Simulating Crowd Vibration with Traffic Load

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Abstract. Streamlined sections in suspended structures can create dynamic responses that are particularly impactful. One notable source of noise and vibration is the weight of human footfall, which can be a nuisance for those using the facility. The objective is to ensure that the structure can withstand the stresses caused by the occupants. The approaches can be the following methods: (i) an analytical approach, which involves calculating the structure's performance during the design phase, and (ii) an experimental approach, which entails measuring the vibrations of the structure during use. This study proposes an experimental modal analysis procedure for evaluating the vibration functionality of an existing structure under the influence of excitation caused by human activity.

1 Introduction

Initial investigations into the forces generated during human locomotion involved analyzing the movement of the body's center of gravity in conjunction with the functions performed by the muscles [1]. Researchers have noted a distinct stress pattern in the vertical and horizontal forces exerted by a single foot on the ground, characterized by two prominent peaks, as observed in numerous studies [2]. The accelerations and decelerations of a human body that go up and down during the journey generate inertial forces and, therefore, fluctuations, over time, of the vertical and horizontal forces in the phase of support and push of the foot. The interaction between the two feet is another parameter influencing the fluctuation of those above horizontal and vertical forces transmitted from the foot to the floor surface [3]. Harper characterized the time signature of the footprint as *substantially similar for all subjects*. A generalization of the horizontal and vertical forces transmitted from the foot to the floor surface could characterize the entire human population [4]. Smith states that the excitement generated by walking takes a periodic course with frequencies between 1.5 Hz and 2.3 Hz. The characterization of periodic excitation and the deduction of structure response represent the objects of research [5]. According to Galbraith and Barton's seminal work from 1970, walking and running generate distinct forces. Running forces are more prolonged and more substantial in magnitude

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compared to walking. During a race, the intervals between successive peaks of force reveal the moments when both feet are in contact with the ground [6]. The type of footwear and the crossing surface slightly affect the forces applied by human movements. According to Blanchard et al. (1977), forced walking serves a periodic function [7]. Their analysis of the Fourier series components reveals that the peak of the fundamental harmonic aligns with a quarter of the walker's weight [8]. Per their proposal, the fundamental harmonics are crucial in stimulating walking movements [9]. According to Ellingwood, more than relying solely on a fundamental harmonic for modeling, the model of the impact of walking on floors is the peculiar aspect. Instead, Ellingwood recommends a method that factors in the heel strike and toe lift, which results in higher harmonics. Meanwhile, Wheeler identifies six modes of human movement that cause floor excitement, including various walking speeds ranging from slow (0.75 m/s) to fast (1.75 m/s) [10].

2 Methodology

The following methods can develop the assessment of vibration on a structure: a) an analytical approach at the design stage and b) an experimental approach using vibration measurements of structures at the testing stage of the structure [11]. The Duhamel integral simulates the response of a system to a single degree of freedom (SDoF) solicited by an external force. Analytical and numerical methods solve the Duhamel integral. An analytical approach solves the Duhamel integral, where the external load assumes a mathematical expression [12]. The Duhamel integral approach hypotheses are as follows:

- The load is stationary.
- The load is perfectly periodic.
- One of the external load harmonics can excite the fundamental resonance of the structure.

The limitation of this approach is that these assumptions may need to be verified. The Duhamel integral can be a conservative approach, offering an incorrect estimate of the system response [13]. The experimental approach has the following phases: 1) modal testing of the structure; 2) acceleration response measurements caused by walking excitation [14]. The modal analysis tests consist of stressing the structure. Frequency response functions (FRFs) are inferred on a matrix $\boldsymbol{G}(\omega)$ by Eq. (2) [15]. If the facility is noisy, the experimental investigation may require many tests for each measuring point-two different types of load act on the structure. In the first set of measures, impulsive load stresses the structure [16]. In the second measuring set, the load of people walking emphasizes the magnitude of vibrations on the structure.

The experimental modal analysis proposes the following:

- *Response to impact test.* The impact test identifies the resonance frequencies of the structure. The impact test shall assess whether the modes with natural frequencies f_k and f_j are close or not according to the following relationship:

$$\mu_{jk} = \frac{2\zeta_j f_j}{f_k - f_j} \tag{1}$$

  where
  - ζ_j indicates the modal damping ratio of the j^{th} mode.
  - The condition $\zeta_j > 0.1$ indicates that the coupling of f_k and f_j is non–negligible.
- *Experimental model development.* The test data are available in the frequency domain as a set of frequency response functions (FRFs) [17]. The process of extracting modal data, as natural frequencies, modal damping and mode shapes, from measured excitation response data is obtained by the experimental modal analysis. The $n \times n$ matrix $\boldsymbol{G}(\omega)$ determines the complete modal information:

$$\boldsymbol{G}(\omega) = \begin{bmatrix} G_{11} & G_{12} & \dots & G_{1n} \\ G_{21} & G_{22} & \dots & G_{2n} \\ \vdots & \vdots & \dots & \vdots \\ G_{n1} & G_{n2} & \dots & G_{nn} \end{bmatrix} \tag{2}$$

  The matrix $\boldsymbol{G}$ of the FRFs of the structure identifies the path or paths with the maximum response of the structure [18].
- *Response to walking excitation.* On commercial floors, individuals typically walk with an average frequency of 2.0 Hz and a speed of 1.4 m/s. On walkways, the average frequency decreases to 1.8 Hz, and the speed decreases to 1.3 m/s. The suggested method ensures that walking excitation can effectively stimulate the appropriate modes of the structure.

3 Results

3.1 Experimental Set–up

The Fig. 1 shows the set consists of a SV 84 vibration accelerometer, a SA 207B metal base, and 6 channel Human Vibration Meter - Analyzer Svantek 106A.

Fig. 1. The set consists of a SV 84 vibration accelerometer, a SA 207B metal base and Svantek 106A

3.2 Experimental Investigations

Figures 2, 3 and 4 show acceleration data acquired along x– y– and z–axis on the floor caused by human actvities: walking, jumping and dancing. A typical time response anf FRF produced by walking on the floor is shown in Fig. 5.

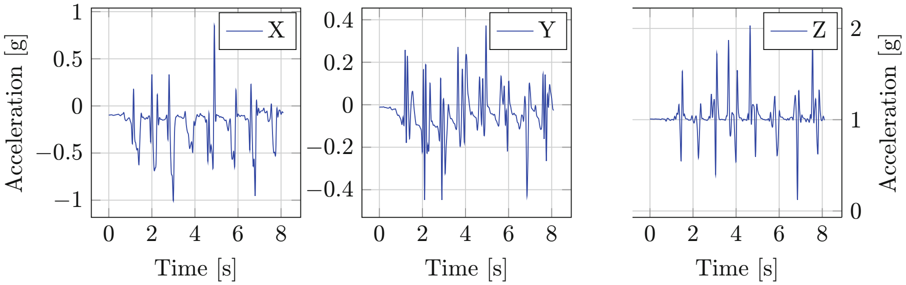


Fig. 2. Acceleration data acquired along x– y– and z–axis on the floor caused by human walking

4 Discussion

Human walking creates a rhythmic pace of 1.5 to 2.5 steps per second that most individuals tend to follow. However, humans cannot consistently maintain this perfect pace and may experience fluctuations in their stimulation frequency. These fluctuations can result in narrow peaks at resonance frequencies in the structure's modulus frequency response (FRFs) functions, causing a slight damping effect. Even a minor deviation between the excitation frequency produced by walking and the structure's resonance frequency can decrease the structure's

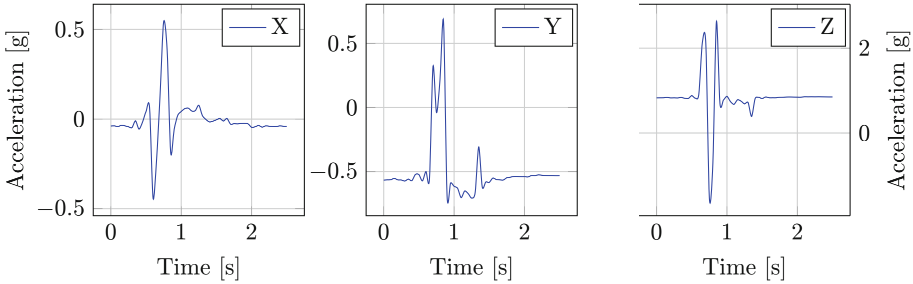


Fig. 3. Acceleration data acquired along x– y– and z–axis on the floor caused by human jumping

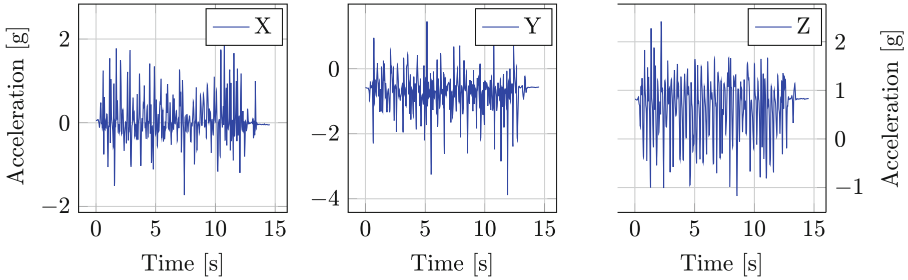
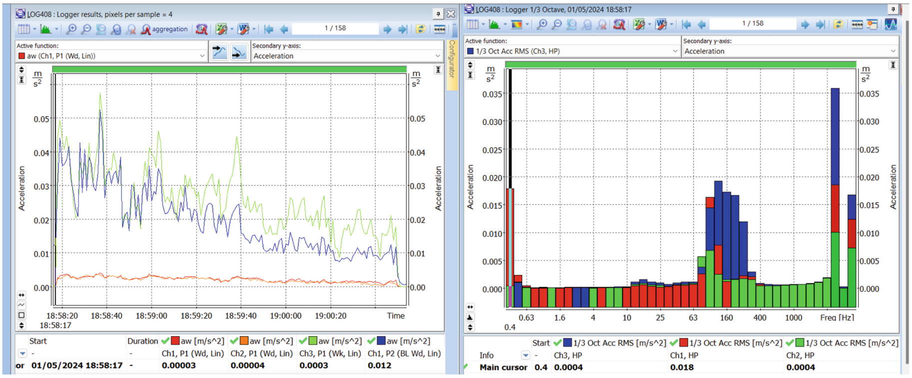


Fig. 4. Acceleration data acquired along x– y– and z–axis on the floor caused by human dancing

response. By contrast, the movement of the dance generates an impulsive and periodic load with peak values of 2 g [12]. Concerning the human-structure interaction, the ISO 10137 procedure offers the first step towards assessing the structure's vibration serviceability and characterizing the following three aspects: the vibration source, the transmission path, and the receiver. ISO 10137 proposes two general classes of vibration serviceability problems depending on the vibration source. The human–structure interaction also concerns structural change. The question is whether and how people's presence can change the structure's mechanical characteristics regarding mass, stiffness, and damping. Moving people and stationary people represent a different distribution of loads on the structure. Humans in motion generate dynamic loads without altering structural dynamic properties. People in stationary conditions can vary the structure's structural mass, stiffness, and damping. The mass-spring-damper systems connected to the structure can represent the presence of people in stationary conditions. If the additional mass of people in stationary conditions is relevant to the structure's mass, the extra mass develops a significant role. The load people offer in stationary conditions arouses attention to the safety and maintenance aspects of places of human assembly.

Modeling an established structure can be intricate, particularly when defining its damping. Fortunately, operational modal analysis (OMA) represents the



Active function: aw (Ch1, P1 (Wd, Lin))
Secondary y-axis: Acceleration

	Start	Duration	✓🟥 aw [m/s^2]	✓🟧 aw [m/s^2]	✓🟩 aw [m/s^2]	✓🟦 aw [m/s^2]
	-	-	Ch1, P1 (Wd, Lin)	Ch2, P1 (Wd, Lin)	Ch3, P1 (Wk, Lin)	Ch1, P2 (BL Wd, Lin)
or	**01/05/2024 18:58:17**	**-**	**0.00003**	**0.00004**	**0.0003**	**0.012**

Active function: 1/3 Oct Acc RMS (Ch3, HP)
Secondary y-axis: Acceleration

	Start	✓🟦 1/3 Oct Acc RMS [m/s^2]	✓🟥 1/3 Oct Acc RMS [m/s^2]	✓🟩 1/3 Oct Acc RMS [m/s^2]
Info	-	Ch3, HP	Ch1, HP	Ch2, HP
✓ **Main cursor**	**0.4**	**0.0004**	**0.018**	**0.0004**

Fig. 5. Time response and Frequency Responce Function of accelerations acquired on the floor and caused by walking

latest and most effective technique for precisely identifying modal parameters of a structure under real-world operating conditions, even in cases where it is challenging or impossible to stimulate the structure artificially. The proper techniques for determining the modal parameters of a structure involve:

- Utilizing an instrumented hammer to measure frequency response (FRF).
- Estimating vibration parameters of multi-degree freedom systems (MDOF) with the collected FRF data.
- Modeling the structure through the finite element method (FEM).
- Correlating the FEM model with experimental FRF data.

Scientific research regarding human assembly sites focuses on safety and maintenance and the perception of low-level vibrations. Understanding a structure's amplitude, dominant frequency, and damping enables the classification of its vibration on a scale of perception-ranging from imperceptible to painful. This knowledge helps make judgments of the vibration's level of annoyance or unpleasantness. The perception of man to vibrations of low levels of large structures and infrastructure is a psychological phenomenon because the users of extensive infrastructure do not predict the movement of the structure, and therefore, discomfort arises. The structure may have only one cycle of motion followed by a decrease of motion or a movement with a certain number of cycles followed by a transient decay of movement. Such oscillatory phenomena can last even a few seconds. The impact of acoustic effects on human perception of vibration can be substantial, resulting in either a reduction or amplification of its magnitude. Standards such as BS 6472 or ISO 10137 utilize RMS acceleration and vibration dose value (VDV) as parameters to gauge the extent of vibration and its consequences [19]. Nonetheless, evaluating vibroacoustic phenomena in structures entails particular uncertainty due to the need for shared vibration and noise perception thresholds in scientific research.

5 Conclusion

Modal structure analysis is a valuable tool for identifying the natural frequencies and forms of a structure's vibrating mode. With knowledge of the modal parameters and proper vibration modes, one can accurately predict the structure's response under various excitation conditions. These predictions can be verified by observing the rhythm of a test subject's path as they walk on the property. By matching the frequency of their steps with one of the harmonic frequencies of the structure, the modal forms can identify the paths that generate the maximum response of the structure.

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