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Vibration analysis and human comfort investigation of floors when subjected to rhythmic human activities

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Abstract. Nowadays, determined buildings structural problems can be associated, for example, to floors excessive vibrations subjected to human rhythmic activities. This type of structural project situation can occur when the rhythmic activities are performed in a group, due to the fact that produces a high degree of synchronization, especially when there is the proximity between one of the excitation frequencies and the floor natural frequencies. This way, this research work consists of the assessment of the structural dynamic response of a real reinforced concrete floor with dimensions of 16 m by 35 m and a total area of 560 m² located on the eighth story of the State University of Rio de Janeiro (UERJ). The main focus of the investigation is to study the human-structure interaction dynamic effect between the occupants and the reinforced concrete floor through the use of several dynamic load traditional only-force models and also based on the use of biodynamic systems (mass-spring-damper systems). The numerical modelling of the reinforced concrete floor was performed using the ANSYS program, based on usual modelling techniques adopting the mesh refinement present in the Finite Element Method (FEM). The maximum values related to the floor dynamic structural response were investigated and compared with the human comfort criteria limits. Therefore, it was verified that the floor presents excessive vibration and human discomfort when the only force models were considered in order to generate the dynamic loads. On the other hand, when the dynamic response of the structure was evaluated considering the dynamic load models generated based on the use of biodynamic systems the structural system attends the human comfort criteria and there are no excessive vibrations. However, it must be emphasized that this dynamic loading mathematical model (biodynamic systems) was formulated based on experimental tests where the dynamic characteristics of the people and the human damping were included in the formulation.

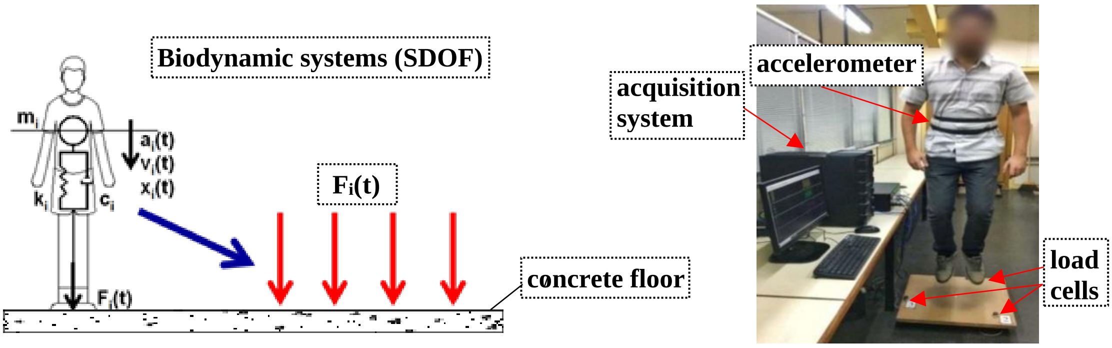
Keywords: Reinforced concrete floor; Dynamic structural analysis; Human comfort.

1 Introduction

The buildings are designed based on normative project criteria. However, over the years a lot of problems associated with excessive vibrations resulting from human activities on the floor have been observed, causing discomfort to the user (Sousa [1], Campista [2] and Toso et al. [3]). Hence, a series of research works were developed to evaluate the dynamic structural behaviour of the floors of buildings when subjected to different human actions. In this sense, several authors have developed mathematical functions used to represent different dynamic loads, such as only-force models. In parallel, other methodologies are being developed, such as modelling by biodynamic systems, this model results indicate consistency, as they are very close to reality, thus an alternative to other models. Therefore, this research work focuses on the investigation of the dynamic structural response of the real reinforced concrete floor located on the 8th story of the State University of Rio de Janeiro (UERJ) based on the use of the Finite Element Method (FEM) via ANSYS [4] software. This way, will be implemented in numerical modelling the following loading models: Campista [2], Faisca [5], AISC [6] and SCI [7]. Afterwards, the maximum values related to the floor dynamic structural response were investigated and compared with the human comfort criteria limits.

2 Modelling of biodynamic systems

Over the years several research works have indicated that the biodynamic model can be used to represent the human as Shahabpoor et al. [8] and Erlinda et al. [9], thus being an alternative to only-force models. In this work, the biodynamic model previously developed by Campista [2] consists of a system with one degree of freedom (SDOF) composed of a mass-spring-damper system. However, it must be emphasized that this dynamic loading mathematical model (biodynamic systems) was formulated based on experimental tests developed by 100 (one hundred) people, individually, jumping over an MDF platform, where the dynamic characteristics of each people (acceleration and force). Therefore, Fig. 1 presents an example of the tests developed in the laboratory, where the following variables of the model were monitored.



(a) (b)

Figure 1. Modelling of biodynamic systems: (a) representation (b) experimental test

This way, the biodynamic systems mathematical formulation was obtained based on the resolution of the optimization problem via generic algorithm method, to solve the dynamic equilibrium equation, see eq. (1). In this sense, the data has been validated through the Pearson good correlation coefficient between the optimized force spectrum with the experimental force spectrum of the 100 tests performed.

$$F_i(t) = \underbrace{4\pi^2 f_i^2 m_i}_{Ki} x_i(t) + \underbrace{4\pi m_i \xi f_i}_{Ci} v_i(t) + m_i a_i(t) \tag{1}$$

Since $F_i(t)$ is the experimental force produced by an individual in (N), k_i is the stiffness of the individual in (N/m), m_i is the mass of individual in (kg), c_i is the damping of individual in (ns/m), $x_i(t)$ is the experimental displacement of the individual over time in (m), $v_i(t)$ is the experimental velocity of the individual over time in (m/s), $a_i(t)$ is the experimental acceleration of individual over time in (m/s²), ξ is the damping coefficient equal to 0.25 (Campista [2]) and f_i is the individual frequency in (Hz).

3 Dynamic loading models: only-force model

Initially, it is worth noting that the only-force model does not consider the characteristics of individuals (mass-spring-damper). The human load modelling was based on the force applied directly on the structure with the use of mathematical formulations that depend on the type of activity performed on the floor. The AISC [6] design guide presents the loading model as a function of the following dynamic coefficients variables, three harmonic components as a function of time and indicates the values of step frequency, see eq. (2).

$$F(t) = P\alpha_i \cos\left(2\pi i f_{step} t\right) \tag{2}$$

Where F(t) represents the dynamic load in (N), f_{step} is the step frequency in (Hz), α_i is the dynamic coefficient, t is the time in (s), i is the harmonic number and P is the person’s weight in (N). Ellis and Ji [10] developed the “only-force” loading model present in the SCI [7] formulated considering the first three terms of the Fourier series obtained via experimental tests, the variables are expressed as a function of the number of participants and the type of activity performed, as expressed in eq. (3).

$$F(t)=G\left\{1+\sum_{n=1}^{\infty} r_{n,v}\sin\left(2n\pi f_p t+\phi_n\right)\right\} \tag{3}$$

Where G is the weight of a person in (N), $r_{n,v}$ is the Fourier coefficient induced by v people, f_p is the loading frequency in (Hz), v is the number of people and ϕ_n is the phase difference. The model proposed by Faisca [5] was based on a series of experimental tests in the laboratory where the human-structure interaction was investigated, then the Hanning mathematical function demonstrated in eq. (4) was used.

$$F(t)=CD\left\{K_p P\left[0.5-0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} \therefore t\le T_c \therefore F(t)=0 \therefore T_c\le t\le T \tag{4}$$

Where P is the weight of a person in (N), K_p is the impact coefficient, CD is the lag coefficient, T_c is the contact period of the activity in (s) and T is the activity period in (s). It should be stressed that were considered the parameters: contact period equals 0.32s and impact coefficient equals 3.07.

4 Structural model and finite element modelling

The investigated structural model corresponds to the real reinforced concrete floor with dimensions of 16 m by 35 m and a total area of 560 m². The structural system corresponds to a fitness centre located on the eighth story of the State University of Rio de Janeiro (UERJ), it is composed of 12 panels of concrete slab with 12 cm thickness (see Fig. 2). The reinforced concrete floor presents secant elastic modulus (E_{cs}) of 17.6 GPa and compression characteristic resistance (f_{ck}) of 13.7 MPa.

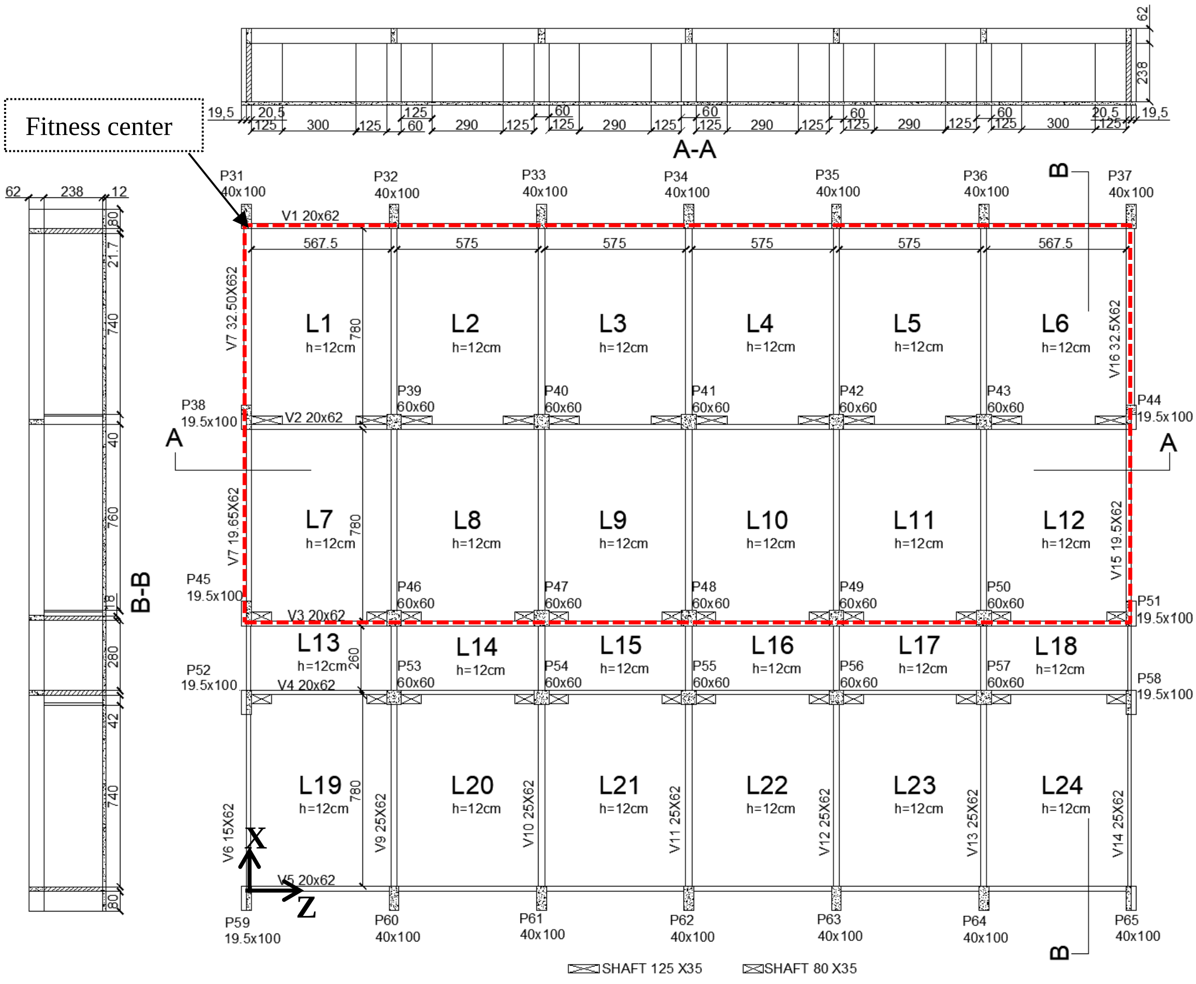
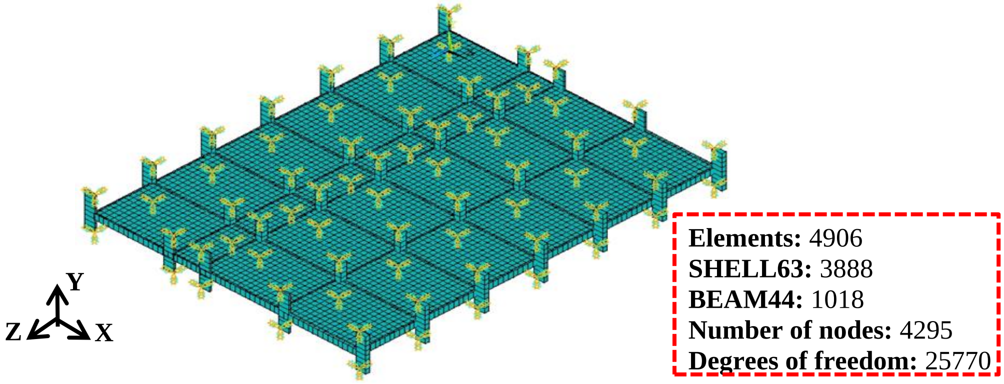


Figure 2. Structural model investigated (units in centimetres)

The numerical modelling of the reinforced concrete floor, composed of concrete slab, beams and pillars was developed through usual mesh refinement techniques present in the Finite Element Method (FEM) simulations and using the software ANSYS [4], as shown in Fig. 3. In the present computational model, the columns and beams were represented by three-dimensional beam elements (BEAM44), while shell elements (SHELL63) were used to describe the concrete slab. It should be emphasized that the material (concrete) works in an elastic-linear regime and the plane sections remain flat after the loading requests (Bernoulli hypothesis).



Elements: 4906
SHELL63: 3888
BEAM44: 1018
Number of nodes: 4295
Degrees of freedom: 25770

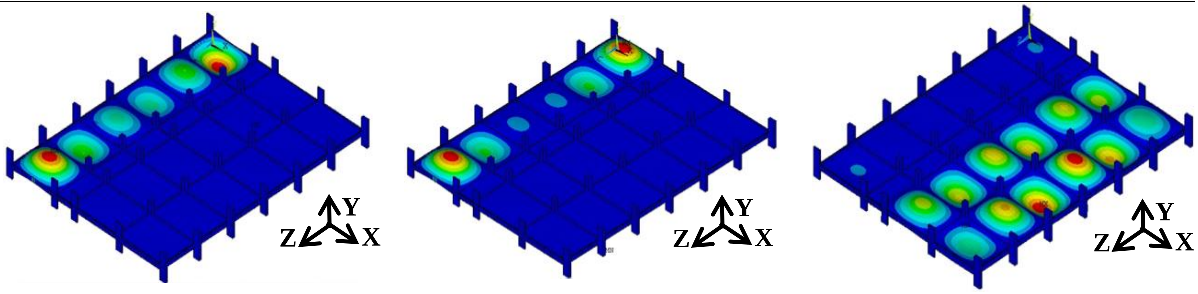
Figure 3. Finite element model

5 Modal analysis

Table 1 presents the first six natural frequencies and their respective dynamic properties of the system: modal mass, modal stiffness and modal damping. Figure 4 presents the first three vibration modes associated with the physical phenomenon (slab flexion). Based on the results relating to a first fundamental frequency of the reinforced concrete floor (f_{01} = 8.12 Hz) it is noteworthy that the value is below that recommended by the standard NBR 6118 [11] (9.6 Hz). In addition, according to SCI [7] and Faisca [5] for activities rhythmic human activities (aerobic gymnastics) the step frequencies related to the third harmonic, range between 4.5 Hz to 8.4 Hz and from 5.66 Hz to 8.57 Hz, respectively. This way, the compatibility between the fundamental frequency with the excitation frequency can cause the incidence of resonance phenomenon, consequently excessive vibrations.

Table 1. Dynamic characteristics of the studied reinforced concrete floor

Frequency (Hz)		Modal mass (kg)	Modal stiffness (N/m)	Modal damping ratios ξ (%)
f_{01}	8.12	9.676	1.26×10^7	1.22%
f_{02}	8.16	8.266	1.09×10^7	1.38%
f_{03}	8.23	21.520	2.87×10^7	1.91%
f_{04}	8.37	15.510	2.15×10^7	2.42%
f_{05}	8.52	12.630	1.81×10^7	2.43%
f_{06}	8.57	9.235	1.34×10^7	2.79%



a) 1° Mode shape (f_{01} = 8.12 Hz) b) 2º Mode shape (f_{02} = 8.16 Hz) c) 3° Mode shape (f_{03} = 8.23 Hz)

Figure 4. Investigated floor vibration modes

6 Forced vibration analysis

In order to investigate the dynamic structural response of the reinforced concrete floor subjected to the application of rhythmic human activities, will be analyses three cases of loading models with 18, 27 and 36 people. LM I (loading model I) refers to loading by 18 people on the L1 and L2 slabs. The LM II (loading model II) refers to loading induced by 27 people on the L1, L2 and L3 slabs. The LM III (loading model III) represents the action of 36 people on the L1, L2, L3 and L4 slabs. It is noteworthy that each loading model was studied independently and the other floor slabs remained free. Thus, it was implemented to the dynamic loading models (Campista [2], Faisca [5], AISC [6] and SCI [7]) an excitation frequency of 2.20 Hz, it is highlighted that it is in the interval 2 to 2.75 Hz which corresponds to the first harmonic frequency range for aerobic activities. Finally, the sections from A to F referring to the centres of each investigated slab were monitored, as shown in Figure 5.

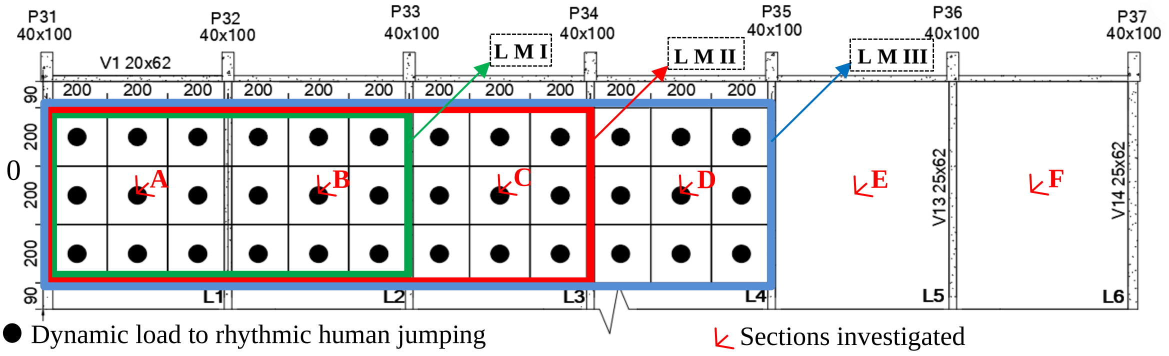


Figure 5. Dynamic loads on the reinforced concrete floor (units in centimetres)

On evaluating the dynamic structural response of the reinforced concrete floor in the sections where the load is applied, it is noted that the results do not show a direct relationship with the number of people (see Fig. 6(a)). On the other hand, when analysing Fig. 6(b) it is emphasized that the unoccupied slabs suffer a lesser influence on the peaks acceleration. However, it is noteworthy the Campista [2] and Faisca [5] models showed peak acceleration results with small differences, while the AISC [6] and SCI [7] models showed higher responses.

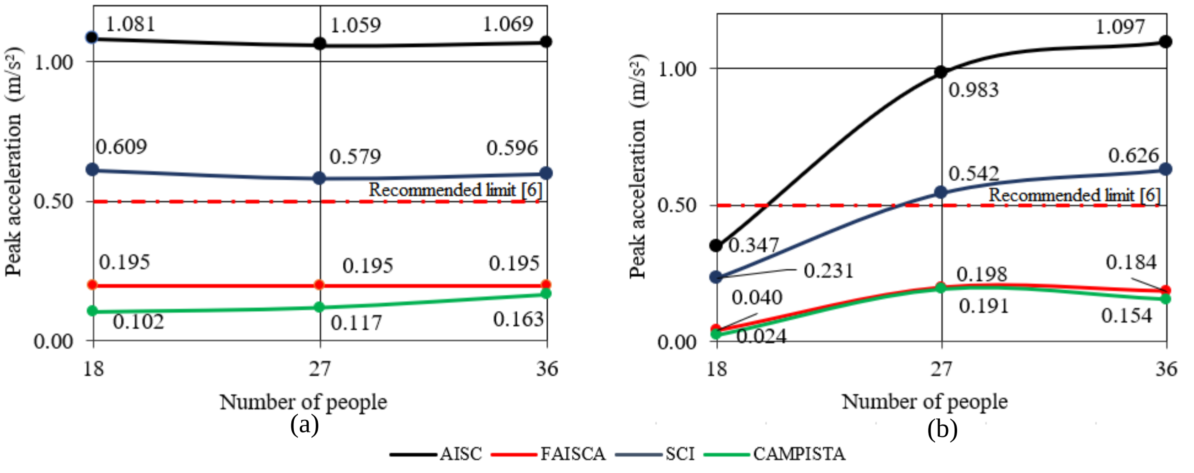


Figure 6. Peak acceleration versus the number of people: (a) structural section A (b) structural section C.

In this sense, Table 2 presents the dynamic responses (a_p: peak acceleration; $a_{w,rms}$: RMS acceleration; VDV: vibration dose values) when different groups perform rhythmic human activities (LM I, LM II and LM III). Based on the peak acceleration tolerance criterion, it is noted that the AISC [6] and SCI [7] models do not meet the design parameters ($a_p \leq 0.5$ m/s²). On the other hand, based on the criteria ($a_{w,rms}$ and VDV) the AISC [6] model presents limits above the acceptable, while the SCI [7] model indicates limits within the allowed. It is important to emphasize that the Biodynamic [2] and Faisca [5] models meet human comfort criteria. This way, the biodynamic [2] model has lower dynamic responses than the other models due to the parameters considered in the biodynamic modelling, such as human damping, which can directly influence the dynamic structural response of the floor. Thus, Fig. 7 presents the results regarding the dynamic response as a function of time and in the frequency domain for the LM III (structural section A).

Table 2. Dynamic structural response: $a_{w,rms}$, a_{peak} and VDV values

	SS	Biodynamic [2]			Faisca [5]			AISC [6]			SCI [7]		
LM I (loading model)		a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV
		m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$
	A	**0.102**	**0.031**	**0.072**	**0.195**	**0.083**	**0.163**	**1.081**	**0.550**	**1.115**	**0.609**	**0.168**	**0.399**
	B	**0.103**	**0.033**	**0.076**	**0.191**	**0.083**	**0.163**	**0.973**	**0.390**	**0.831**	**0.543**	**0.166**	**0.378**
	C	0.024	0.009	0.021	0.040	0.012	0.027	0.347	0.200	0.400	0.231	0.040	0.133
	D	0.008	0.003	0.008	0.012	0.002	0.007	0.130	0.088	0.174	0.082	0.013	0.051
	E	0.010	0.002	0.005	0.004	0.001	0.002	0.070	0.047	0.094	0.034	0.005	0.021
	F	0.004	0.001	0.003	0.002	0.000	0.001	0.035	0.024	0.048	0.017	0.003	0.011
LM II (loading model II)	SS	Biodynamic [2]			Faisca [5]			AISC [6]			SCI [7]		
		a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV
		m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$
	A	**0.117**	**0.037**	**0.084**	**0.195**	**0.085**	**0.166**	**1.059**	**0.424**	**0.878**	**0.579**	**0.154**	**0.369**
	B	**0.103**	**0.033**	**0.075**	**0.175**	**0.073**	**0.144**	**1.071**	**0.500**	**0.999**	**0.620**	**0.135**	**0.374**
	C	**0.191**	**0.045**	**0.104**	**0.198**	**0.087**	**0.171**	**0.983**	**0.384**	**0.829**	**0.542**	**0.156**	**0.359**
	D	0.036	0.013	0.029	0.038	0.012	0.026	0.313	0.174	0.347	0.225	0.034	0.118
	E	0.014	0.006	0.012	0.012	0.002	0.006	0.135	0.094	0.186	0.084	0.013	0.050
	F	0.007	0.003	0.006	0.005	0.001	0.003	0.069	0.051	0.101	0.040	0.007	0.025
LM III (loading model III)	SS	Biodynamic [2]			Faisca [5]			AISC [6]			SCI [7]		
		a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV
		m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$
	A	**0.163**	**0.045**	**0.104**	**0.195**	**0.084**	**0.165**	**1.069**	**0.446**	**0.931**	**0.596**	**0.143**	**0.354**
	B	**0.195**	**0.053**	**0.121**	**0.175**	**0.074**	**0.147**	**1.058**	**0.411**	**0.820**	**0.597**	**0.130**	**0.360**
	C	**0.154**	**0.042**	**0.097**	**0.184**	**0.078**	**0.153**	**1.097**	**0.452**	**0.911**	**0.626**	**0.133**	**0.367**
	D	**0.150**	**0.042**	**0.098**	**0.185**	**0.082**	**0.161**	**0.932**	**0.368**	**0.796**	**0.545**	**0.136**	**0.321**
	E	0.033	0.012	0.027	0.037	0.011	0.025	0.327	0.197	0.394	0.228	0.034	0.124
	F	0.015	0.005	0.012	0.014	0.002	0.007	0.150	0.112	0.221	0.103	0.016	0.064
Tolerance peak acceleration: 0.5 m/s^2													
Limits: $a_{w,rms}<0.35$ m/s^2 SCI [7]; VDV<0.50 $m/s^{1,75}$ Setareh [12] and VDV<0.66 $m/s^{1,75}$ Ellis & Littler [13];													

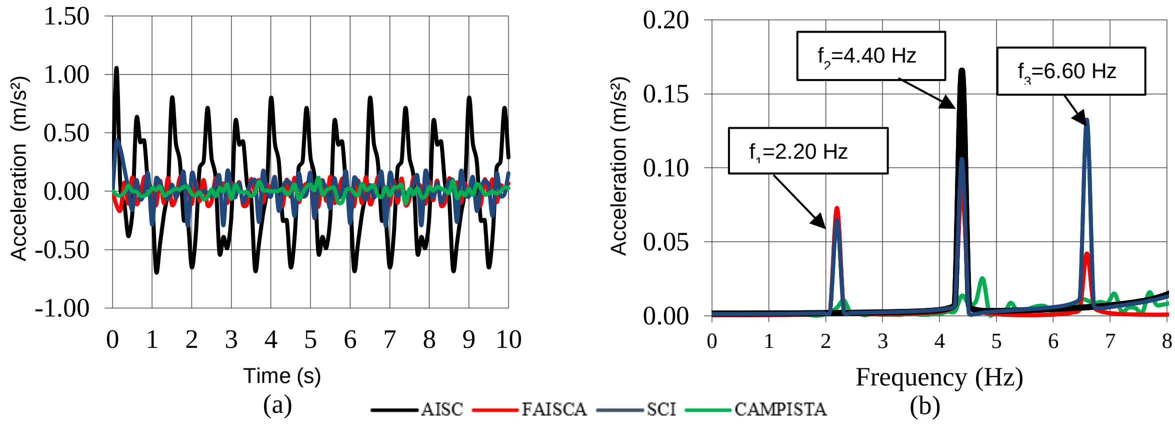


Figure 7. Floor acceleration: time and frequency domain (LM III: Structural Section A)

7 Conclusions

According to the results obtained in the numerical modelling regarding the monitoring the dynamic structural behaviour of a reinforced concrete floor, it is clear that further investigations a series of experimental tests on real structures need to be carried out in order to identify the most adequate dynamic load model with reality. This way, one may conclude that:

1. Considering the first fundamental frequency of the reinforced concrete floor (f_{01} = 8.12 Hz) is noteworthy that the value is below that recommended by the standard NBR 6118 [11] (f_{min} = 9.6 Hz). Thus, excessive vibrations can be perceived by users.
2. The mathematical model developed by Campista [2] includes the people-structure dynamic interaction effect, and the biodynamic modelling considers the human damping, which can directly influence the structural response. This way, the floor dynamic response determined based on the use of Campista model [2] presented lower values when compared to the traditional “only-force” models.
3. The floor dynamic response calculated using AISC [6] and SCI [7] design guides surpass the recommended limits, and do not attend the human comfort criteria. The peak accelerations are equal to 1.097 m/s² [LM III: Section C] and 0.626 m/s² [LM III: Section C], respectively, while the Campista [2] and Faisca [5] models present results with acceptable limits in all investigated cases. On the other hand, based on the criteria ($a_{w,rms}$ and VDV) the AISC [6] model presents limits above the acceptable, while the SCI [7] model indicates limits within the allowed.

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