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Determination of the dynamic load factors for crowd jumping using motion capture technique

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ABSTRACT

The effect of imperfect synchronization is a key factor for modeling crowd jumping loads. Knowledge on this effect is limited due to the lack of crowd jumping experiments. This paper presents an experimental study of crowd jumping of 48 subjects at a frequency range between 1.5 Hz and 3.5 Hz with an interval of 0.1 Hz. The jumping movements of all participants were synchronously and simultaneously monitored using a three-dimensional (3D) motion capture technique. Based on the measured data, dynamic load factors (DLFs) against crowd sizes were determined using the Monte Carlo method. Then, they were converted to the DLF ratios to reduce numerical errors. Results show that the DLF ratios tend to be a constant for a crowd over 48. A simple expression of the ratios is provided using curve fitting. Then the crowd jumping load model was summarized and compared with the measured and published results. Finally, limitations of this study were discussed.

1. Introduction

With new development of construction technology and building materials, modern public structures, such as long-span floors, exhibition halls, grandstands and concert venues, have been characterized by their low natural frequencies that are prone to fall into the frequency range of dance type activities [1]. When the frequency of such activities is equal or close to the natural frequency of the structure, resonant or near-resonant vibrations will occur and may lead to serious structural problems [2,3]. These vibrations may make people feel uncomfortable, panic and even cause casualties [4–9]. Such vibration problems can be avoided at a design stage by gaining a good understanding of rhythmic crowd loads. Jumping action is generally considered as the most severe loading scenario among all individual activities [10]. Besides, crowd jumping to beats or music are common for audiences at concerts or sport games. During a pop concert held in London in 1994, a temporary grandstand collapsed under the audiences' rhythmic jumping with the beat of music, and "more than 50 people were injured" [11]. In 2011, a group of people were exercising at an aerobics center in a 39-story building in Seoul, South Korea, when the generated vibrations were elevated to the point that their activity frequency was close to the building's natural frequency of 2.7 Hz. As a result, "the building shook vertically for about 10 min" which caused occupants to flee in panic [12]. Therefore, it is becoming a critical aspect in design to assess the vibration serviceability of modern public structures due to rhythmic crowd loads where jumping is involved [13,14].

A reliable and practical jumping load model is a prerequisite for vibration serviceability assessment. There have been plenty of experimental and theoretical studies of individual jumping loads and the load model has been well understood [15–17]. When a crowd jumps to follow a music beat, perfect synchronization is unlikely to be achieved. This is because a group of people may not be able to jump at the same time, the same height and the same frequency even following a music beat, which will effectively attenuate the action of the human loads and consequently the response of a structure subjected to such a loading.

In 2004, Ellis and Ji [18] conducted a set of jumping tests up to 64 people on a 6 m × 9 m floor panel following music beats or metronome. The DLFs for groups were identified through the measured displacement-time histories and the known dynamic behavior of the floor panel. Therefore, the load model for an individual jumping could be adopted by using the DLFs for a crowd replacing that for an individual. This load model for synchronized crowd activities where jumping is involved has been adopted by BRE Digest 2004 [19]. Then, Parkhouse and Ewins [20] developed a crowd jumping load model, which analyzed the synchronization between jumping persons and metronome beats based on 600 measured individual jumping load histories. Later, Sim et al. [21] calculated crowd jumping loads by summing up their simulated individual jumping loads, and then proposed displacement and

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acceleration response spectra of crowd jumping.

Single person jumping loads are commonly measured using a force plate, but it no longer works for crowd jumping measurement due to its size limitation. Fortunately, the emergence of an optical motion capture technique in recent years, such as the Vicon system, provides an alternative way to conduct crowd jumping experiments. This technique is based on multiple 3D high-speed cameras to capture the markers, which are attached to the key points of the jumper's body. The trajectories of markers can represent the jumper's motion and be used to calculate loads. Several investigators demonstrated this technique was suitable for their verification experiments [22,23].

In this study, we attempt to conduct a crowd jumping experiment using the 3D motion capture technique, and then develop a crowd load model that considers the synchronization between jumpers based on the measurements. To this end, Section 2 describes a crowd jumping experiment involving up to 48 participants, and a validation experiment was conducted using a force plate. Based on the experimental data, Section 3 studies the key parameters of crowd jumping loads model. Section 4 provides a detail procedure for generating crowd loads, and compares the proposed model with experiment and published results. Section 5 discusses some limitations in this work. Finally, Section 6 summarizes the key findings.

2. Crowd jumping experiment

2.1. Experimental protocol

A set of crowd jumping experiment was conducted on a rigid floor at the basement of a building at Tongji University, China. Up to forty-eight students participated in the experiment and each subject passed a preliminary fitness test that checked their fitness to take the jumping activity. The test protocol satisfied the requirements by Tongji Medical Ethics Committee. The volunteers were uniformly arranged on an 8 m × 6 m test area. A total of 18 3D high-speed cameras were installed in the left, right and front of the test area to ensure that every test area can be captured by at least three cameras at the same time. To capture the movement of participants relatively easily and reliably, three markers were attached to the left, right and middle of each volunteer's clavicles. The experimental setup is shown in Fig. 1.

In the experiment, all the volunteers were asked to jump with the beats of a metronome at selected frequencies. Meanwhile, the trajectories of markers on each volunteer's body were captured at a rate of 100 frames per second. Twenty-one jumping test cases in the range of 1.5–3.5 Hz with an interval of 0.1 Hz were selected and each test case was conducted twice. This led to 42 tests at 21 jumping frequencies. In order to avoid the insensitivity of repeating the same tests, the jumping frequency for tests was randomly selected. As continuous jumping requires the participants to be energetic, the duration of each test was limited to 30 s. Then the participants had a one-minute to rest after each jumping test and a twenty-minute rest after four tests.

Fig. 1. Experimental setup.

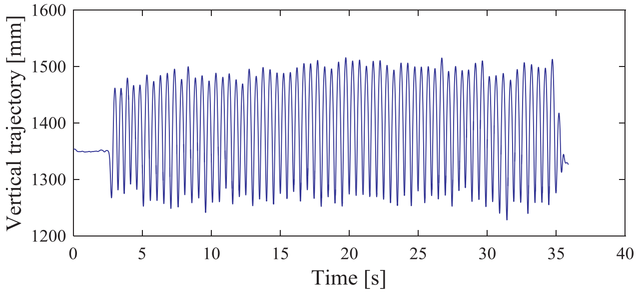

Fig. 2. The vertical movement of a marker at 2.0 Hz.

2.2. Experimental data

After the experiment, a total of 42 sets of crowd jumping data were collected. Since the same jumping frequency test was conducted twice, they will be called the first and second attempts respectively.

Fig. 2 shows the measured vertical movement of a marker from a volunteer who jumped at 2.0 Hz frequency. The vertical acceleration of the jumper was calculated by differentiating the vertical displacement twice. Then a normalized pseudo-load of jumping to the body weight of the jumper is the sum of the normalize body weight and the ratio of the estimated acceleration to the gravity, g, i.e.

$$\overline{F}(t) = \frac{mg + ma(t)}{mg} = 1 + \frac{a(t)}{g} \tag{1}$$

where $\overline{F}(t)$ is the normalized pseudo-load, m is the body mass of the jumper, $a(t)$ is the calculated vertical acceleration from marker. Fig. 3 compares the pseudo-loads of three markers of one volunteer and shows a complete match so that any one of them can represent the other two. However, some markers were not always captured when they were blocked by the neighbouring jumpers, causing the recorded data to become intermittent. For this reason, when none of the three markers for a jumper provided a complete set of data in one test, the measurement of the jumper was considered being invalid and removed. All of the data were checked and the number of valid pseudo-loads at each

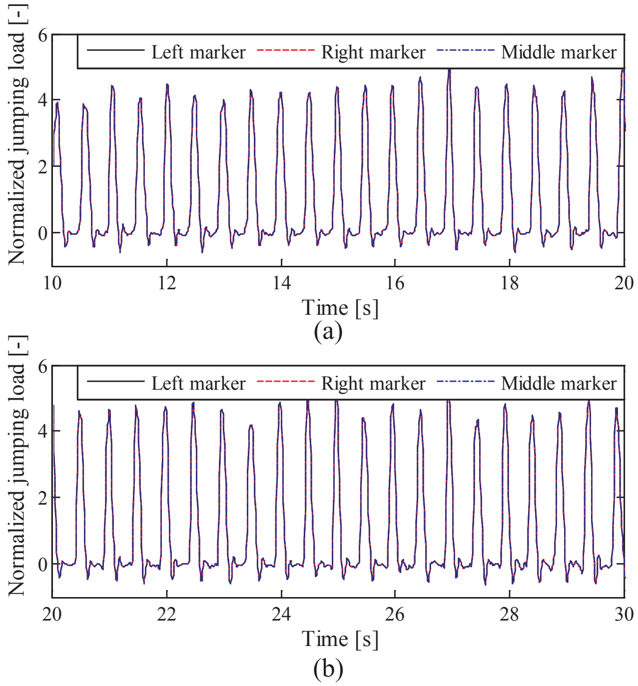

Fig. 3. Comparison of normalized jumping loads belonging to one volunteer at 2.0 Hz (a) Section 10–20 s, (b) Section 20–30 s.