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Comfort level identification for irregular multi-storey building

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ABSTRACT

In this article, the system identification approach is being used to identify the vertical frequencies of the top storey in a multi-storey building prefabricated from reinforced concrete in Stockholm. Before building construction, detailed investigation indicated that the building will not be affected by train vibrations from the nearby railway yard. After building completion, disturbing vibrations were observed in the building. Three measurement types, namely, ambient vibration test, forced vibration test on the rails, and forced vibration test, have been performed in order to specify the probable reasons for these vibrations.

Five methods of structural identification approach, specifically ARX, ARMAX, BJ, OE, and state-space models, have been implemented for the identification process in this study using the tests' results. All the test types and model structures utilized have identified a concentration in the vertical frequencies within the range of (7.5–12.5) Hz for the 10th floor only, which is close to the frequencies of human body parts. Furthermore, the article concludes that the ARMAX model and the output error model have indicated an excellent performance to predict the mathematical models of vibration's propagation in the building, when compared with other models used from the three types of tests.

In addition, the results of the aforementioned system identification methods, implemented for this study, have indicated that there are no other reasons for the disturbing vibrations still observed in the building. Furthermore, the results confirmed the correctness of the previous theoretical and experimental results obtained by different specialists, who stated that the values of floor acceleration are within the acceptable limits, and the probable reason for any disturbance is the resonance between the generated low frequencies and the human body parts' frequencies.

1. Introduction

Mechanical vibrations in structures are being generated by many sources, such as motion of different types of heavy machines, railway systems, construction activities, earthquakes, and storms, which have serious effects on these structures. For example, train's traffic on tracks results in noise and vibrations, which are usually regarded as one and the similar discipline since both are resulted from the oscillations of rails and wheels during train's movement on the track [1]. At lower frequencies, the excitation energy will transmit through the ground in the form of vibrations. At the end, these vibrations will be attenuated in the human body, and its energy will be absorbed by the different human body's organs, while for the higher frequencies, the energy will expand through the air in the form of noise. Finally, both the vibrations and noise will cause a discomfort to the buildings' inhabitants [2].

Actually, one of the main features of the modern life is the high noise level all around the world, and thus, it is very important to take the necessary precautions to avoid the existence of such noise in the buildings due to its effects on the mental and physical well-being of humans. For instance, the percentage of people who are living in noisy environments, with sound pressure levels more than 65 dB and subjected to its effects, only in Europe is approximately 10% [3]. A self-answered questionnaire was carried out by Bayo et al. [4] to evaluate the peoples' subjective responses to noise in a hospital in Spain revealed that the noise levels affected even the recovery of patients in the hospital. Furthermore, a study performed by Piccolo et al. [5] showed that more than 25% of the inhabitants of Messina city in Italy are extremely disturbed by noise resulted from road traffic. Thus, in order to successfully protect the people from the noise pollution, the need is urgent for advanced well-aimed measures.

A state-of-the-art study conducted by Hemsworth [6] called the attention to the deficiency of standards in the estimation of ground borne noise and conflict in the handling of low-frequency vibration in other standards. The spread of noise in Klaipeda city in Lithuania was examined by Vaidotas and Tomas [7] to identify the source of bigger noise areas in the city and to evaluate the measured noise levels against the permissible standards. The performance requirements for comfort levels, safety, serviceability, and security were evaluated using the fuzzy probabilistic optimization approach for a building by [8].

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Moreover, a deterministic model depending on the Monte Carlo simulation method was used by Gilchrist et al. [9] to estimate the magnitude and frequency of the noise levels produced by construction equipment and their effects on an eight-storey parking garage in London. Furthermore, a three-dimensional numerical model was presented by Degrande et al. [10] to estimate the vibrations in the free field from excitation caused by trains' traffic in the subways using the finite-element method. Also, the wavenumber finite and boundary element methods were successfully used by Sheng and Jones [11] to predict the disturbance to buildings' inhabitants from trains' traffic.

The research efforts on utilizing the system identification approach to evaluate the noise levels in buildings until now have been very limited. Nowadays, the most applications of the system identification concept, in the field of civil engineering, are mainly in the area of damage detection [12–19]. However, system identification methods have promising capabilities and can be used to predict mathematical models to define the dynamics of many aspects in a building, like temperature, humidity, and CO_2 level of a room, which are parameters that can be very helpful to perform a sequential control of the heating, the ventilation and the air conditioning (HVAC) [20]. Moreover, system identification methods have been utilized successfully in mechanical engineering to study the contribution of noise sources, to determine the transmission paths by defining the transfer function between the sources and responses, and to develop a mathematical model that defines the dynamics of the noise propagation [21].

Despite the enormous developments in parametric time-domain identification methods, their relative merits and performance as correlated to the vibrating structures are still incomplete. The reason for this limited knowledge is due to the lack of comparative studies under various test conditions [22] and the lack of extended applications and verification of these methods with real life data.

In this article, the system identification concept has been used to measure the noise levels in an irregular multi-storey reinforced concrete building. The black box linear parametric models, as transfer-function models (ARX, ARMAX, BJ, and OE), and the state-space models have been utilized to identify the comfort level in the top storey of an irregular (i.e., long and narrow wedge-shaped) prefabricated from reinforced concrete building using three kinds of vibration tests, namely, the ambient vibration test and two types of forced vibration tests, while a comparison among them has also been made. The novelty of this research is to use the available vibration measurements to contribute in the study of the relative merits and performance of the well-established identification methods as correlated to the vibrating structures. Moreover, this article investigates the potentials of the identification methods, usually encountered in electrical and mechanical engineering applications in order to benefit from their capabilities and widen their applications in the civil engineering field.

Thus, the system identification approach was used to calculate the noise levels in the structure due to different kinds of excitation to validate the results obtained by the classical method of vibration propagation calculations already conducted by some specialist and to explore whether there are other reasons for the disturbing vibrations still observed in the building.

The rest of the article is organized as it follows. In Section 2, a short review about comfort levels will be presented. Section 3 will establish the mathematical models for the dynamic systems utilized in the presented comfort level identification processes. In the sequel, the case study and the measurements conducted will be depicted in Section 4, while Section 5 outlines the Methodology adopted in this study. The results of the system identification approaches will be presented in Section 6, while the conclusion will be drawn in Section 7.

2. Comfort levels

Actually, most of the buildings are exposed to ambient vertical vibrations in the range between (1 and 80) Hz [23], while the horizontal frequency for high-rise buildings lays in the range of (0.1–15) Hz [24]. In general, the evaluation of these noise levels is a complex task, while the methods specified by the related standard regulations are tricky and involve complicated calculations [25]. The scientific methods that have been appeared in the field of predicting noise in structures can be classified generally into the following three categories, based on the frequency content: (1) finite-element analysis (FEA), which is used in the case of low frequencies [26] (2) statistical energy analysis (SEA), which is utilized for high frequencies [27] and (3) hybrid FEA-SEA [28]. In addition to these methods, there have been various empirical and semi-empirical methods as it can be investigated in the following references [25,29,30].

From a different consideration, human body parts have distinct natural frequencies. However, for vertical vibrations with frequencies less than 2 Hz, the human body may be considered as one mass, while in case of high frequencies, the body different parts have their distinctive frequencies, and it can be defined as a lumped mass model [31].

In such a body consideration, vertical vibrations in the range between 4 and 8 Hz are the most important because they may cause resonance in some of the internal parts of the body, while Table 1 displays some indicative human body parts' frequencies when subjected to vertical vibrations [32]. Acceptable limits of human exposure to vibrations are dependent on the time of day, the nature of activities in the place, and the direction utilized by vibrations to enter the human body as it is presented in Fig. 1 [23]. Overall, weighted root-mean-square acceleration (RMS) in each orthogonal axis is used to evaluate the vibrations' levels. Acceptable values for continuous and impulsive vibration acceleration according to the British standards BS 6472 are being presented in Table 2 [33].

3. System identification

In general, two approaches are frequently used to create mathematical models of processes: physical modeling and system identification. The physical modeling utilizes the physical principles and laws like the Newton second law of motion to create these mathematical models. Despite the good accuracy of the physical model obtained by this approach, it is not suitable for experimental modeling purposes because it is difficult to measure all the degrees of freedom of the system and the physical model is in continuous time, while the measurements are obtained in discrete time. Moreover, noise from unknown excitation sources or/and measurement's should be taken into consideration in order to have a better representation of the vibrating structure. On the other hand, the system identification approach is used to develop the mathematical models in the case of limited physical information about the dynamic system. Thus, this model will be able to represent and replicate the behavior of the system based on the possible previous knowledge and by utilizing the obtained input/output data [34].

A typical dynamic system is depicted on Fig. 2, subjected to the input $u(t)$ and the response of the system is described by the output $y(t)$, which is affected by disturbance $v(t)$. The input $u(t)$ is produced by the environment and affects the system. This input is assumed to

Table 1
Human body parts' frequencies when subjected to vertical vibrations [32].

Body part name	Natural frequencies (Hz)
Abdominal mass	4–8
Arm	5–10
Chest wall	5–10
Eyeball	20–90
Hand	30–50
Head (axial mode)	20–30
Legs—flexing knees	2
Legs—rigid posture	20
Shoulder	4–5
Spinal column (axial mode)	10–12