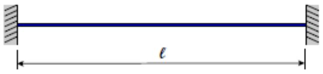
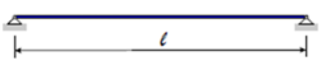
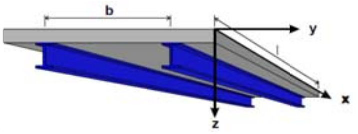
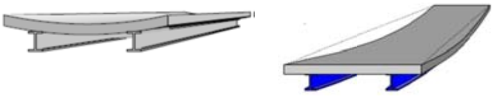
Beams		$f=\frac{4}{\pi}\sqrt{\frac{3EI}{0{,}37\mu l^4}}$
		$f=\frac{2}{\pi}\sqrt{\frac{3EI}{0{,}49\mu l^4}}$
Orthotropic floors		$f_1=\frac{\pi}{2}\sqrt{\frac{EI_y}{\mu l^4}}\sqrt{1+\left[2\left(\frac{b}{l}\right)^2+\left(\frac{b}{l}\right)^4\right]\frac{EI_x}{EI_y}}$
Orthotropic floors- Dunkerley approach		$\frac{1}{f^2}=\frac{1}{f_1^2}+\frac{1}{f_2^2}$
Natural frequency from the self-weight approach		$f=\frac{1}{2\pi}\sqrt{\frac{K}{M}}=\frac{1}{2\pi}\sqrt{\frac{4g}{3\delta_{max}}}=\frac{18}{\sqrt{\delta_{max}(mm)}}$

Table 4. Simple calculation methods for determination of natural frequencies

If FEM analysis is applied for determination of dynamic properties for vibration analysis, it should be considered that structural model for this analysis may differ from that used for ultimate limit state verification. These differences are especially related to the selection of boundary conditions (hinged connection in ULS analysis may be assumed as full moment connection in the vibration analysis), different concrete modulus of elasticity (concrete dynamic modulus of elasticity should be considered to be 10% larger than the static tangent modules) and usage of 10% to 20% of characteristic value of imposed loads as a quasi permanent part of imposed loads for calculation of the masses (Feldmann et al. 2009). Simple calculation methods for determination of dynamic properties of floor structures are represented in Table 4 (Feldmann et al. 2009).

5. DESIGN CRITERIA

Human response to floor motion is very complex phenomenon, involving the magnitude of motion, the surrounding environment and human activity. Attempts to quantify human response to vibrations of floor structures have been known for many years. Historically, two types of design criteria have been developed: criteria for human response to known or measured vibrations and design criteria which include an estimation of dynamic floor response.

In 1931, Reiher and Meister developed first generally applicable design criteria which was based on a human perception to measured vibrations with frequencies of 5 to 100 Hz and amplitudes of 0,01 mm to 10 mm. In 1961, after studding composite steel-concrete floor structures Lenzen suggested modified Reiher-Meister scale as shown in Fig. 7. Lenzen did not suggest any limits of frequencies ranges and amplitudes to assure acceptable criteria for different floor structures. Modified Reiher-Meister scale, Murray acceptable criteria form 1975 and Canadian Standards Association Scale (CSA Scale) where developed only for heel-drop impact and should not be used for any other types of impact. CSA Scale (Fig. 8), applicable only for heel-drop impact, is incorporated in The Canadian Steel Building Standard CAN/CSA-S16.1 (recently changed with CAN/CSA-S16.14). A design formula to estimate acceleration of the floor structures is included in this standard (Murray et al. 2003).

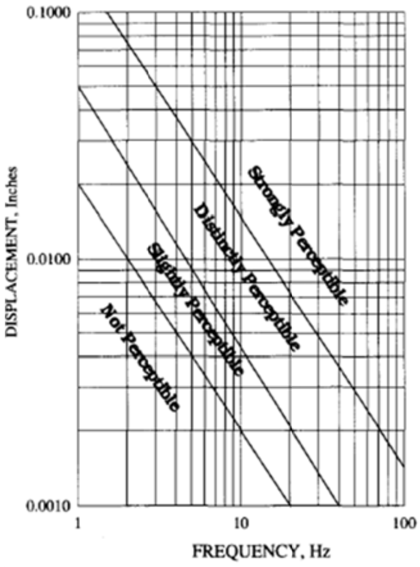


Fig. 7. Modified Reiher-Meister scale

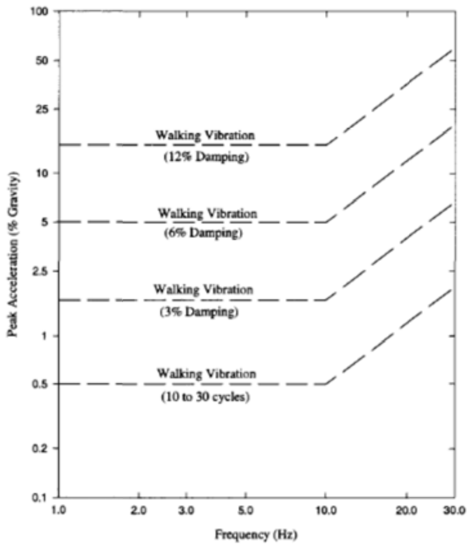


Fig. 8. Canadian Standards Association scale

Many design recommendations and standards are based on the International Organization for Standardization's standard ISO 2631-2:1989 (changed with ISO 2631-2:2003) which is written to cover many building vibration environments. This standard presents acceleration limits for mechanical vibrations as a function of exposure time and frequency, for both longitudinal and transverse direction. Limits for different type of constructions are given in terms of root mean square (rms) acceleration as multiples of the baseline curve, as shown in Fig. 9 (Murray et al. 2003). Murray et al. (2003) gave a detailed design guide with basic principles and simple analytical tools for calculation of vibrations induced by walking, based on the ISO Scale. According to this design recommendation, dynamic load is presented with Eq. (2) and it represents time dependent harmonic force component which matches the fundamental frequency of the floor. A response function can be calculated according to Eq. (8):

$$\frac{a}{g} = \frac{R\alpha_i P}{\beta W}\cos(2\pi i f_s t) \tag{8}$$

where:

a/*g* is the ratio of the floor acceleration to the acceleration of gravity;
R is the reduction factor;
β is the modal damping ratio;
W is the effective weight of the floor.

Feldman et al. (2009) developed new design recommendations for floor vibrations induced by person's walking which are the background document in support to the implementation, harmonization and further development of the Eurocodes. Development of the diagrams shown in Fig. 10 (Feldman et al. 2009) is based on the measurements carried out in Delft with 700 persons in total and each point in the diagram is based on the statistical evaluation of 700 combination functions of step frequency and body mass. Determination of the limits for OS-RMS-value$_{90}$ for comfort is based on various standards for standardizing human perception such as ISO 10137 (2007) and ISO 2631-2 (2003).

The design procedure based on these diagrams provides three steps: determination of the basic floor characteristics (natural frequency shown in Table 4, modal mass and damping) as an input data, determination of the OS-RMS-value$_{90}$ from the design chart which characterizes the floor response to walking and comparison OS-RMS-value$_{90}$ with the recommended value or required limits for different floor occupancies, shown in Table 5 (Feldman et al. 2009). According to EN 1990:2002 (2006) natural frequency of vibrations of the structure or structural member should be kept above appropriate values which depend upon the function of building.

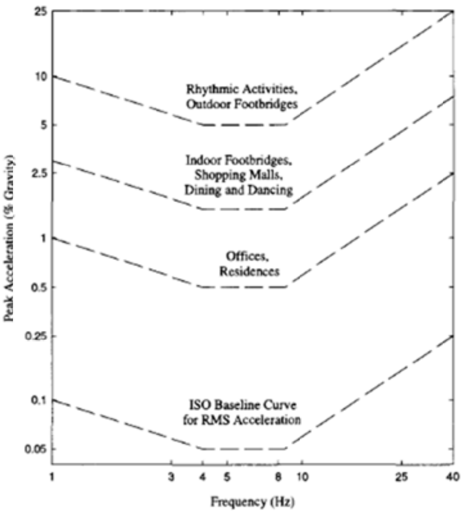


Fig. 9. International Standard Association Scale

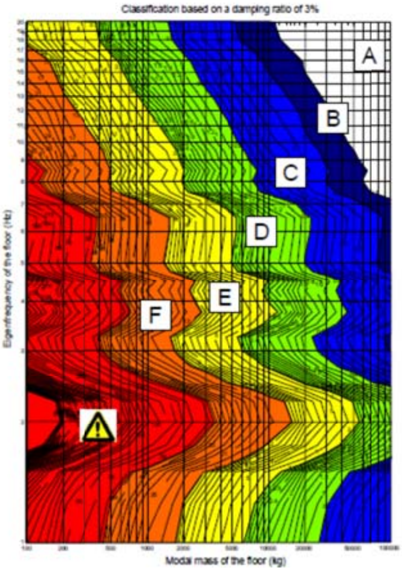


Fig. 10. Diagrams for determination of assurance of floor structures due to vibrations

Class	OS-RMS$_{90}$		Usage of the floor structure									
	Lower limit	Upper limit	Critical areas	Hospitals, surgeries	Schools, training centers	Residential buildings	Office buildings	Meeting rooms	Senior citizens' residential buildings	Hotels	Industrial workshops	Sports facilities
A	0,0	0,1	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
B	0,1	0,2		▒	▒	▒	▒			ed	▒	▒
C	0,2	0,8	■	▒	▒	▒	▒	▒	▒	▒	▒	▒
D	0,8	3,2	■			▒	▒	▒	▒	▒	▒	▒
E	3,2	12,8	■	■	■			l			▒	▒
F	12,8	51,2				ded	■	■	■	■		

Table 5. Comfort limits for different floor structure's usage

If the natural frequency of vibrations of the structure is lower than the appropriate value, a more refined analysis of the dynamic response of the structure, including the consideration of damping, should be performed. Acceleration of floor structure can be used as more precise criteria for estimation of its acceptance. According to EN 1990 (Annex A2) pedestrian comfort criteria should be defined by National Annex, but recommended maximum values of acceleration are given for vertical (0.7 m/s^2) and horizontal (0.2 m/s^2) vibration. Appropriate values for natural frequencies of vibrations and acceleration of the structure and more definitions for more refined analysis should be defined in National Annexes.

According to EN 1991-1-1:2001 (2001), if dynamic actions on structures induced by synchronized rhythmical movement of people, dancing or jumping can cause resonant effects on structures, different dynamic load models should be determined for dynamic analysis and different procedures may be defined in National Annexes, such as NA to BS EN 1991-2:2003 (2008).

6. CONCLUSIONS

Annoying vibrations caused by human activities is an important serviceability problem, which can significantly affect the comfort of people, quality of life and structure functionality. This paper presents a short survey of the dynamic loads modeling induced by human activities, simplified procedures of determination of dynamic characteristics of floor structures and historical developments of the acceptance criteria of floor vibrations. Special attention is paid to dynamic modeling of continuous and impulse loading induced by human activities. Dynamic load modeling and analysis of vibrations is extremely complex and development of simplified procedures for determination of floor vibrations is very important in order to prevent problems with excessive vibration. Also, defining dynamic loads modeling as well as acceptability criteria for floor vibrations through implementation of National Annexes for different parts of European Standards is extremely important, and should facilitate design of constructions exposed to the dynamic loads.

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