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Human-Induced Dynamics: Footfall Force Measurement and Structural Response

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Abstract

Wooden buildings are increasingly used due to their low environmental impact and their contribution to sustainable construction. However, their reduced mass and increased flexibility make them more sensitive to human-induced vibrations, particularly those generated by walking activities. In many situations, occupant comfort rather than structural safety becomes the governing design criterion.

Most engineering approaches represent pedestrian loads as perfectly periodic excitations with constant frequencies and harmonic amplitudes. Although these assumptions simplify structural design procedures, they do not accurately reproduce the natural variability observed in human gait.

This work investigates how walking variability influences the characteristics of pedestrian loading and, consequently, the dynamic behavior of lightweight floors. The study is based on an experimental campaign conducted at ETH Zürich (Human Movement Lab) using an instrumented walkway composed of six consecutive force plates. Three participants with different body masses (60 kg, 75 kg and 100 kg) performed several walking trials at prescribed walking frequencies ranging from 1.6 Hz to 2.1 Hz (The cadence was controlled using a metronome while allowing participants to walk as naturally as possible across the instrumented area.

Only the vertical ground reaction force was considered, as it is the dominant component responsible for vertical floor vibrations. MATLAB algorithms were developed to automatically process the experimental data. Individual footsteps were detected, validated and normalized with respect to body weight in order to compare signals independently of the participants' mass.

The analysis first focused on the biomechanical characteristics of the measured footsteps. Although the overall force pattern remained highly repeatable, significant variations were observed from one step to another, even when the walking frequency was kept constant. The comparison between left and right feet also revealed very similar behaviors, allowing all footsteps to be analyzed together in subsequent stages.

The analysis investigated two sources of gait variability: the variability of individual footstep force profiles and the variability of step frequency. Frequency-domain analyses were performed using the Fast Fourier Transform (FFT).

The results show that variability in individual footstep forces directly affects the harmonic content of the excitation by modifying harmonic amplitudes. Variability in step frequency, on the other hand, progressively reduces the coherence between successive footsteps and spreads the energy around the harmonic frequencies. Furthermore, higher-order harmonics exhibit smaller average amplitudes but a broader energy distribution, leading to increased relative variability.

Compared with perfectly periodic assumptions, realistic walking signals produce broader and less pronounced harmonic peaks. These modifications influence the structural response by reducing the

concentration of energy at a single resonance frequency while increasing the frequency range over which vibrations may occur.

Overall, this study demonstrates that human walking cannot be considered a strictly periodic process. Incorporating experimentally observed gait variability leads to a more realistic representation of pedestrian loading and may improve future vibration assessment methodologies for lightweight structures.

Human-Induced Dynamics: Footfall Force Measurement and Structural Response

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0.1 Introduction

Lightweight timber floors are increasingly used in modern buildings due to their low environmental impact and favourable structural properties. However, their reduced mass and stiffness make them particularly sensitive to human-induced vibrations.

Current design guidelines, such as Eurocode 5, generally represent pedestrian walking using deterministic harmonic loads with constant frequencies and amplitudes. In reality, human walking is inherently variable. Variations occur both in the shape and amplitude of the footstep forces and in the walking cadence itself.

These fluctuations may significantly influence the interaction between pedestrians and floor structures.

The objective of this study is to investigate the influence of natural walking variability on the vibration response of lightweight floors.

Two experimental databases were first analysed to characterize pedestrian walking variability. Different loading protocols were then developed and applied to a finite element floor model to quantify their influence on the structural response.

0.2 Experimental Measurements and Walking Variability

Two experimental campaigns were conducted. The first dataset was acquired at the Human Movement Laboratory of ETH Zürich. Three healthy participants walked at imposed frequencies ranging from 1.6 Hz to 2.1 Hz, with increments of 0.1 Hz, while vertical ground reaction forces were measured using six force plates. Each participant performed five walking trials at every frequency.

Figure 1: Experimental setups used at ETH Zürich

The second dataset was collected at Ziegler Consultants under more restrictive measurement conditions using two force plates (KI-jump 9229A). One participant performed approximately ten walking trials at each investigated frequency. The same frequency range as the ETH Zürich campaign was considered.

Figure 2: Experimental setups used at Ziegler Consultants

Raw measurements were processed to detect, validate and normalize individual footsteps.

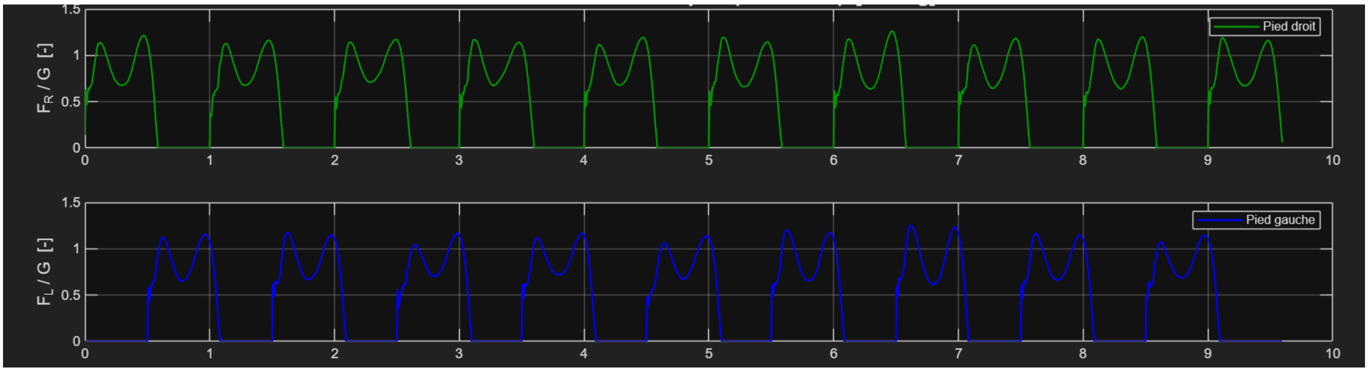


Figure 3: Detected, validated and normalized footsteps obtained from the ETH Zürich measurements

The results show that both experimental protocols correctly identify the imposed walking frequencies.However, the measurements from ETH Zurich generally exhibit better accuracy with lower dispersion around the theoretical diagonal. This difference can be partly explained by the length of the signals available for analysis. The sequences measured at ETH Zurich contain several successive steps, which improves the frequency resolution of the Fourier transform. Conversely, the measurements taken in the offices only allow for the use of a single walking cycle, which reduces the accuracy of the frequency estimation (Figure 4). To quantify this difference, the relative error in the fundamental frequency was calculated for each walking frequency. The results show an average error of 3.78% for the measurements from ETH Zurich compared to 5.72% for the measurements taken at Ziegler Consultants' offices.

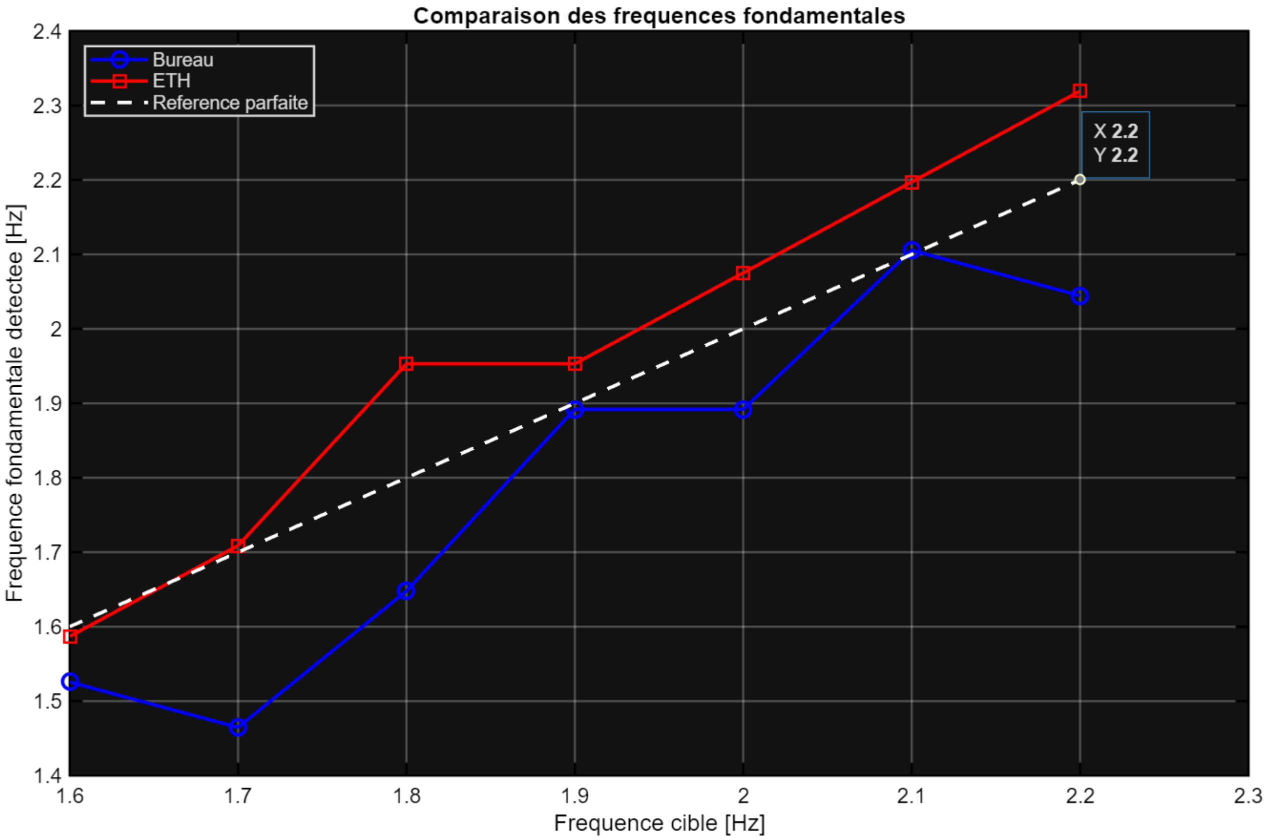


Figure 4: Comparison of fundamental frequencies detected for ETH and Ziegler signals Consultants

A harmonic analysis of the signals was also performed to evaluate the frequency richness of the measured signals. Total harmonic distortion (THD) quantifies the importance of secondary harmonic components relative to the main harmonic. The results presented in Figure 5 show that the signals from the Ziegler Consultants measurements have a higher average THD (0.630) than those from ETH Zurich (0.512). This increase in THD reflects a greater presence of secondary frequency components as well as more pronounced variability in the measured signals. The ETH Zurich measurements thus appear more regular and exhibit a more organized spectral content.

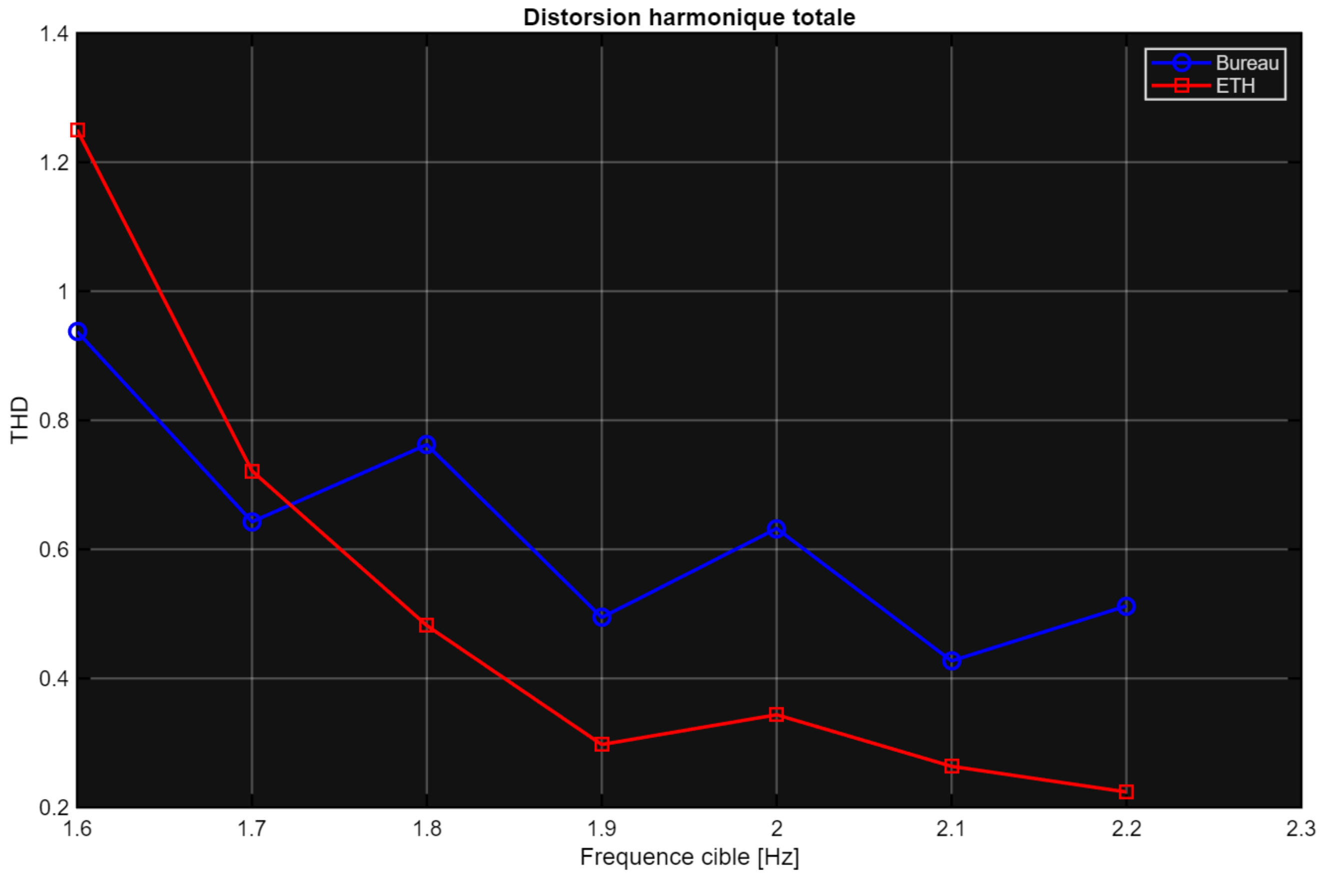


Figure 5: Comparison of the total harmonic distortion of the reconstructed signals

Based on these observations, the ETH Zürich dataset was selected for the numerical simulations.

Although both datasets were suitable for characterizing pedestrian walking, the ETH Zürich measurements better represent natural walking conditions. Participants could walk continuously along a dedicated walkway, whereas the Ziegler Consultants setup imposed stronger experimental constraints. In particular, participants had to target a limited measurement area corresponding to the two force plates, which may have altered their natural gait.

In addition, the ETH Zürich measurements provided longer walking sequences, a better adherence to the imposed cadence and a larger experimental database. These characteristics make this dataset more suitable for investigating walking variability and its influence on floor vibrations.

0.3 Loading Protocols and Numerical Model

Three loading protocols were developed to investigate the influence of walking variability.

1. Fixed cadence with variable footsteps.

2. Variable cadence with fixed footsteps.

3. Combined cadence and footstep variability.

Examples of these loading protocols are shown in Figure 6.

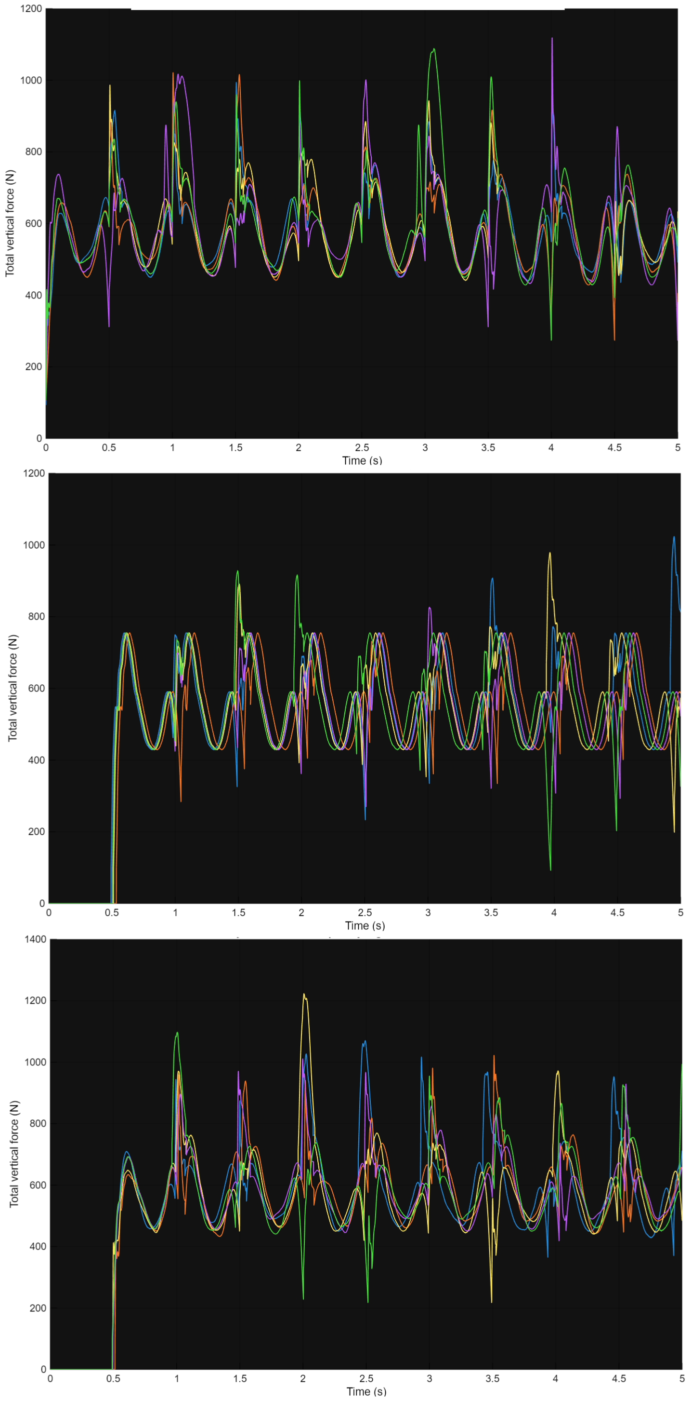


Figure 6: Examples of the three loading protocols: fixed cadence with variable footsteps (up), variable cadence with fixed footsteps (centre), and combined variability (down)

A finite element model was developed in MATLAB to simulate the dynamic response of a lightweight timber floor.

The floor dimensions are 8 m × 6 m with a thickness of 0.20 m. The structure is discretized using Mindlin-Reissner plate elements.

Simply supported boundary conditions are applied along all edges. The first natural frequency is adjusted to 8 Hz and a damping ratio of 3% is introduced using Rayleigh damping.

The dynamic response is computed using the Newmark-β integration scheme.

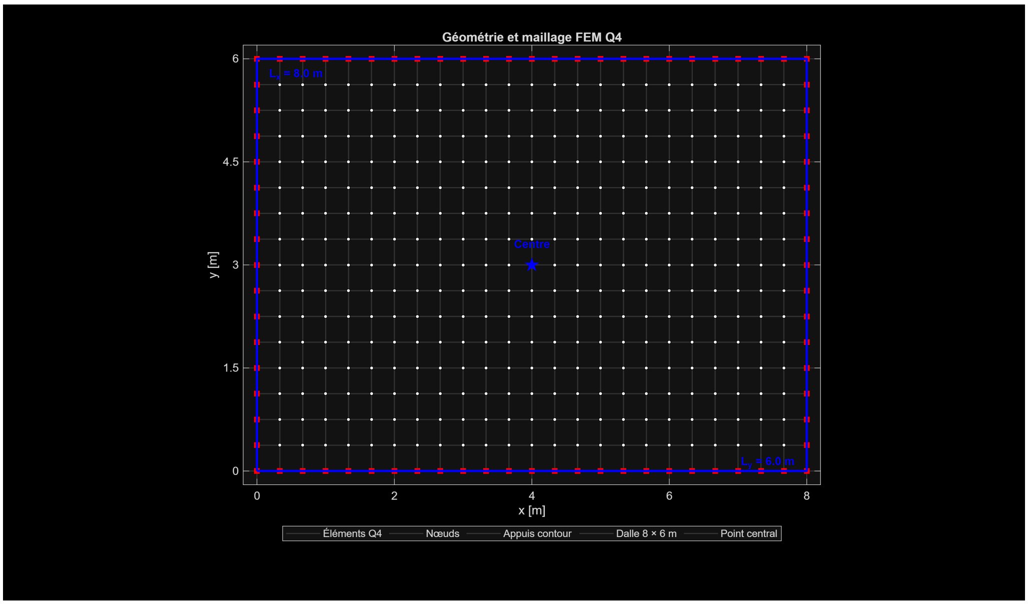


Figure 7: Finite element mesh used for the floor simulations.

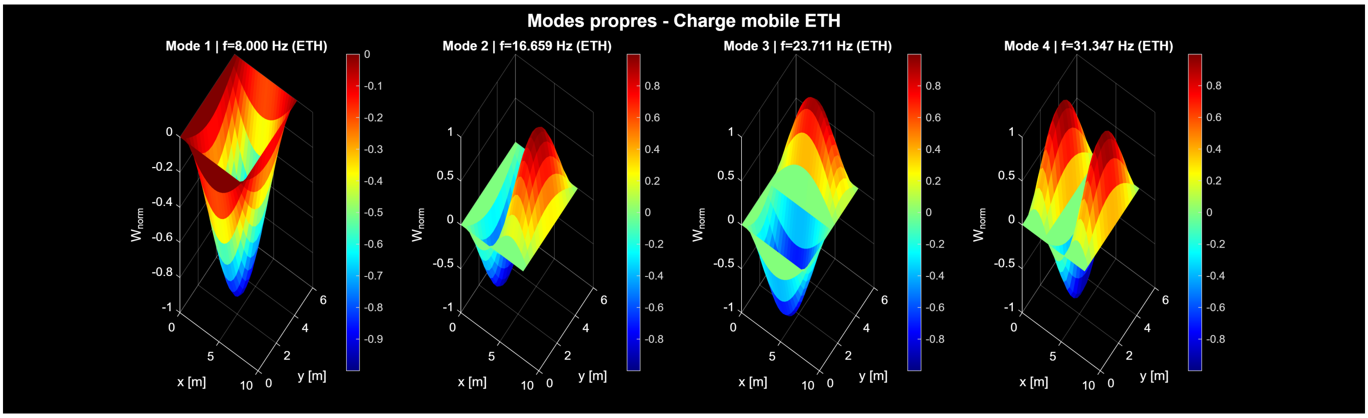


Figure 8: First vibration modes obtained from the modal analysis.

0.4 Results and Discussion

Two hundred simulations were performed for each loading protocol.

The analysis first focuses on a floor with a natural frequency of 8 Hz.

The results show that the three loading protocols lead to relatively similar vibration levels. The maximum average response is 2.54 mm/s for Protocol 1 (constant cadence), compared with 2.14 mm/s when cadence variability is introduced (Protocol 2). Protocol 3, which combines cadence and footstep variability, remains close to the reference case.

A similar trend is observed for the RMS velocities. Introducing cadence variability decreases the average RMS velocity by approximately 32

These results suggest that cadence variability is the dominant mechanism governing the vibration response. Small fluctuations in the duration of successive steps progressively introduce phase shifts between the different loading contributions. As a result, the temporal coherence of the excitation is partially lost, reducing the efficiency of energy transfer to the structure.

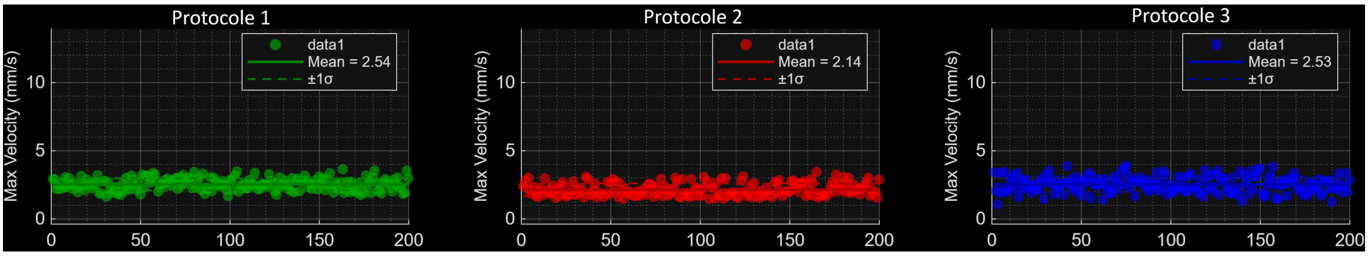


Figure 9: Maximum velocities obtained for the three loading protocols at 8 Hz.

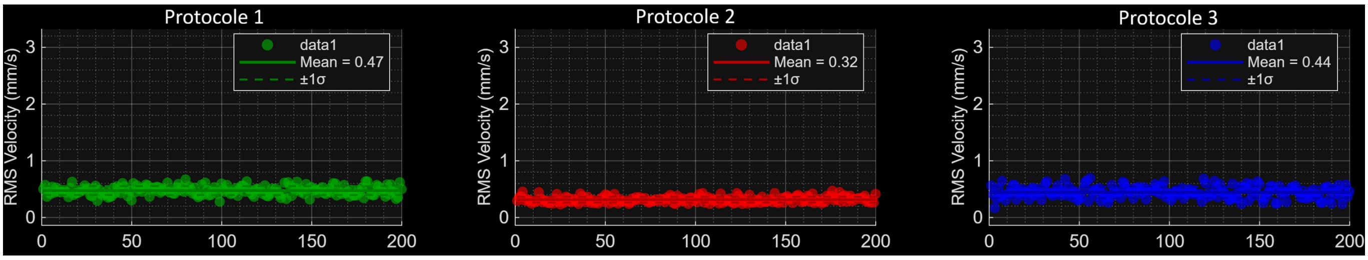
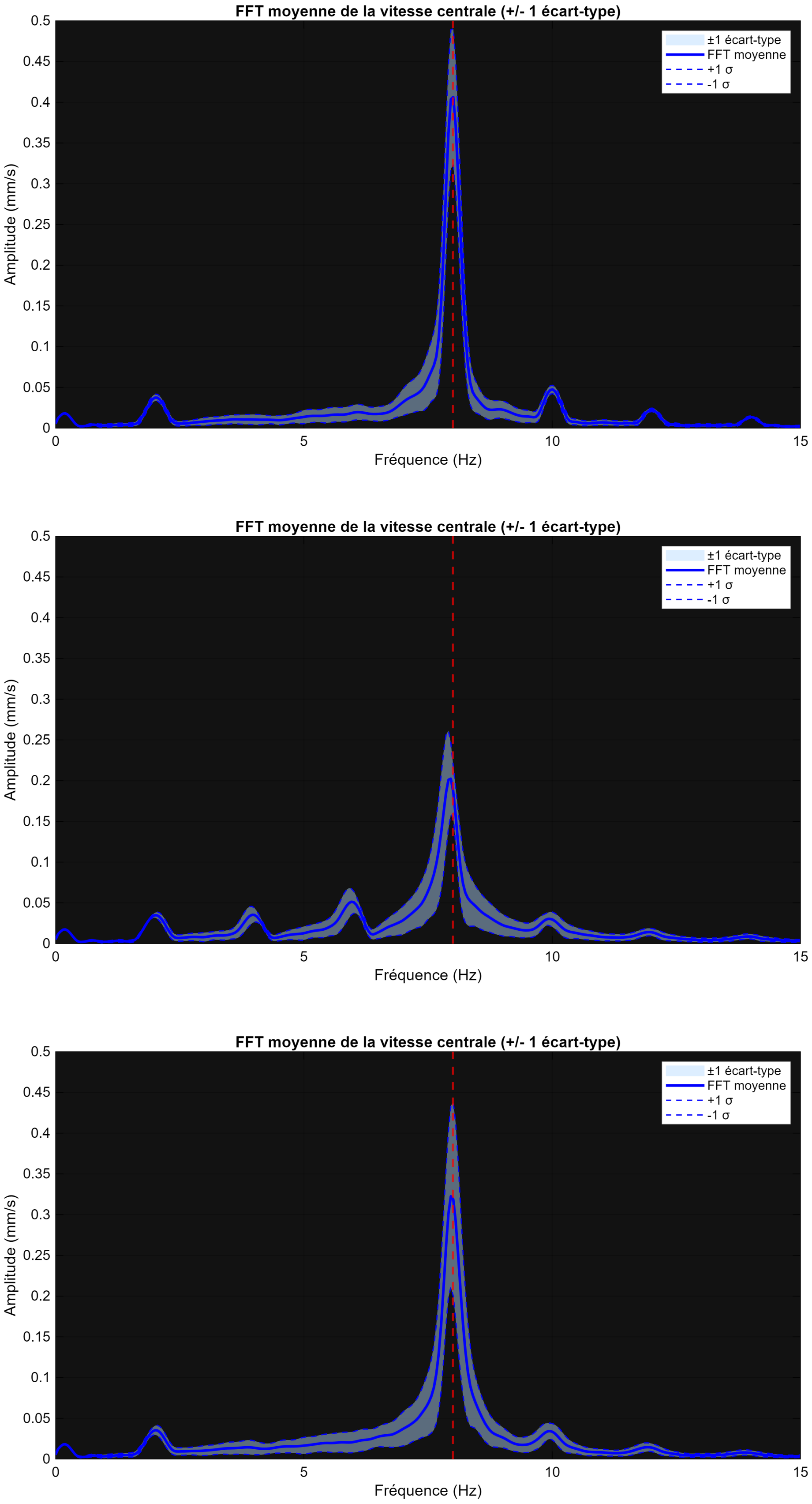


Figure 10: RMS velocities obtained for the three loading protocols at 8 Hz.

To better understand the mechanisms responsible for these differences, a frequency analysis of the structural responses was performed.



FFT moyenne de la vitesse centrale (+/- 1 écart-type)

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Figure 11: Average velocity spectra obtained for the three loading protocols at 8 Hz.

Protocol 1 (constant cadence) is characterized by a narrow, high-amplitude spectral peak. This concentration of energy around a single frequency reflects the strong temporal coherence of the excitation, as successive footsteps remain nearly in phase and therefore add constructively.

When cadence variability is introduced, this coherence is progressively lost. Small fluctuations in the walking period create cumulative phase shifts between successive loading contributions. Consequently, the energy is no longer concentrated at a single frequency but distributed over a wider frequency band. This results in both a reduction of the peak amplitude and a broadening of its frequency content.

These observations are consistent with the previous analysis of pedestrian loading. Cadence variability mainly acts as a frequency dispersion mechanism: the total energy is not suppressed but redistributed around the walking harmonics.

Protocol 3 (combined cadence and footstep variability) produces an intermediate behaviour. The response amplitudes remain higher than those obtained for Protocol 2, suggesting that variations in footstep shape and amplitude may locally create more favourable excitation conditions and partially compensate for the loss of temporal coherence.

Additional simulations were then performed for floor natural frequencies of 4 Hz, 8 Hz, 8.3 Hz and 12 Hz.

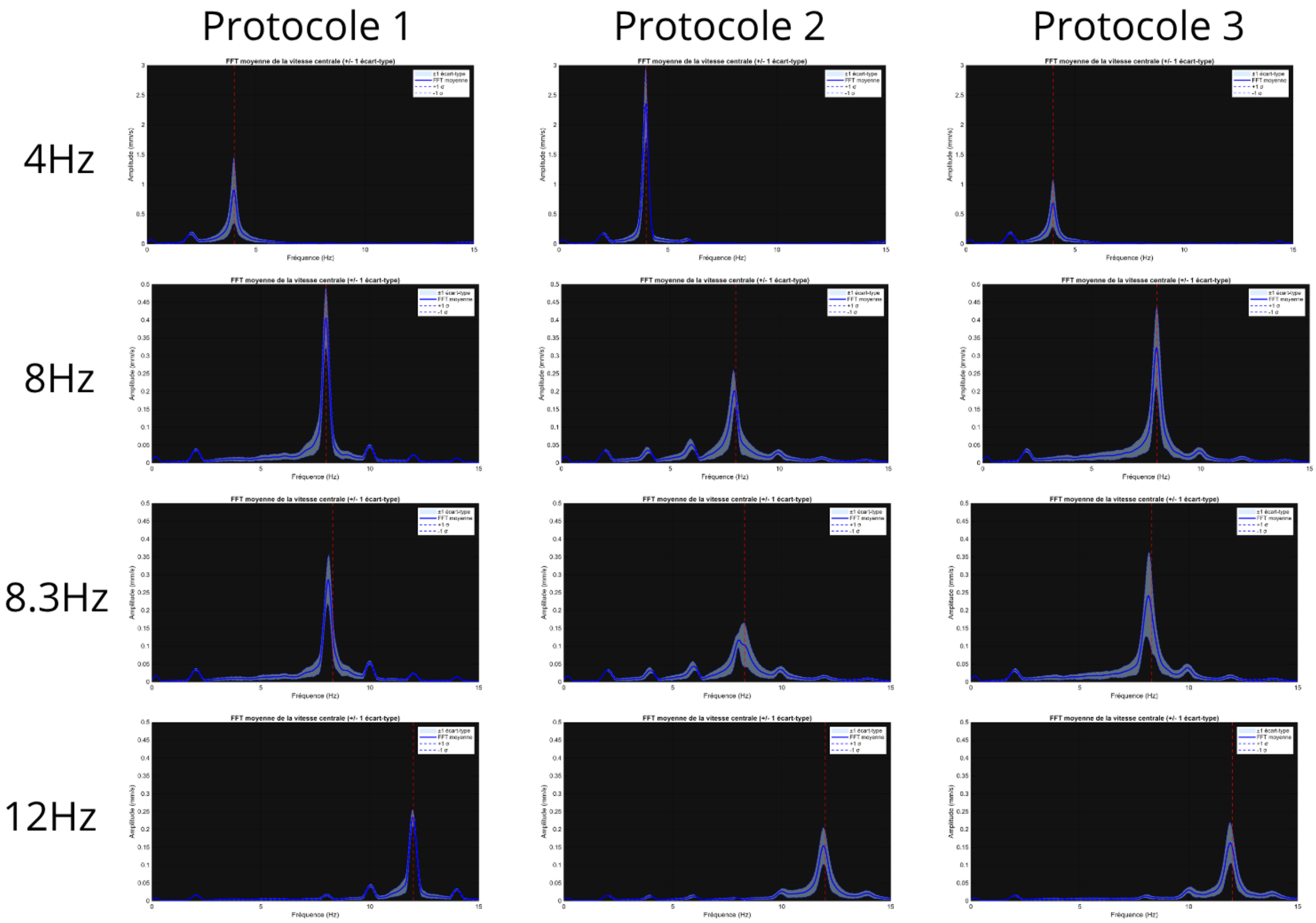

Figure 12: Average velocity spectra obtained for the different floor natural frequencies investigated.

For all cases, the response remains dominated by frequency components located close to the floor natural frequency. The structure therefore acts as a dynamic filter that selectively amplifies excitation frequencies in its vicinity.

However, the influence of walking variability strongly depends on the degree of overlap between the walking harmonics and the floor resonance frequency.

The 4 Hz case is the most sensitive to variability because it coincides with the second harmonic of a 2 Hz walking frequency, which is one of the most energetic components of pedestrian loading. Under perfectly periodic walking conditions, successive footsteps remain synchronized with the floor motion, leading to strong resonance amplification.

When cadence variability is introduced, phase shifts progressively accumulate and the excitation becomes less synchronized with the structural response. This desynchronization broadens the spectral peak and redistributes the energy over a wider frequency range, significantly reducing resonance amplification.

In contrast, the 8 Hz and 12 Hz cases are much less sensitive to variability. Although these frequencies correspond to the fourth and sixth walking harmonics, respectively, only small changes in peak amplitude and width are observed between the different protocols.

This lower sensitivity can be explained by the naturally smaller amplitudes of higher-order harmonics. In these cases, the response is governed more by the modal properties of the structure than by perfect synchronization between successive footsteps.

The 8.3 Hz case is particularly interesting because it does not correspond exactly to an integer multiple of the walking frequency. Without variability, the overlap between the excitation harmonics and the floor natural frequency is less favourable. However, the spectral broadening induced by variability increases the probability that part of the excitation energy will fall close to resonance.

Two competing mechanisms therefore coexist. On the one hand, walking variability reduces temporal coherence and tends to decrease resonance amplification. On the other hand, it broadens the frequency content of the excitation and increases the probability of exciting nearby structural modes.

The vibration response ultimately results from the balance between these two effects.

0.5 Conclusions

This study investigated the influence of natural walking variability on the vibration response of lightweight timber floors.

The results show that cadence variability is the dominant parameter governing the structural response.

Walking variability simultaneously reduces temporal coherence and broadens the excitation spectrum. Depending on the floor natural frequency, these two competing mechanisms may either decrease or increase vibration levels.

These findings also highlight some limitations of the current Eurocode 5 approach, which assumes perfectly periodic pedestrian loads.