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SOFTVER ZA PRORAČUN VIBRACIJA MEĐUSPRATNIH KONSTRUKCIJA USLED DINAMIČKE SILE PEŠAKA

Rezime:

Trendovi u savremenoj arhitekturi, koji diktiraju projektovanje komercijalnih i stambenih zgrada sa otvorenim prostorom, prouzrokovali su problem prekomernih vibracija međuspratnih konstrukcija velikih raspona usled aktivnosti ljudi koji se po njima kreću. Saniranje prekomernih vibracija već izgrađenih konstrukcija je skupo i vremenski zahtevno. Zbog toga je najefikasnije i najekonomičnije ovaj problem eliminisati već u fazi projektovanja. U radu je predstavljen softver za procenu vibracija međuspratnih konstrukcija izazvanih pešačkim opterećenjem, jednostavnog grafičkog okruženja i pogodan za svakodnevnu upotrebu u projektovanju.

Ključne reči: vibracije, međuspratna konstrukcija, dinamička sila pešaka

SOFTWARE FOR CALCULATION OF PEDESTRIAN-INDUCED VIBRATION OF FLOORS

Summary:

Trends in contemporary architecture towards open-plan spaces in commercial and residential buildings have created problems with excessive vibrations of large-span floors induced by active people. Solving vibration serviceability problems of as-built structures is costly and time-consuming. Therefore, such a problem is the most efficiently and economically addressed at the design stage. This paper presents software developed by the authors for assessing pedestrian-induced vibrations of floors. The software is designed as a user-friendly graphical interface that could be utilised in everyday design practice.

Key words: vibration, floor, serviceability, pedestrian-induced load

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1. INTRODUCTION

Development of modern, high-strength materials has supported trends in contemporary architecture toward open-plan spaces in commercial and residential buildings. Engineers have been enabled to design long-span and lightweight floors with a tendency towards lower natural frequencies and reduced effective damping. Therefore, floors have become more dynamically responsive, and vibration serviceability (VS) issues have become more prominent [1, 2].

When people walk, they induce dynamic forces that cause structural vibrations. These vibrations are small and rarely cause structural damage. However, excessive vibrations can cause human discomfort and malfunction of vibration-sensitive equipment [3]. Solving VS problems of as-built structures is costly and time-consuming. Only significant changes in structural mass, stiffness or damping can produce a noticeable reduction in vibration. Therefore, such a problem is the most efficiently and economically addressed at the design stage.

Early vibration design criteria were formulated to limit the floor's fundamental frequency or self-weight deflection to prevent excessive vibration. SCI P076 [4], published in 1989, was the first widely recognised design guideline pertinent to the vibration of floors based on the performance-based assessment approach. It described the calculation procedure for predicting the floor vibration response that could arise from a pedestrian walking. In addition, it made an essential distinction between the floors prone to resonant vibrations due to footfall excitation (*low-frequency floors* – LFF) and those whose response is a series of transients due to each footfall (*high-frequency floors* - HFF). Until recently, for floor VS, Eurocode [5] have been providing recommendations for limiting the fundamental frequency of floors. It referred to ISO 10137 [6], which contains only general criteria for vibration perception. To complement the Eurocode in providing a simplified procedure for determining and verifying floor design due to human-induced vibrations, Hivoss guideline [7] was published. It defines the vibration classes depending on floor purpose. Based on the floor's fundamental frequency, modal mass and damping ratio, one can evaluate if the floor can satisfy a defined class. Guidelines popular in the USA(AISC [8]) and the UK(SCI P354 [9]) provide simplified equations for calculating peak or r.m.s. (*root-mean-square*) acceleration values due to walking excitation for both LFFs and HFFs. However, they are mainly focused on steel-concrete composite floors.

The calculation of the human-induced vibration is complicated, even with the floor's most straightforward geometry and material. Floors with complex shapes and those made of non-conventional building materials emphasise the need for a reliable predictive tool to evaluate their vibration performance. Arup's methodology [10], based on the basic principle of structural dynamics, applies to any structure without limits regarding the floor complexity and material. Pavic et al. presented the software VSATs [11] with several procedures for assessing the VS of floors. However, this software was developed in-house and is not made available to the public.

The lack of commercially available software for VS assessment of floor structures that would enable a designer to carry out complex and lengthy hand calculations in a fraction of a second is the key motivation behind the research described in this paper. This paper presents *Hindu,* a prototype of such software that has been developed by the authors for research purposes so far. The *Hindu* is designed as a user-friendly graphical interface (GUI) that provides quick dynamic response calculation and effective visualisation of calculated responses. Thus, it has a great potential to simplify design and make it more user-friendly and reliable.

2. BASIC PRINCIPLES IN ESTIMATING VIBRATION LEVELS

This Section aims to present the fundamental principles and terminology used in VS assessment applied in *Hindu*. According to ISO 10137 [4], every VS problem can be rationalised into vibration *source*, vibration *path*, and vibration *receiver*. Following that framework, the Section is organised to review these three components regarding pedestrian-induced vibration of floors.

2.1. PEDESTRIAN-INDUCED FORCE AS VIBRATION SOURCE

Floors are constantly subjected to excitation induced by human activity. Extensive studies [12] showed that many factors, such as pedestrian height, gender, weight, and walking speed, contribute to the variability of induced dynamic load. Additionally, two types of floor response require different load models: one for resonant response (LFFs) and the other for transient response (HFFs). When assessing the vibration response of LFF, the walking force F_p is assumed to be a perfectly periodic function, represented by a Fourier series:

$$F_p(t) = G + \sum_{h=1}^{N} \alpha_h G \sin(2\pi h f_p t - \varphi_h) \tag{1}$$

where:
G is the pedestrian weight;
α_h is the Fourier's coefficient, or dynamic load factor (DLF) of the h^{th} walking harmonic;
f_p is the walking frequency;
φ_h is the phase shift of the h^{th} walking harmonic;
N is the total number of contributing harmonics.

Force models proposed by various authors [10, 13-15] differ according to the parameters used in Eq. (1), most commonly in the N and DLF values.

Response of the HFFs is dominated by the impulsive, transient response. In that case, it is appropriate to model a dynamic load as a series of impulses representing each footstep [10, 15].

2.2. FLOOR AS VIBRATION PATH

The floor structure itself is a medium for transmitting vibrations from the source to the receiver. The floor's modal characteristics: natural frequencies, mode shapes, modal masses, and damping define the vibration path. Guidelines usually offer simplified expressions for calculating the floor's modal characteristics. These expressions are limited to floors with simple geometry and boundary conditions. For reliable response estimation, it is necessary to determine floor modal properties as accurately as possible. Nowadays, the Finite element method (FEM) is the most commonly used. Using FEM, natural frequencies, modal masses and mode shapes can be determined. However, damping cannot be calculated numerically. It is usually adopted according to experimental testing (if possible), experience or recommendations.

2.3. VIBRATION RECEIVER

Applying multi-modal analysis, the floor's vibration response is calculated based on the calculated modal properties, assumed damping and a given pedestrian force model. Once the response is calculated, the appropriate vibration criteria for the floor's serviceability should be specified depending on the vibration receiver.

ISO 10137 [6] distinguishes three types of receivers: human occupants, building contents and building structures. Excessive vibration can cause minor damage to structural and non-structural elements if the receiver is the building structure. If the building contents are the receiver, the criteria include a vibration level that assures the sensitive equipment's functioning. Finally, if humans are the receiver, their comfort, life quality, and working efficiency can be reduced.

The acceptable vibration level for people depends on their environment and activity [6]. In BS 6472:1992 guide [16], base curves representing vibration magnitudes for approximately equal human responses in different environments were defined. The vibration level above the base curve increases the probability of adverse comments. The complaints are uncommon if the vibration magnitude is below the base curve.

3. SOFTWARE DEVELOPMENT

Hindu is a Python-based [17] GUI-based software developed by authors for vibration response calculation of floors. Previously developed solver [18] for calculating vibration response based on modal superposition method was upgraded to include pre-and post-processing modules. Fundamental methods incorporated into the software are presented in the first part of this Section (3.1). After that, GUI and its use are illustrated (Section 3.2). It is important to highlight that *Hindu* is fully functional software but still in the developing stage. The main idea is to make the software and GUI expandable and incorporate more features in the future.

3.1. CALCULATION OF VIBRATION RESPONSE

Response calculation process using *Hindu* software consists of several steps, following the framework explained in Section 2. The first step is to define the vibration path. As *Hindu* does not calculate the modal characteristics of the floor, they are imported from the FEM-based software. When the floor's characteristics are loaded, the next step is to define the dynamic force: the user can choose between several so far implemented force models. The user can set the walking path for moving dynamic force, simulating the pedestrian walking. After the receiver point is defined, the vibration response can be finally calculated. The response calculation procedure is based on the modal superposition method [19]. Therefore, it does not contain limitations regarding floor complexity or material. So far, *Hindu* cannot estimate the serviceability of the floor. According to the calculated response and the target vibration level, the user should determine if the floor satisfies the vibration criteria (e.g. proposed in [16]).

3.2. HINDU GRAPHICAL USER INTERFACE

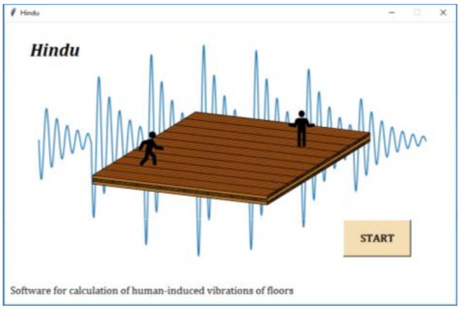
To make *Hindu* user-friendly, a GUI has been developed by using Python's package Tkinter as an application. Running the software opens the start window presented in Figure 1. The *start* button opens the main window (Figure 2).

3.2.1. Main window

Five critical sections of the main window are defined (Figure 2).

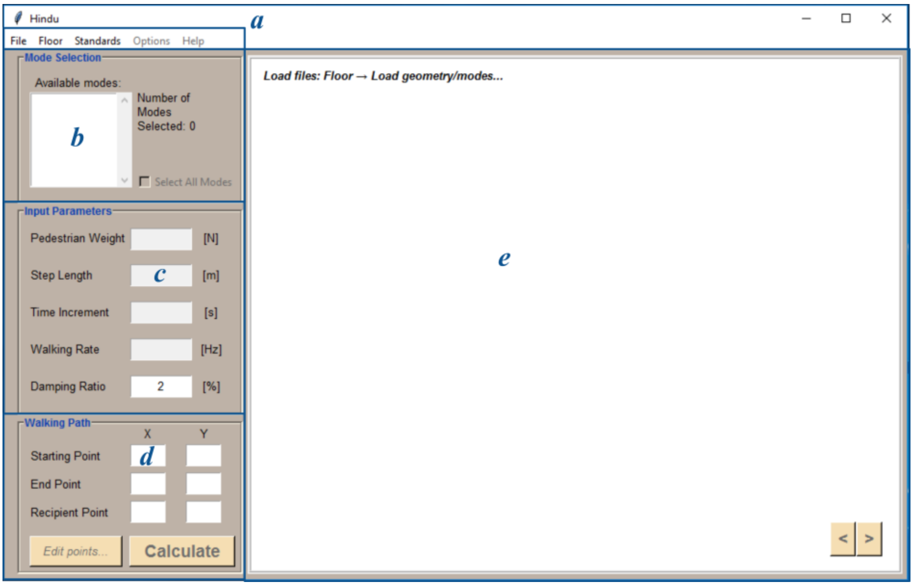
The *Menu bar* contains five tabs: File, Floor, Standards, Options and Help (Figure 2a). The tabs were designed to facilitate typical dynamic response analysis in *Hindu*.

The *Mode selection* section (Figure 2b) allows users to select modes to be included in the modal superposition-based dynamic response analysis.



Software for calculation of human-induced vibrations of floors

Figure 1 – Hindu software start window



Number of Modes Selected: 0

Damping Ratio 2 [%]

Load files: Floor → Load geometry/modes...

Figure 2 – Hindu software main window and its components: a-Menu bar, b-Mode Selection, c-Input Parameters, d-Walking Path, e-Canvas

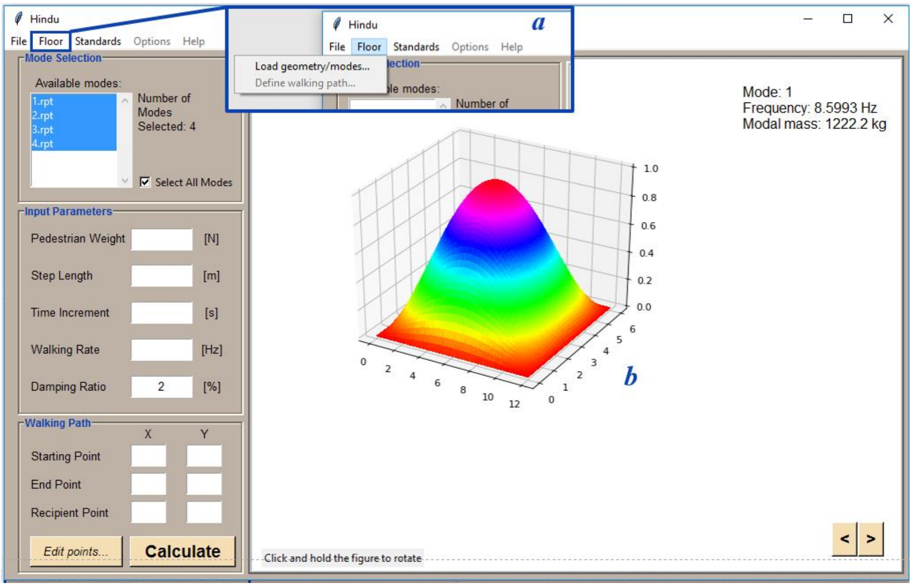
Before performing the analysis, several parameters should be defined in the *Input Parameters* section (Figure 2c). Dynamic load represented by the pedestrian weight, step length and walking frequency, as well as the damping ratio and time increment, are input parameters required to solve the SDOF equation of motion for each mode.

In the *Walking Path* section (Figure 2d), the user can define the walking path as a straight line by choosing the start and endpoint. Afterwards, the user can select the receiver point.

Most of the main window is occupied by *Canvas* (Figure 2e), which displays and visualises the loaded floor's modal characteristics and results of the performed modal analysis.

3.2.2. Load FEM model

The *Floor* tab contains two options (Figure 3a): *Load geometry/modes* and *Define walking path*. Users can insert modal characteristics calculated in the FEM software by clicking the *Load geometry/modes*. So far, *Hindu* enables the user to import modal characteristics of the analysed floor from Abaqus CAE [20]. When modal characteristics are loaded, they are graphically presented in *Canvas* (Figure 3b), and available modes are listed in section *Mode Selection*.



Number of Modes Selected: 4

Damping Ratio 2 [%]

Mode: 1
Frequency: 8.5993 Hz
Modal mass: 1222.2 kg

Click and hold the figure to rotate

Figure 3 – (a) Floor tab – available options, (b) Displayed loaded modal characteristics

3.2.3. Design guidelines and recommendations

The *Standards* tab enables the user to select the dynamic force model (Figure 4).

Option *ARUP* uses walking force models defined in [10] for both LFFs and HFFs. The methodology distinguishes if the floor is LFF or HFF based on the fundamental frequency and applies an appropriate dynamic force model. Some harmonic force models recommended by various authors are also implemented. Force models proposed by Rainer [13] and Kerr [14] can be applied only to LFFs, while Živanović [15] suggested an advanced force model that can be used for both LFFs and HFFs.

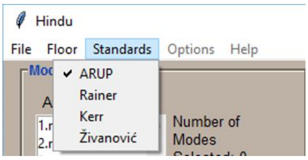
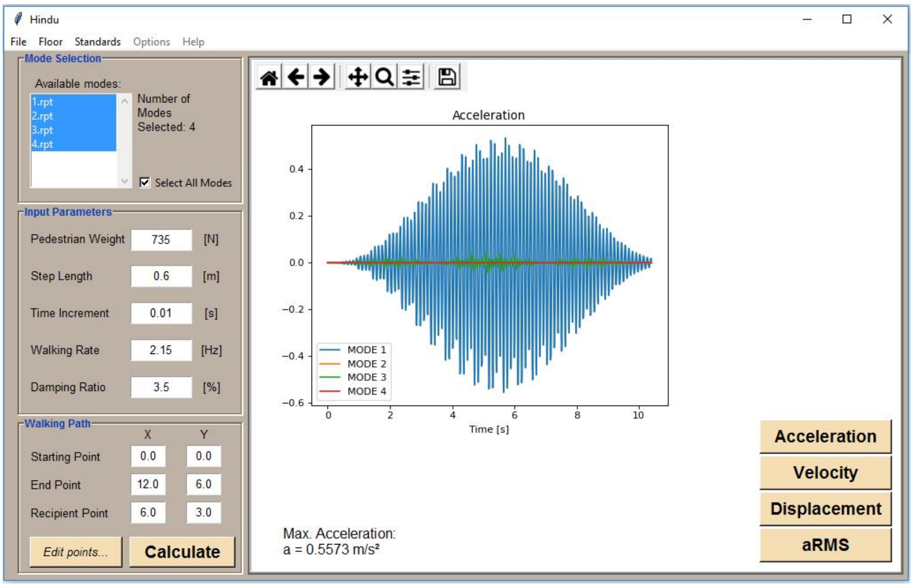


Figure 4 – Standard tab – implemented procedures/dynamic force models

3.2.4. Visualisation & reports

Once all parameters are defined, the software calculates floor response in the receiver point by pressing the button *Calculate*. The time-history acceleration diagram is, by default, presented on *Canvas*, and the maximum value is given as well. In addition, the user can switch between the time-history diagrams for acceleration, velocity, displacement, or calculated so-called running a_{rms} trend (Figure 5).

Finally, the results of the performed analysis can be exported into .pdf and .doc file formats. The file contains the results of the modal analysis, specified input parameters, defined walking path, as well as time-history diagrams. Created reports can be attached to the floor design project.



Available modes:
1.rpt
2.rpt
3.rpt
4.rpt

Number of Modes Selected: 4

☑ Select All Modes

Pedestrian Weight	735	[N]
Step Length	0.6	[m]
Time Increment	0.01	[s]
Walking Rate	2.15	[Hz]
Damping Ratio	3.5	[%]

	X	Y
Starting Point	0.0	0.0
End Point	12.0	6.0
Recipient Point	6.0	3.0

Max. Acceleration:
a = 0.5573 m/s²

Figure 5 – Displaying results on Canvas

4. NUMERICAL EXAMPLE

Main features and efficiency of *Hindu* are demonstrated through the numerical example of the cross-laminated timber (CLT) floor. Due to the high stiffness-to-weight ratio, CLT structures are flexible and may experience vibration issues. The floor's dimensions are 6x12m, and the cross-section comprises five 3cm thick crosswise layers (Figure 6). The floor is simply supported (S) along all four edges. The outer layers are oriented in the *y*-direction.

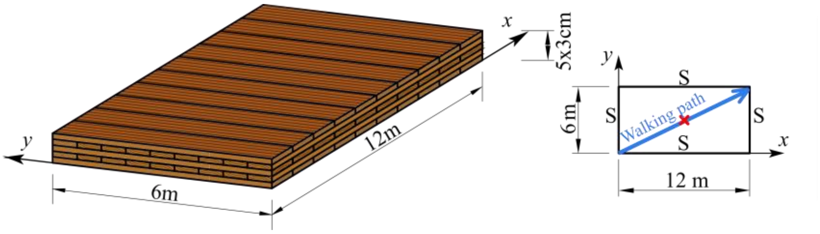


Figure 6 – Numerical example - CLT floor

The CLT floor is modelled in Abaqus CAE using S4R finite elements (4-node linear rectangular shell element with reduced integration) with a composite section. Each lamina is made of a C24 timber class with material properties presented in Table 1. A mesh size of 0.1m is used. Results of the modal analysis are exported from Abaqus CAE, and the first four natural frequencies and modal masses are elaborated in Table 2.

Based on Arup's applied methodology, the floor is classified as LFF. Thus, it is prone to a resonant build-up response. The pedestrian walks along the walking path defined according to Figure 6. The walking frequency of 2.15 Hz is adopted, so the fourth harmonic of the dynamic walking force coincides with the floor's fundamental frequency. Additional parameters used in the numerical example are pedestrian weight 735 N, step length 0.6 m, damping ratio 3.5% and time increment 0.01 s.

Table 1 – Material properties for C24 timber class of CLT panel

ρ [kg/m^3]	E_L [MPa]	E_R=E_T [MPa]	G_{LR}=G_{LT} [MPa]	G_{RT} [MPa]	ν_{LT}	ν_{LR}	ν_{RT}
450	11000	370	690	69	0.49	0.39	0.64

Table 2 – Natural frequencies and modal masses of CLT floor

Mode	1	2	3	4
Frequency [Hz]	8.60	10.40	14.57	21.21
Modal mass [kg]	1222.2	1219.5	1219.2	1220.5

Calculated response in the receiver point (marked with a red x in Figure 6), in terms of time-history diagrams for acceleration, velocity, displacement, and running arms trend (moving average), is presented in Figure 7.

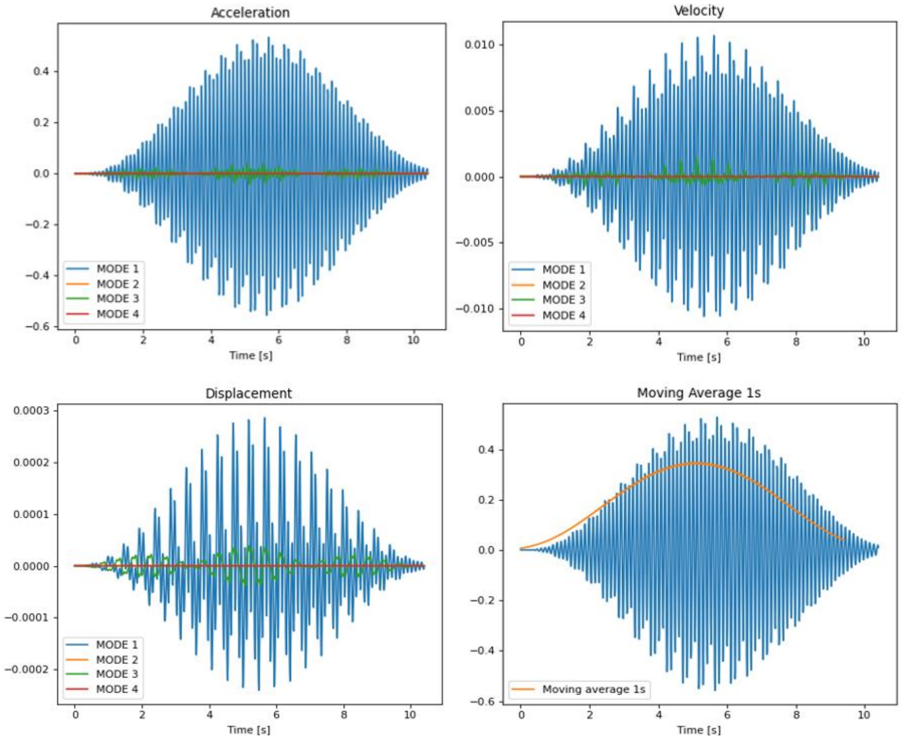


Figure 7 – Calculated response of 6x12 m CLT floor

5. CONCLUSION

The era of a rough estimation of the floor vibration is over, and performance-based methods are widely used to assess the floor serviceability under human-induced loading.

Hindu software developed for VS assessment of floors subjected to pedestrian-induced dynamic excitation is a step in the right direction. Basic properties of the developed GUI for pre- and post-processing as well as the calculation procedure were demonstrated through the illustrative example.

The software has several limitations since it is still in its infancy. One of them is compatibility with only one FEM software for modal analysis. Additionally, one guideline and a few recommendations for vibration calculation have been implemented so far. *Menu bar* functions (*Options, Help*) that could provide users additional benefits have not been developed.

The software's significant advantage is that Python is open source programming package. It has a simple GUI and is intuitive and straightforward. It can be used for floors of any shape and material. *Hindu* offers the option of calculation reports and has a great potential to be utilised in research and design. One of *Hindu*'s essential features is the potential for further upgrades. The plan for future work will be directed toward creating possibilities to import modal properties from other FEM-based software, to include additional guidelines for calculating the floor's dynamic response and finally, to make *Hindu* an efficient tool for vibration serviceability assessment regarding human-induced vibrations.

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