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Acceleration response spectrum for predicting floor vibration due to occupants jumping

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ABSTRACT

This paper proposes an acceleration response spectrum to predict floors' responses due to occupants jumping. Experiments were conducted on individual jumping loads resulting in 506 records. Each record was applied to a single-degree-of-freedom system with various frequencies and damping ratios to obtain a corresponding acceleration response spectrum. Statistical analysis of the results led to a representative spectrum, which is further used to derive an analytical design spectrum curve. The suggested design spectrum covers a structural frequency range of 0.5–15 Hz and consists of three main parts: the first plateau, the second plateau and the descent. Design values for spectrum parameters were determined by fitting each part's mathematical function to actual data. The proposed spectrum was verified by comparing its predictions with measured responses from an experimental floor model and floors of existing structures induced by both single individuals and crowds jumping.

1. Introduction

In recent years, long-span floors have become more and more popular in the design of modern assembly structures in order to provide open-plan and multifunctional spaces required by clients. Long-span floors are characterized by their low vibration frequencies and low damping ratios, making them prone to vibrations induced by crowd activities such as walking, jumping, bobbing, and dancing [1–5]. The maximum load is typically generated by jumping, which is an activity that person jumps up and down at a single location with both feet leaving the ground repeatedly [6]. Excessive floor vibrations will cause vibration serviceability problems that make the occupants uncomfortable, impair the structure performance, lower the potential commercial value of the building and even lead to panic [7–9]. In a 1985 concert held at Nya Ullevi Stadium in Sweden, excited audiences jumped along with the music and caused damage to the foundation of the stadium [10]. In 1994, during a pop concert in London the temporary grandstand collapsed due to the audience's rhythmic motions including jumping. Fifty people were injured [11]. More recently in July 2011, residents in a 39-story building in Seoul, Korea felt strong vertical vibrations for about 10 min. People thought the building might collapse and fled in panic. The building was closed for two days for field investigation. It revealed that there were no records of an earthquake or strong winds at that time. The most likely cause of the vibration was human group activity at the 12th floor's fitness center [12]. The authors are also aware of several similar incidents of jumping-induced structural vibrations. Most of these incidents, however, have not been publicly reported for various non-technical reasons. Nevertheless, vibration serviceability problems have become a major concern, even a dominating factor, in the design of long-span structural floor systems [13,14].

To assess and prevent the vibration serviceability problem, two common design criteria have been adopted: limitation on the floor's fundamental frequency and limitation on the maximum vibration amplitude. These design criteria are reflected in the AISC Design Guide (1997) [15], International Organization for Standardization 10137:2007 [16], and China's concrete structure design code GB50010-2010 [17]. However, examples show that frequency limitation criteria may result in uneconomical designs, such as a massive concrete floor system with both low frequency and low amplitude properties [13]. Although more accurate than frequency limitation method, the amplitude limitation method has its own drawbacks, such as low computational efficiency. In design practice, in order to calculate a floor's dynamic responses to human-

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induced loads, a finite element model (FEM) needs to be established on which the loads are applied. The subsequent time domain analysis is a time consuming process. Moreover, the human-induced load varies in both time domain and space domain, requiring extra time to assign such a moving load to FEM nodes. A floor's design may often change due to structural, aesthetic and functional reasons, which makes the calculation procedure even longer. For structural engineers who are always working under pressure of time, an efficient yet accurate approach for quickly predicting a floor's maximum response is urgently needed.

The response spectrum method is a very useful tool to predict a structure's maximum response under dynamic loads. The response spectrum is a plot of the maximum representative response parameters versus the natural period of many linear single degree of freedom oscillators to a given load. One well-known use of response spectrum is in assessing the peak response of buildings to earthquakes [18]. Inspired by this idea, we conducted feasibility study attempting to develop an acceleration response spectrum approach to predict the peak response of a floor due to single person jumping [19]. The current study improves this approach by simplifying the mathematical expressions, proposing a modified mode superposition criteria and including crowd jumping effect. Section 2 discusses the experiments conducted in this research to collect the jumping load records that are essential to develop a reliable response spectrum. Section 3 proposes a design-oriented acceleration response spectrum together with its piece-wise mathematical expression. Section 4 studies the design values for spectrum parameters based on statistical analysis. Section 5 provides a detailed application procedure for the response spectrum approach, while its verification follows in Section 6 using both experimental and field measurements. Finally, Section 7 summarizes the key findings in this study.

2. Experiments for collecting jumping load records

It is well known that a database containing a large number of earthquake records is a prerequisite for developing a seismic design spectrum. Similarly, many jumping load records are necessary to establish the jumping response spectrum. Therefore, experiments were conducted to collect individual jumping load records. The experiments were performed in two stages involving in total 92 healthy test subjects. Statistics of age, body weight, and height of all the test subjects are reported in Table 1.

Sixty-seven test subjects took part in the first stage of the experiment (Fig. 1a). Each subject completed five test cases on a floor-mounted force plate (AMTI OR6-7, USA), including four cases with fixed jumping frequencies timed by a metronome and one free jumping case without sound instruction. The four fixed jumping frequencies were 1.5, 2.0, 2.67, and 3.5 Hz, which were the same as those used in experiments by Parkhouse and Ewins [20]. Each test case lasted for more than 25 s in order to obtain stable force records.

To further increase the jumping records in both number and frequency contents, the second stage of the experiment was conducted on twenty-five test subjects using wireless dynamometer pressure-insole sensor technology. The Novel Pedar system (Novel Co., Germany), as shown in Fig. 1b, was adopted. This innovative wireless insole force measurement technology provides the same data quality as that provided by force plate data while allowing the test subject to jump in a more 'natural' way without worrying about landing outside the 'measurement range', which often happens when using force plates. Each test subject completed seven tests including one free jumping and six tests with fixed jumping frequencies at 1.5, 1.9, 2.3, 2.7, 3.1, and 3.5 Hz.

Table 1
Statistics of age, body mass and height of test subjects.

Gender	Number	Age (year)		Body mass (kg)		Height (cm)	
		Mean	Std.	Mean	Std.	Mean	Std.
Male	52	23.4	1.69	65.6	10.08	174.2	5.7
Female	40	24.0	1.97	52.8	5.56	160.5	4.5

A sampling rate of 100 Hz was used in both the first and the second stages of the experiment. All together, 506 individual jumping force records were recorded. Three typical records for slow, moderate and fast jumping frequency are shown in Fig. 2 together with their corresponding Fourier amplitude spectra.

3. Derivation of the design response spectrum

3.1. Response spectrum of each jumping force record

Each jumping load record $F(t)$ was first normalized by the test subject's body weight G and then applied to a single-degree-of-freedom system (SDOF) with a unit mass. The corresponding equation of motion is

$$\ddot{u} + 2\omega\zeta\dot{u} + \omega^2 u = F(t)/G \tag{1}$$

where $\ddot{u}, \dot{u}$ and u are dimensionless pseudo-acceleration, velocity and displacement responses of the SDOF, $\boldsymbol{\omega}$ is the angular natural frequency and ζ is the damping ratio of SDOF. For a given natural frequency and damping ratio, dynamic responses were obtained by solving Eq. (1) numerically. Four commonly used measures (here also called parameters) in vibration serviceability assessment were extracted from the pseudo-acceleration responses (hereafter acceleration response): the peak acceleration a_{peak}, the root-mean-square (RMS) value of the whole response a_{RMS}, the peak 1-s running RMS a_{RMS}^{1s}, and the peak 10-s running RMS a_{RMS}^{10s}. The response spectrum of each record was then established by varying the frequency $\boldsymbol{\omega}$ in the range of 0.05–15 Hz with an increment of 0.05 Hz. Additionally, five levels of damping ratio, 0.01–0.05 with an increment of 0.01, were considered. In total, one jumping load record would generate 20 spectra, i.e. four representative values at each of five damping levels. Fig. 3 shows the $a_{peak}, a_{RMS}, a_{RMS}^{1s}$, and a_{RMS}^{10s} spectrum for one jumping record at 1.9 Hz for damping ratio 0.01, and their amplitudes are 62.17, 44.03, 39.64 and 33.92, respectively. Note that the four spectra are quite similar to each other. They all show dominant peaks corresponding to dominant force harmonics. The derivation procedure of design response spectrum for all the four representative parameters are the same. Therefore, the following discussion will mainly use results relevant to the a_{RMS}^{10s} (hereafter, 10s-RMS).

3.2. Representative response spectra

Previous research has indicated that the human jumping loading is a narrow-band random process, whose randomness comes from two sources: the intra-subject variability and the inter-subject variability [21–23]. The former means that a subject cannot generate identical force pulses during one jumping exercise. The latter means that different test subjects do not generate the same jumping force–time histories even when jumping at the same frequency. Since each test subject contributed several jumping force records in the experiment, multiple response spectra are associated with each test subject. For a given damping ratio, the envelope curve of all the spectra for one test subject was taken as his/her representative spectrum to account for the intra-subject variability. A quantile curve of all 92 subjects' representative spectra was then determined to reflect the inter-subject variability. Fig. 4 shows an example of a representative spectrum for a female test