International Journal of Civil and Structural Engineering– IJCSE
Volume 2 : Issue 1 [ISSN : 2372-3971]
Publication Date: 30 April, 2015

Human Comfort Evaluation of Composite Floors

An investigation of the effect of human rhythmic activities modelling

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***Abstract*—A growing number of structural problems associated with excessive vibrations of steel-concrete composite floors due to human rhythmic activities is the main motivation for the development of an analysis methodology supported by design guides and several researches to obtain the dynamic response of a steel-concrete composite floor spanning 40 by 40 m when subjected to human rhythmic dynamic loads. Therefore, this research develops a study based on the use of two different mathematical formulations used for modelling human rhythmic actions (aerobics). Furthermore, it was observed that high levels of annoying vibrations were reached during the aerobic activity.**

***Keywords*—steel-concrete composite floors, dynamic loading models, human comfort, excessive vibrations, human comfort.**

I. Introduction

Floor vibrations induced by human rhythmic activities like walking, running, jumping or aerobics consist on a very complex problem. The dynamic excitation characteristics generated during these activities are directly related to the individual body adversities and to the specific way in which each human being executes a certain rhythmic task. All these aspects do not contribute for an easy mathematical or physical characterization of this phenomenon. The analysis of the structural vibrations should include a dynamic analysis and a comparison of the predicted accelerations to the human allowances related to comfort, although simplified criteria may often be used based on the floor flexibility or the natural frequency.

The increase of vibration problems related to human rhythmic activities has been reported in the last decades. It can be emphasized that this situation is not due to an only single cause but rather a combination of several ones. The technological advance in the materials field has allowed the use of more resistant and low weight materials that result in slender and more flexible structural systems. Therefore, this condition tends to decrease their masses and also the natural frequencies. Besides, it has been observed in design practice low floor damping ratios [1], which is related to the type of construction, materials, presence of non-structural elements, age and quality of construction. The structural damping plays an important role on the steel-concrete composite floor dynamic response [2].

On the other hand, most disturbing vibrations related to human perception are in the range of 4 to 8 Hz [3], [4], [5] and at the same time most of the natural frequencies of steel-concrete composite floor systems lie also in this range. In addition, the excitation force frequencies due to human rhythmic activities occur in this range as well. All these combinations make the structural systems more susceptible to the resonance phenomenon, causing undesirable vibrations in the frequency range that is the most noticeable to humans.

II. Rhythmic Activities Modelling

The representative mathematical function of the rhythmic dynamic loading can be described by two different experimental approaches such as proposed by Faisca [6] and Ellis and Ji [7],[8]. The dynamic loading model I (1) corresponds to the model proposed by Faisca [6] and the dynamic loading model II was developed by Ellis and Ji [7],[8] (2), (3), (4) and (5). Fig. 1 shows an example of the dynamic force in the frequency domain used in this work considering 64 persons with weight equal to 800N.

$$\begin{aligned} F(t) &= CD\left\{K_p P\left[0.5-0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} && t \le T_c \\ F(t) &= 0 && T_c \le t \le T \end{aligned} \tag{1}$$

Where, F(t): dynamic loading function (N); t: time (s); T: activity period (s); Tc: activity contact period (s); P: person's weight (N); K_p: impact coefficient; CD: phase coefficient.

$$F(t) = G\left\{1+\sum_{n=1}^{\infty} r_{n,v}\,\sin\left(2n\pi f_p t+\phi_n\right)\right\} \tag{2}$$

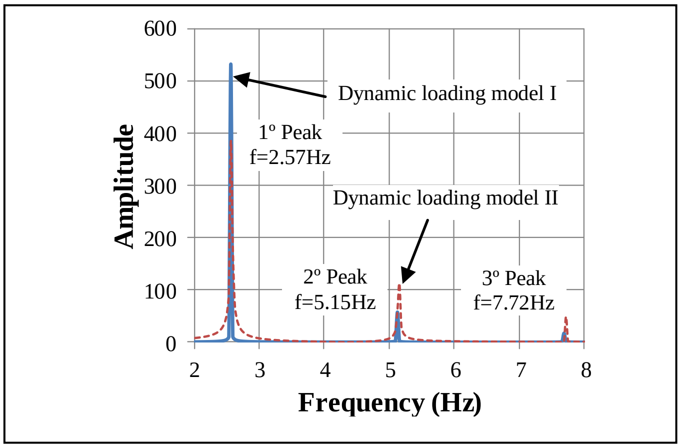
$$r_{1,v} = 1.61v^{-0.082} \tag{3}$$

$$r_{2,v} = 0.94v^{-0.24} \tag{4}$$

$$r_{3,v} = 0.44v^{-0.31} \tag{5}$$

Where, F(t): dynamic loading function (N); t: time (s); f_p: frequency of the jumping load (Hz); v: number of persons; $r_{n,v}$: Fourier coefficient of the n^{th} term; G: person's weight (N); ϕ_n,: phase lag of the n^{th} term.

Figure 1. Dynamic loading induced by aerobics.



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III. Investigated Composite Floor

The structural system represents a typical interior composite floor of a commercial building spanning 40m by 40m. The floor is supported by steel columns and is currently submitted to aerobics. The structural system is made from composite beams and a 100 mm thick concrete slab, see Fig. 2. The steel sections used were welded wide flanges (WWF) made from a 345 MPa yield stress steel grade and a 205×10^3 MPa Young's modulus. The concrete slab has a 30 MPa specified compression strength and a 26×10^3 MPa Young's Modulus. The live load considered corresponds to one person (800N) for each 4.0m^2 [4]. Table I shows the geometrical characteristics of the steel sections. Fig. 3 presents the finite element model developed in the ANSYS program [9].

TABLE I. GEOMETRIC CHARACTERISTICS OF THE FLOOR. UNITS IN MM.

Profile Type	Height (d)	Flange Width (b_f)	Top Flange Thickness (t_f)	Bottom Flange Thickness (t_f)	Web Thickness (t_w)
Beams W 610 x 140	617	230	22.2	22.2	13.1
Beams W 460 x 60	455	153	13.3	13.3	8.0
Columns HP 250 x 85	254	260	14.4	14.4	14.4

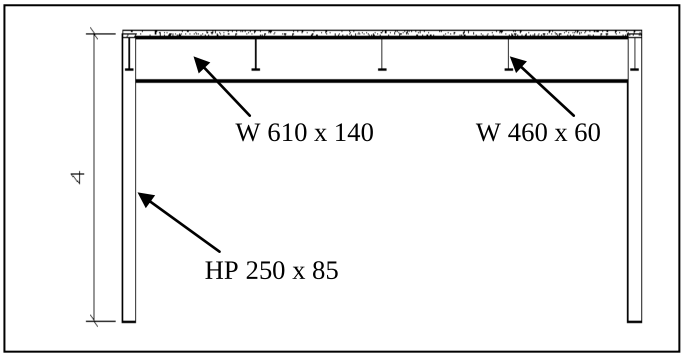


Figure 2. Typical floor bay cross section. Dimensions in (m).

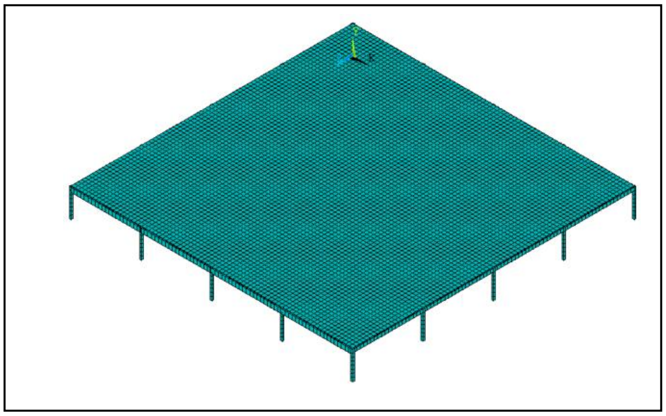
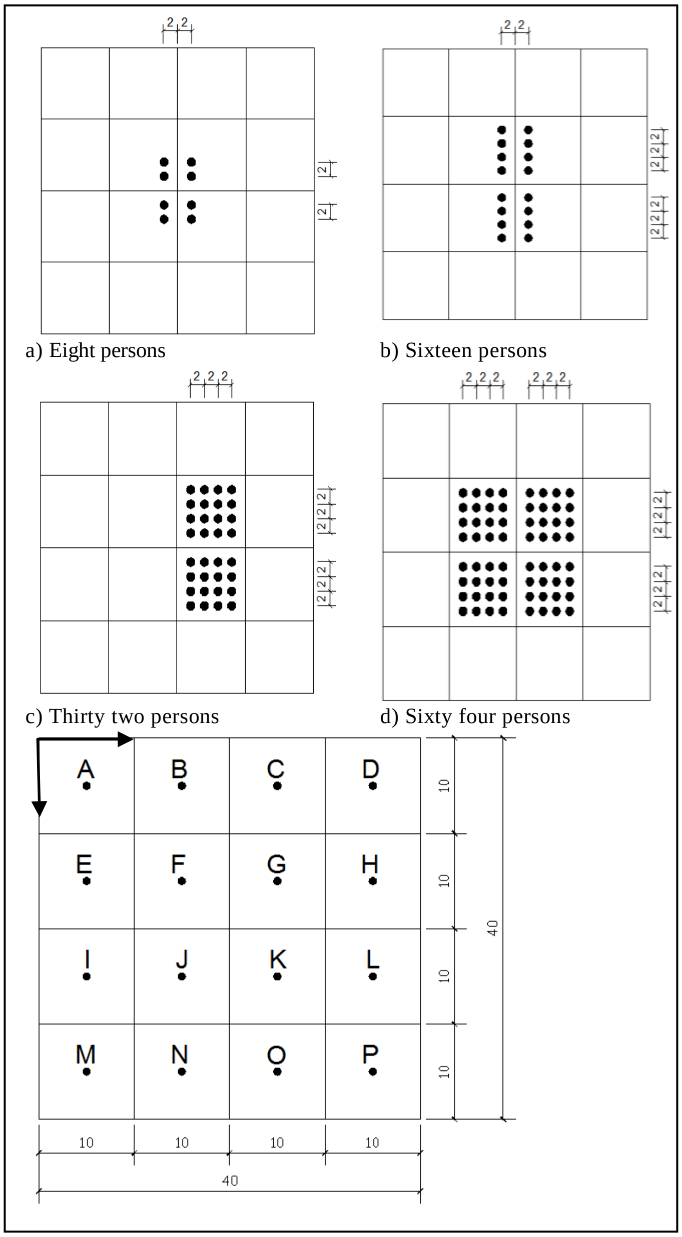


Figure 3. Steel-concrete composite floor finite element model.

IV. Floor Dynamic Response

The modal analysis was carried out and it was verified that the first sixteen natural frequencies of the analysed floor, varying from 6.06Hz to 7.79Hz, are close to the excitation frequency range (aerobics). In this situation, the frequency of the third harmonic of the dynamic loading, varying from 4.5 to 8.57 Hz [6],[7],[8], may match these natural frequencies and therefore lead the composite floor to resonance. Consequently, such situation might result in undesirable vibrations and thus human annoyance [5]. This way, in order to investigate this possibility, four loading cases of 8, 16, 32 and 64 persons were applied on the steel-concrete composite floor, see Fig. 4 considering the resonance with the fifteenth vibration mode of the structure, as illustrated in Fig. 5.



a) Eight persons

b) Sixteen persons

c) Thirty two persons

d) Sixty four persons

Figure 4. Persons' positioning along the floor. Dimensions in (m).

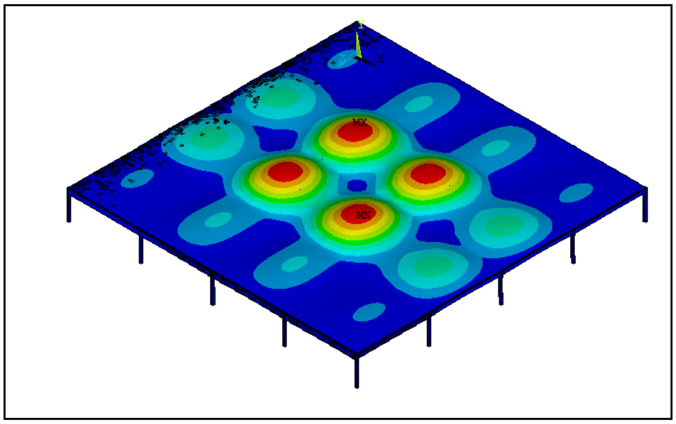


Figure 5. Steel-concrete composite floor 15th Vibration mode (f_{15}=7.72Hz).

V. Human Comfort Evaluation

Tables II, III, IV and V show the results obtained using the four load cases, based on the dynamic load models I [6] and II [7], [8] and Table VI shows the human comfort acceptance criteria [8], [10], [11].

TABLE II. FLOOR DYNAMIC RESPONSE FOR 8 PERSONS

Node	Dynamic Loading Model I			Dynamic Loading Model II		
	Acceleration (m/s²)		*VDV ($m/s^{1,75}$)*	*Acceleration (m/s²)*		*VDV ($m/s^{1,75}$)*
	a_p	$a_{w,rms}$		a_p	$a_{w,rms}$	
A ; M	0.021	0.012	0.025	0.099	0.065	0.132
B ; N	0.045	0.027	0.055	0.193	0.132	0.267
C ; O	0.045	0.027	0.055	0.193	0.132	0.267
D ; P	0.021	0.012	0.025	0.099	0.065	0.132
E ; I	0.065	0.041	0.085	0.326	0.214	0.438
F ; J	0.173	0.106	0.219	**0.881**	**0.568**	**1.161**
G ; K	0.173	0.106	0.219	**0.881**	**0.568**	**1.161**
H ; L	0.065	0.041	0.085	0.326	0.214	0.438
Limiting Acceleration = 0.5m/s² [5]						

TABLE III. FLOOR DYNAMIC RESPONSE FOR 16 PERSONS

Node	Dynamic Loading Model I			Dynamic Loading Model II		
	Acceleration (m/s²)		*VDV ($m/s^{1,75}$)*	*Acceleration (m/s²)*		*VDV ($m/s^{1,75}$)*
	a_p	$a_{w,rms}$		a_p	$a_{w,rms}$	
A ; M	0.030	0.013	0.028	0.151	0.057	0.118
B ; N	0.046	0.024	0.051	0.181	0.106	0.215
C ; O	0.055	0.032	0.065	0.235	0.121	0.247
D ; P	0.032	0.019	0.038	0.191	0.07	0.145
E ; I	0.065	0.041	0.084	0.263	0.166	0.334
F ; J	0.155	0.102	0.209	**0.626**	**0.422**	**0.859**
G ; K	0.175	0.101	0.207	**0.706**	**0.459**	**0.931**
H ; L	0.088	0.047	0.099	0.454	0.216	0.437
Limiting Acceleration = 0.5m/s² [5]						

TABLE IV. FLOOR DYNAMIC RESPONSE FOR 32 PERSONS

Node	Dynamic Loading Model I			Dynamic Loading Model II		
	Acceleration (m/s²)		*VDV ($m/s^{1,75}$)*	*Acceleration (m/s²)*		*VDV ($m/s^{1,75}$)*
	a_p	$a_{w,rms}$		a_p	$a_{w,rms}$	
A ; M	0.100	0.060	0.130	**0.56**	0.244	**0.507**
B ; N	0.210	0.120	0.260	**0.743**	**0.461**	**0.938**
C ; O	0.210	0.130	0.270	**0.876**	**0.459**	**0.934**
D ; P	0.110	0.060	0.130	**0.67**	0.251	**0.535**
E ; I	0.330	0.220	0.440	**1.203**	**0.737**	**1.491**
F ; J	**0.840**	**0.540**	**1.100**	**2.867**	**1.878**	**3.825**
G ; K	**1.000**	**0.550**	**1.150**	**3.404**	**2.029**	**4.17**
H ; L	0.360	0.210	0.430	**1.277**	**0.783**	**1.593**
Limiting Acceleration = 0.5m/s² [5]						

TABLE V. FLOOR DYNAMIC RESPONSE FOR 64 PERSONS

Node	Dynamic Loading Model I			Dynamic Loading Model II		
	Acceleration (m/s²)		*VDV ($m/s^{1,75}$)*	*Acceleration (m/s²)*		*VDV ($m/s^{1,75}$)*
	a_p	$a_{w,rms}$		a_p	$a_{w,rms}$	
A ; M	0.187	0.119	0.244	**0.547**	**0.359**	**0.726**
B ; N	0.384	0.248	**0.507**	**1.033**	**0.704**	**1.424**
C ; O	0.384	0.248	**0.507**	**1.033**	**0.704**	**1.424**
D ; P	0.187	0.119	0.244	**0.547**	**0.359**	**0.726**
E ; I	**0.648**	**0.407**	**0.835**	**1.789**	**1.175**	**2.386**
F ; J	**1.725**	**1.045**	**2.155**	**4.831**	**3.078**	**6.285**
G ; K	**1.725**	**1.045**	**2.155**	**4.831**	**3.078**	**6.285**
H ; L	**0.648**	**0.407**	**0.835**	**1.789**	**1.175**	**2.386**
Limiting Acceleration = 0.5m/s² [5]						

TABLE VI. HUMAN COMFORT ACCEPTANCE CRITERIA

Smith et al. [8]	**Ellis and Littler [10]**	**Setareh [11]**	**Person's Reaction**
$a_{w,rms}$ (m/s²)	VDV ($m/s^{1.75}$)	VDV ($m/s^{1.75}$)	
< 0.35	< 0.66	< 0.50	**Reasonable limit: passive persons**
0.35 - 1.27	0.66 - 2.38	0.50 - 3.50	**Disturbing**
1.27 - 2.47	2.38 - 4.64	3.50 - 6.90	**Unacceptable**
> 2.47	> 4.64	> 6.90	**Probably causing panic**

The modal damping ratio of 1% was chosen according to ISO 10137 [2] and lies in the extreme range of 0.5% to 8.0% for fully composite steel beams with shear connectors to concrete slab. The total time in which the aerobic activity was performed was equal to 10s for all loading cases. The dynamic response of the composite floor was obtained from the central node of each floor bay which is represented by the letters A to P (see Fig. 4)

Considering the results from Tables II, III, IV and V, the steel-concrete composite floor dynamic response related to the nodes A to P presented a symmetrical behaviour so that they were grouped for simplicity.

Therefore, it was found that the dynamic loading model II [7], [8] presented higher peak accelerations, RMS weighted accelerations ($a_{w,rms}$) and vibration dose values (VDV) than the dynamic loading model I [6].. It can be noted that the load cases for eight and sixteen persons did not present discomfort for the dynamic loading model I [6]. On the other hand, the human comfort criterion for the dynamic model loading II [7], [8] was exceeded for the all four cases.

The nodes F, J, G and K represent the points of highest values associated with harmful excessive vibrations considering the human comfort. Regarding the worst loading case (64 persons and dynamic loading models I [6] and II [7], [8]), the maximum acceleration values of 1.72m/s²; 1.05 m/s² and 2.15 $m/s^{1.75}$ for the dynamic loading model I [6] (peak acceleration, RMS and VDV, respectively) and 4.83 m/s²; 3.08 m/s² and 6.28 $m/s^{1.75}$ for the dynamic loading model II [7], [8] (peak acceleration, RMS and VDV, respectively) were found along the analysis. These values indicate extremely uncomfortable vibration levels to the persons who practice the aerobic activity (see Table VI).

It can be observed that beyond the floor bays where aerobic activity is practiced, adjacent bays showed disturbing and unacceptable vibrations. Thus, other activities might be carried out on these areas, such as related to fitness equipment, office, cafeteria, etc. Consequently, a greater discomfort could be felt by these people [5].

The composite floor dynamic response in time and frequency domain (nodes G and K) corresponding to the worst load case (64 persons and dynamic loading models I [6] and II [7], [8]) is shown in Fig. 6, 7, 8 and 9, respectively.

It must be emphasized that the resonance with the third harmonic of the force function was obtained in both dynamic loading models according to Fig. 7 and 9. The dynamic loading model II [7], [8] presented accelerations values three times greater than the dynamic loading model I [6]. It means that the third Fourier coefficient of the force function correlated to the second loading model is more energetic than the first one.

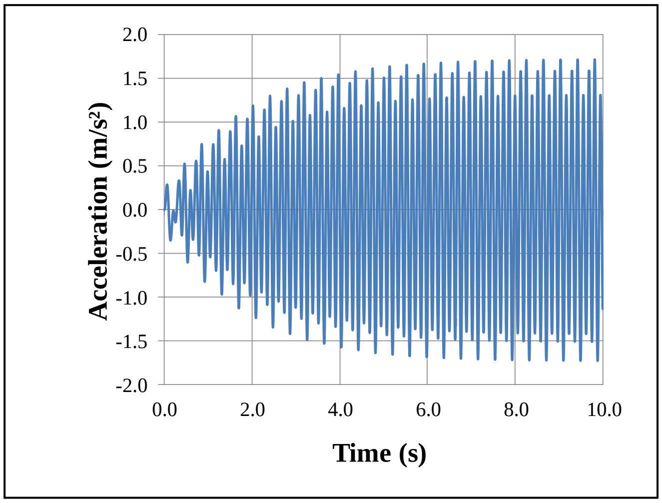


Figure 6. Floor dynamic *reponse for 64 persons.Nodes G and K. Time domain. Dynamic loading model I.*

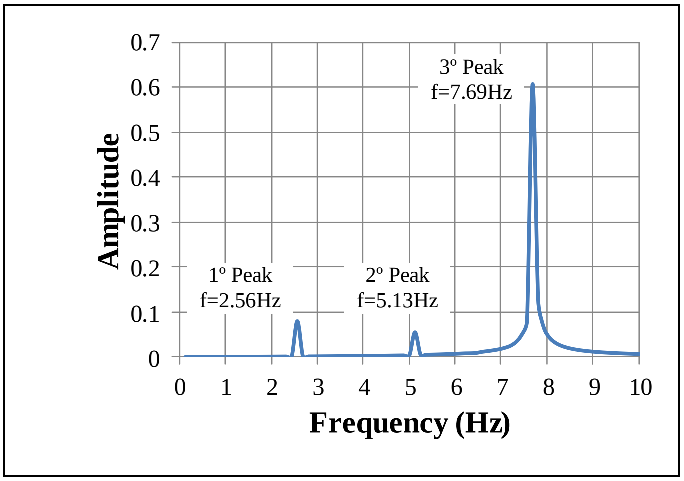


Figure 7. Floor dynamic response for 64 persons. Nodes G and K. Frequency domain. Dynamic loading model I.

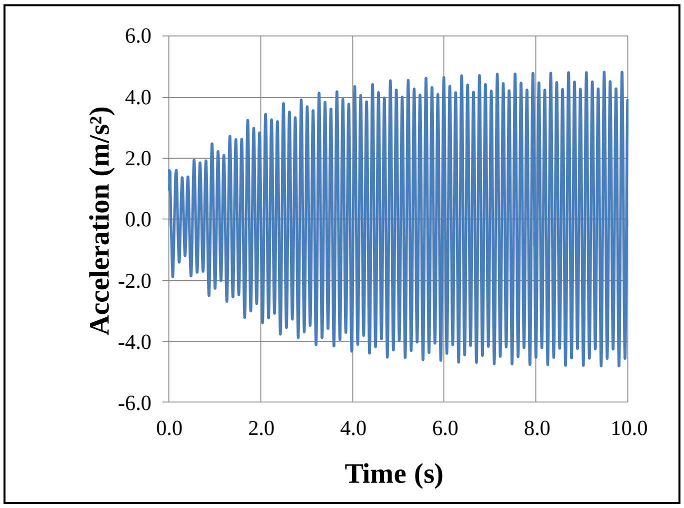


Figure 8. Floor dynamic response for 64 persons. Nodes G and K. Time domain. Dynamic loading model II.

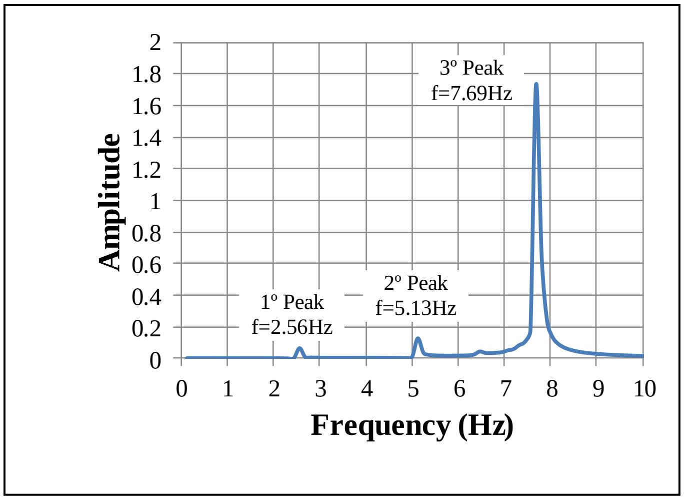


Figure 9. Floor dynamic response for 64 persons. Nodes G and K. Frequency domain. Dynamic loading model II.

VI. Final Remarks

This paper investigated the dynamic behaviour of a steel-concrete composite floor spanning 40m by 40m and subjected to rhythmic human activities (aerobics). The dynamic analysis was developed through numerical simulations based on the finite element method aiming to obtain the peak accelerations of the structure.

The natural frequencies of the investigated structural system are in the range of 6.06Hz to 7.79Hz and their vibration modes may resonate with the third harmonic of the human rhythmic activity practiced on the structure so that excessive vibrations might cause human discomfort.

In order to evaluate the vibrations levels on the floor four loading cases of individuals practicing aerobics on the composite floor were considered i.e. eight, sixteen, thirty-two and sixty-four persons. In addition, two representative mathematical models of human rhythmic activities were studied, evaluated and compared.

Considering the worst dynamic loading case (64 persons, see Fig. 4) and the investigated loading models I [6] and II [7], [8], the maximum acceleration values of peak acceleration, RMS and VDV were equal to 1.72m/s²; 1.05 m/s² and 2.15 $m/s^{1.75}$, respectively, for the dynamic loading model I [6]. On the other hand, when the load model II [7], [8] was considered in the analysis, these values were equal to 4.83 m/s²; 3.08 m/s² and 6.28 $m/s^{1.75}$.

It must be emphasized that these acceleration values have indicated extremely uncomfortable vibration levels to the persons who practice the aerobic activity according to design standards and technical recommendations, considering the two studied dynamic load models. Furthermore, it was also verified that the dynamic loading model II [7], [8], presented acceleration values three times greater than the dynamic loading model I [6], which might lead to a more conservative design recommendation.

Acknowledgment

The authors gratefully acknowledge the financial support for this work provided by the Brazilian Science Foundation's CAPES, CNPq and FAPERJ.

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