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Modelling of biodynamic systems using artificial neural networks for evaluation of reinforced concrete floors dynamic structural behaviour when subjected to human rhythmic activities

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Abstract. The current trends in structural design pointed out for the use of more efficient building floors solutions, characterized by a good structural response combined with lightness, slenderness, flexibility, and economy, when compared to conventional approaches. The development of structural systems with these characteristics frequently results in floors with low damping ratios and natural frequencies values close to those associated with human activities, such as walking, running, jumping, and dancing, inducing resonance, excessive vibration problems, and human discomfort. This way, in this study, biodynamic models are utilised to represent the effects of rhythmic human actions, specifically jumps performed in aerobics classes, on reinforced concrete building floors. To do this, Artificial Neural Networks (ANNs) were developed to generate biodynamic models associated with single degree of freedom (SDOF) mass-spring-damper systems. Based on these models, it becomes possible to evaluate the dynamic structural response of building floors when subjected to rhythmic jumping. The proposed analysis methodology aims to demonstrate that the models developed from ANNs are capable of considering the dynamic contributions that individuals exert on building floors structures, standing out as a viable and more realistic alternative in comparison with the traditional mathematical models of dynamic loading (only force models).

Keywords: Reinforced Concrete Floors, Dynamic Structural Behaviour, Human Comfort Assessment.

1 Introduction

Modern structural designs favour efficient building floor systems, characterized by lightness, slenderness, and flexibility. While economically and aesthetically beneficial, these characteristics often result in low damping ratios and natural frequencies that can approach frequencies induced by rhythmic human activities, leading to resonance phenomena, excessive vibration, and occupant discomfort. Therefore, the evaluation of the dynamic behaviour of floors subjected to human-induced loading is of paramount importance.

Traditional mathematical models of dynamic loading (only force models) may not realistically represent the complex interaction between the individual and the structure. Recent studies [1-5] have demonstrated that the presence of individuals can significantly modify structural dynamic behaviour, altering characteristics such as damping and natural frequency. Considering the human as a biodynamic system, becomes essential for a more precise analysis.

This study utilises biodynamic models to represent the effects of rhythmic human actions, with a specific focus on jumps performed during aerobics classes, on reinforced concrete floors. The main objective is to develop and apply Artificial Neural Networks (ANNs) to generate the key parameters (maximum positive and negative peak amplitudes) required for constructing the force used in biodynamic models associated with SDOF. The developed methodology aims to demonstrate that the force constructed using ANN-generated parameters is capable of representing the experimental force typically used in biodynamic models. These systems, which considers the dynamic contributions of individuals exerted on the floor structures, offers a more viable and realistic alternative compared to traditional dynamic loading models that employ only force models.

2 Biodynamic systems and artificial neural networks

Biodynamic modelling offers a more realistic representation of human beings in structural analysis by considering human-structure interaction, where the individual's dynamic characteristics influence the structure's behaviour. The biodynamic system used, which aligns with those proposed by Sousa [2] and Campista [4], is a single degree of freedom (SDOF) mass-spring-damper system. This system is defined by the individual's mass (m_i), damping (c_i), and stiffness (k_i). In this model, the system is subjected to acceleration (a_i (t)), velocity (v_i (t)), and displacement (x_i (t)) in the time domain, while the force (F_i (t)) is directly applied to the structural system.

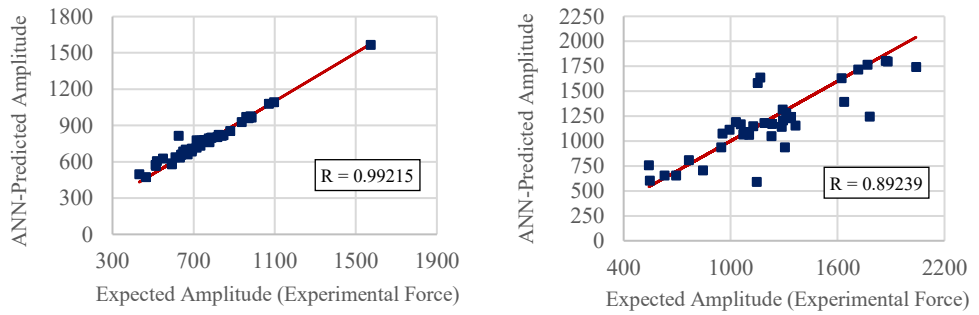
This study presents the initial stage of a broader methodology under development, which ultimately aims to determine all biodynamic model parameters using ANNs and MATLAB [6] software. As a first step, this paper focuses on employing ANNs and MATLAB [6] to construct the dynamic force in the time domain associated with rhythmic human jumping activity, thereby aiming to replace the reliance on direct experimental force measurements. The ANNs were developed to determine only two key values: the maximum positive and negative peak amplitudes, which were fixed for all respective peaks, assuming no amplitude variation for simplification. Subsequently, the full force time history was generated in MATLAB [6] by constructing a modified sinusoidal wave incorporating these distinct peak amplitudes and other characteristics, detailed in this study.

For the development of the ANNs, it was necessary to present data where the behaviour of the investigated activity is known. To achieve this, experimental data from Sousa [2] on rhythmic jumping tests (at 2.0 Hz) performed by different individuals on a platform were used for training (70%), validation (15%), and testing (15%).

The ANNs were implemented entirely via programming in MATLAB [6]. This approach, unlike simplified graphical interfaces such as MATLAB's nnstart application, allowed for detailed control over all aspects of the network's architecture. This direct coding optimised flexibility in experimenting with different configurations and ensured the reproducibility of the model, facilitating fine adjustments.

The developed networks comprise 3 input neurons for individual's characteristics (mass, damping, stiffness) and 2 output neurons for the maximum positive and negative peak amplitudes. After training approximately 50 networks, varying hidden layer neurons, hidden layer numbers, data normalisation techniques, learning rates, and batch sizes, a highly precise network (i.e., outputs closest to expected values) was identified. This optimal configuration consisted of 1 hidden layer with 6 neurons, utilising the Levenberg-Marquardt training algorithm.

Specifically, ANNs 1 and 2 were selected for predicting the maximum positive and negative peak amplitudes, respectively. The correlation coefficient is employed to analyse network performance, as illustrated in Fig 1.



(a) Positive peak amplitude (ANN 1) (b) Negative peak amplitude (ANN 2)

Figure 1. Correlation Coefficients of the Artificial Neural Networks

ANN 1 demonstrated exceptional performance in predicting the maximum positive peak amplitude, with a strong linear correlation (R = 0.99215), indicating almost perfect precision between predicted and experimental values. Similarly, ANN 2 effectively predicted the maximum negative peak amplitude, showing a strong positive correlation (R = 0.89239). While this value is slightly lower than for ANN 1, it is still considered very good, particularly given the greater variability observed in the negative peak data. Nevertheless, the results remain technically robust for predicting this characteristic.

3 Investigated structural model and finite element modelling

The investigated structural model corresponds to a real reinforced concrete floor with dimensions of 16 m by 35 m, and area of 560 m². The structural system under consists of a fitness centre situated on the eighth floor of the State University of Rio de Janeiro (UERJ). It comprises twelve concrete slab panels, each with a thickness of 12 cm, as detailed in Fig. 2. The concrete has an elastic modulus of 17.6 GPa and a compressive strength of 13.7 MPa. The numerical modelling of the floor, illustrated in Fig. 3, was developed using the finite element software ANSYS [7]. The three-dimensional beam element BEAM44 was used to represent the beams and columns, whilst the SHELL63 shell element was adopted for the slabs. The floor's behaviour was considered under linear-elastic conditions, assuming that cross-sections remain plane after deformation, in accordance with Bernoulli's theorem.

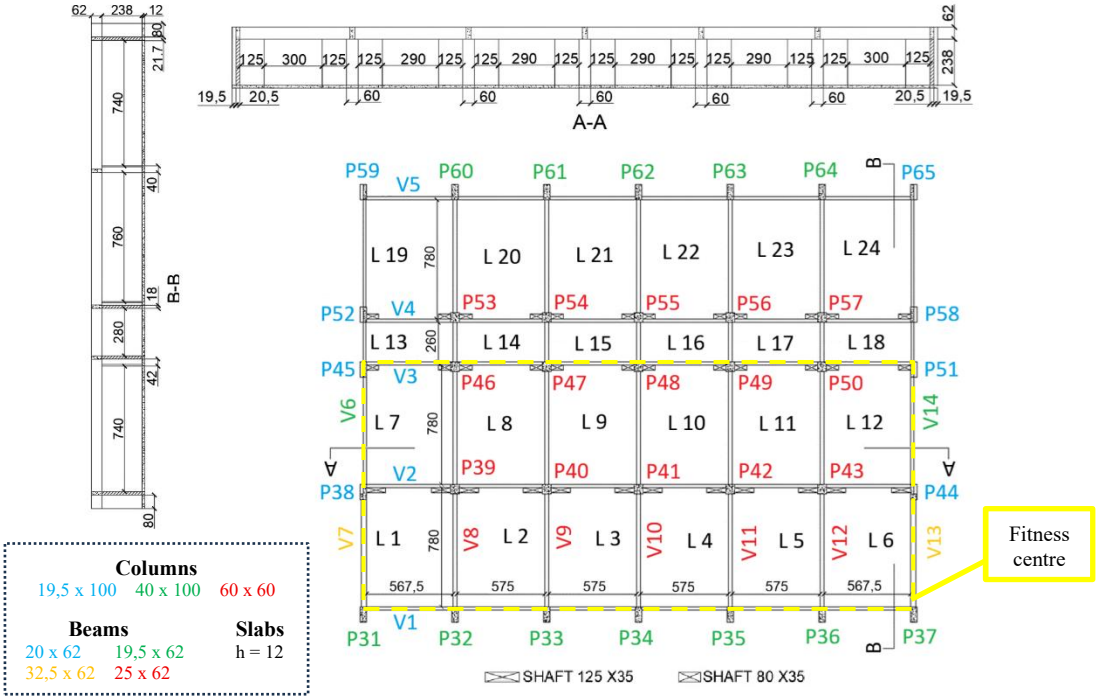


Figure 2. Investigated structural model (units in centimetres)

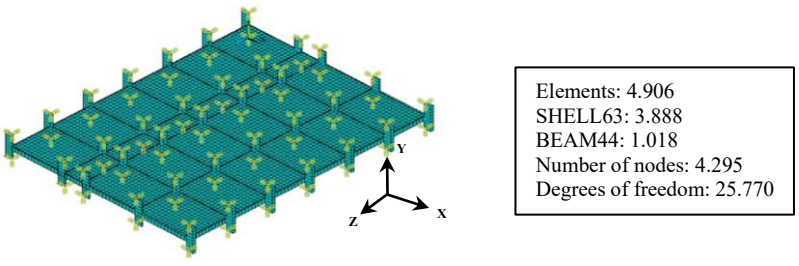


Figure 3. Finite element model

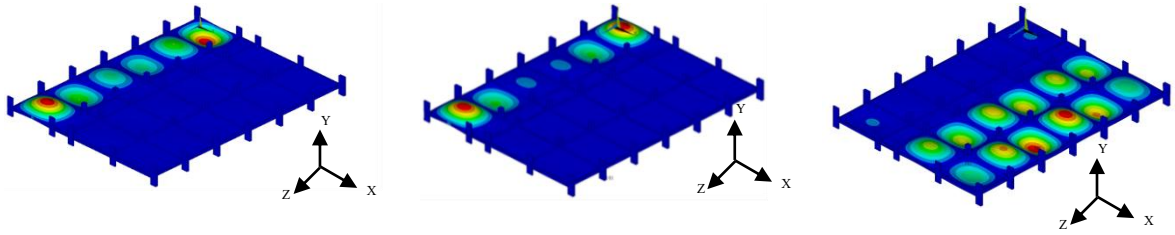
4 Modal analysis

The modal analysis, performed using ANSYS [7] software, provided essential data regarding the dynamic characteristics of the reinforced concrete floor. Table 1 details the natural frequencies (eigenvalues) and the main dynamic properties of the structural system, such as modal mass, modal damping, and modal stiffness. Figure 4 illustrates the first three vibration modes (eigenvectors). From the modal parameters in Tab. 1, the floor's fundamental natural frequency (f_{01} =7.89 Hz) is notably below the 9.6 Hz recommended by NBR 6118 [8].

Furthermore, this frequency lies within the range of excitation frequencies corresponding to the third harmonic for rhythmic aerobics activities [9, 10]. This proximity significantly increases the structure's susceptibility to resonance, which can lead to excessive vibration and human discomfort.

Table 1. Dynamic characteristics of the studied floor

Frequency (Hz)		Modal mass (kg)	Modal stiffness (N/m)	Modal damping (Ns/m)
f_{01}	7.89	$4{,}72 \times 10^3$	$1{,}16 \times 10^7$	$1{,}95 \times 10^4$
f_{02}	7.90	$4{,}35 \times 10^3$	$1{,}07 \times 10^7$	$1{,}80 \times 10^4$
f_{03}	8.02	$1{,}15 \times 10^4$	$2{,}92 \times 10^7$	$1{,}71 \times 10^4$
f_{04}	8.12	$1{,}57 \times 10^4$	$4{,}08 \times 10^7$	$6{,}61 \times 10^4$
f_{05}	8.14	$1{,}54 \times 10^4$	$4{,}03 \times 10^7$	$6{,}51 \times 10^4$



(a) 1° Mode shape (f_{01} = 7.89 Hz) (b) 2º Mode shape (f_{02} = 7.90 Hz) (c) 3° Mode shape (f_{03} = 8.02 Hz)

Figure 4. Investigated floor vibration modes

5 Forced vibration analysis

Forced vibration analyses were performed, considering rhythmic human activities induced by 18 equal individuals, as illustrated in Fig. 5. The biodynamic models employed mass (m=88.250 kg), stiffness (k=848.173 N/m) and damping (c=44353.265 Ns/m) parameters, all corresponding to individual number 5 from the Sousa [2] tests. Additionally, acceleration, velocity and displacement variables from the same individual 5, extracted from these mentioned tests, were utilised. This modelling strategy, which assumes identical individuals, was adopted with the primary objective of validating the performance of the ANN-generated force by comparing it against a single experimental force under controlled conditions. This approach eliminates the natural variability of human biodynamic characteristics, allowing for a clear, direct assessment of the model's predictive capability and its accuracy in representing the experimental data. Future work will extend this analysis to a more realistic scenario, considering the variability of biodynamic parameters in a diverse crowd. Two models were developed: one with the experimental force from individual 5 (model BD-1) and another with forces generated by Artificial Neural Networks (model BD-2). The objective of the analysis was to verify whether the created dynamic force would accurately represent the experimental force associated with rhythmic human jumping activity, which is necessary for the utilisation of the biodynamic model.

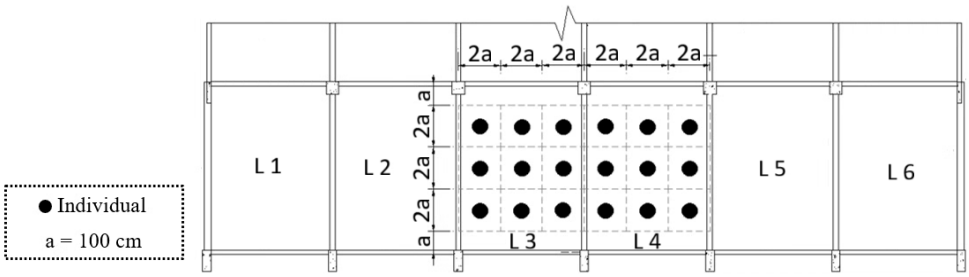


Figure 5. Distribution of the 18 individuals on the floor during rhythmic activity simulation

Results were compared using the following the dynamic response parameters: peak accelerations (a_p), average accelerations (a_m), RMS accelerations (a_{RMS}), maximum absolute displacements ($d_{máx\ ABS}$), average displacements (d_m), RMS displacements (d_{RMS}) and vibration dose values (VDV). These were calculated at the structural section of the floor with the largest reading range of slab 3.

After determining the amplitudes via the ANNs, the optimal frequency (2.01 Hz) that best approximated the experimental force was identified by comparing the range 1.99–2.02 Hz. Subsequent analyses revealed that including harmonic distortion in the generated forces produced dynamic results closer to those obtained with the experimental force. A parametric analysis of the initial phase angle (0°, 90°, 180°, and 360°) indicated that 270° resulted in the highest accuracy.

Based on preliminary tests, the forces generated for the biodynamic model were constructed in MATLAB [6] from a modified sinusoidal wave, with a fundamental frequency of 2.01 Hz and an initial phase angle of 270°. This base wave incorporates distinct amplitudes for its positive and negative peaks, determined by the ANNs, to better represent the asymmetry of the experimental force. Harmonic distortion was then added through the superposition of sinusoidal waves whose frequencies are integer multiples of the fundamental frequency, further altering the main waveform. This superposition, with specific amplitudes and phases defined in MATLAB [6] for each harmonic, allows for the representation of double peaks and other irregularities observed in the experimental force, resulting in a more accurate representation of rhythmic human action.

To more accurately represent results obtained using the experimental force, forces with distinct harmonic distortions were generated. After calculating the fundamental component (f=2.01 Hz), harmonic distortion was added by superimposing sinusoidal waves at integer multiples of the fundamental frequency. As clearly observed in Figures 6 and 7 and Tables 2 and 3, testing various combinations (Analyses 1-4, including 2nd, 3rd, 4th, and 5th harmonics) revealed that the 3rd and 5th harmonics (Analysis 4) produced dynamic results (accelerations and displacements) closest to those from the experimental force (Model BD-1). Detailed comparisons of these forces and their dynamic responses for Model BD-1 and the Model BD-2 (2.01 Hz, 270°, with 3rd and 5th harmonic distortion) are presented in Figures 8 to 10.

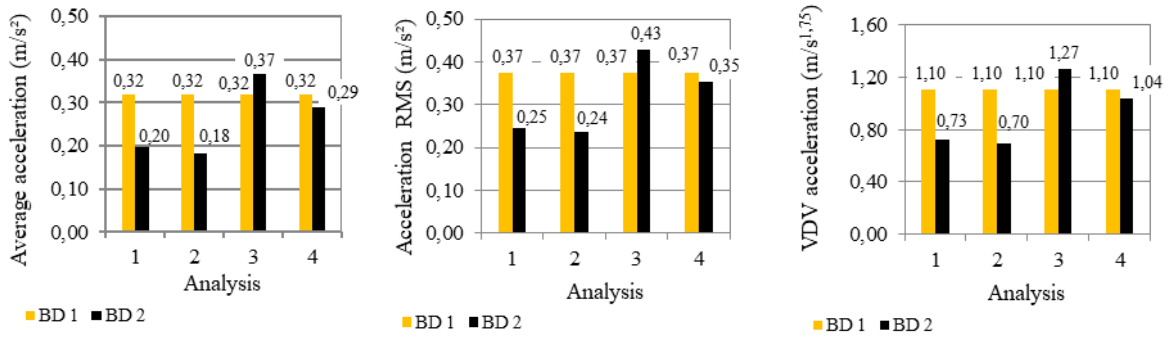


Figure 6. Dynamic response parameters (acceleration)

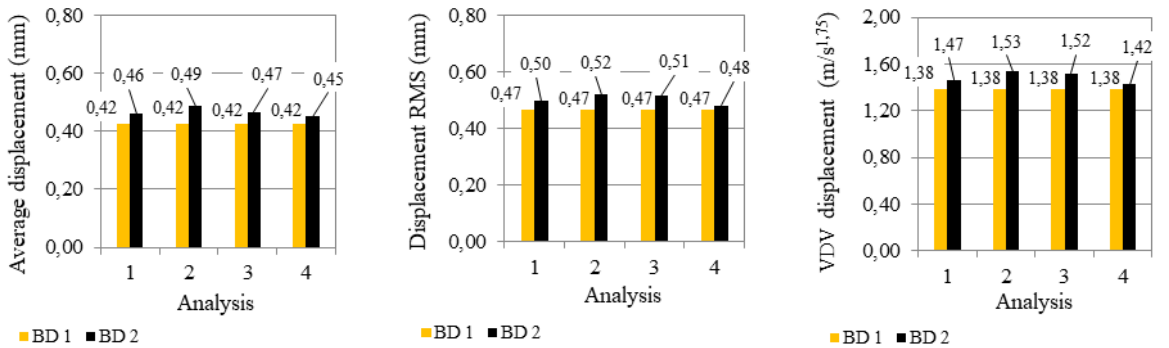


Figure 7. Dynamic response parameters (displacement)

Table 2. Dynamic response parameters (model BD-1)

a_p (m/s²)	a_m (m/s²)	a_{RMS} (m/s²)	VDV (m/s^{1,75})	$d_{max\ ABS}$ (mm)	d_m (mm)	d_{RMS} (mm)	VDV (m/s^{1,75})
0.81	0.32	0.37	1.10	0.84	0.42	0.47	1.38

Table 3. Dynamic response parameters (model BD-2)

Analysis	Harmonic distortion	a_p (m/s²)	a_m (m/s²)	a_{RMS} (m/s²)	VDV (m/s^{1,75})	$d_{max\ ABS}$ (mm)	d_m (mm)	d_{RMS} (mm)	VDV (m/s^{1,75})
1	2 e 3	0.47	0.20	0.25	0.73	0.79	0.46	0.50	1.47
2	3	0.38	0.18	0.24	0.70	0.72	0.49	0.52	1.53
3	3 e 4	0.87	0.37	0.43	1.27	0.83	0.47	0.51	1.52
4	3 e 5	0.72	0.29	0.35	1.04	0.70	0.45	0.48	1.42

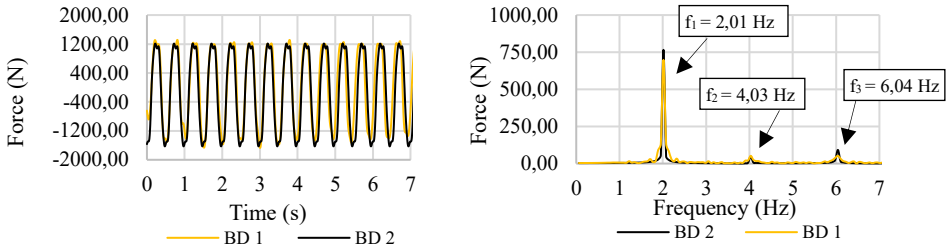


Figure 8. Force

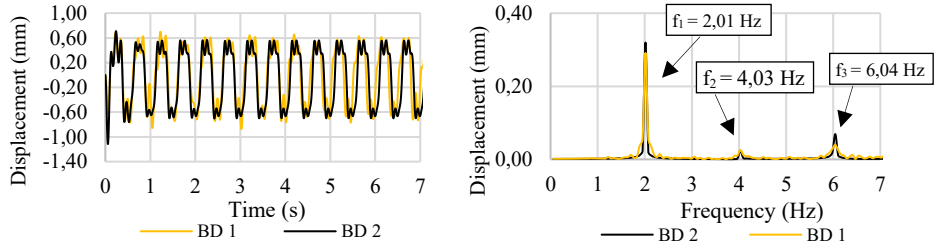


Figure 9. Dynamic response (displacement)

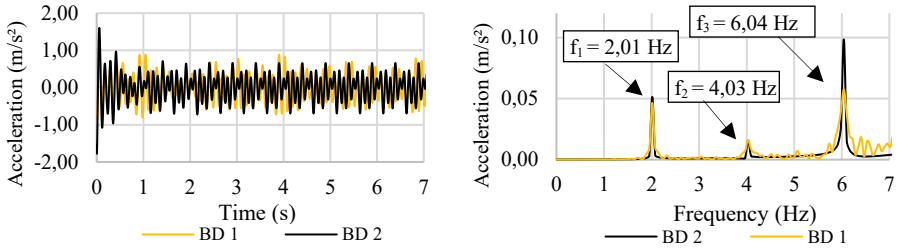


Figure 10. Dynamic response (acceleration)

6 Conclusions

This study investigated the development of an ANN-based methodology to generate key parameters for constructing dynamic forces for SDOF biodynamic models, specifically for rhythmic human jumping, aiming to overcome the reliance on extensive experimental data. The main findings and their implications are summarised below:

1. The ANNs demonstrated high predictive capability for maximum positive (R = 0.99215) and negative (R

= 0.89239) peak amplitudes, validating the feasibility of using artificial intelligence to assist in the representation of complex dynamic loads.

2. Modal analysis indicated that the investigated floor is prone to excessive vibration and human discomfort. Forced vibration analysis, conducted using a simplified model with identical individuals, showed that the force constructed using parameters generated by the ANN, with a fundamental frequency of 2.01 Hz, an initial phase angle of 270°, and the addition of harmonic distortion (specifically with the 3rd and 5th harmonics in Analysis 4), produced dynamic responses (accelerations and displacements) that were very close to those obtained with the experimental force. This crucial result validates the ANN approach for generating forces for biodynamic models, which more realistically represent the dynamic action of rhythmic jumps compared to traditional models (force-only models) [9, 11, 12].

3. This study demonstrates the effectiveness of ANNs in generating parameters that enabled the creation of the force employed in biodynamic models. By generating dynamic forces through ANNs, this approach offers engineers a rapid, cost-effective tool for design analysis, reducing the need for extensive experimental testing. The biodynamic models are a more robust and precise tool for ensuring human comfort, preventing excessive building vibrations, and avoiding overly conservative or uneconomical designs.

4. The consideration of harmonic distortion brought the result generated by the created force closer to the result obtained when using the experimental force, especially when compared to forces created without harmonic distortion. However, challenges remain for future studies, which will focus on a more in-depth parametric analysis of the components used to create these harmonic distortions and on extending the analysis to more realistic groups of individuals, thereby further bridging the gap between research and practical design application.

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