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A data-driven wavelet-based approach for generating jumping loads

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ABSTRACT

This paper suggests an approach to generate human jumping loads using wavelet transform and a database of individual jumping force records. A total of 970 individual jumping force records of various frequencies were first collected by three experiments from 147 test subjects. For each record, every jumping pulse was extracted and decomposed into seven levels by wavelet transform. All the decomposition coefficients were stored in an information database. Probability distributions of jumping cycle period, contact ratio and energy of the jumping pulse were statistically analyzed. Inspired by the theory of DNA recombination, an approach was developed by interchanging the wavelet coefficients between different jumping pulses. To generate a jumping force time history with N pulses, wavelet coefficients were first selected randomly from the database at each level. They were then used to reconstruct N pulses by the inverse wavelet transform. Jumping cycle periods and contract ratios were then generated randomly based on their probabilistic functions. These parameters were assigned to each of the N pulses which were in turn scaled by the amplitude factors β_i to account for energy relationship between successive pulses. The final jumping force time history was obtained by linking all the N cycles end to end. This simulation approach can preserve the non-stationary features of the jumping load force in time-frequency domain. Application indicates that this approach can be used to generate jumping force time history due to single people jumping and also can be extended further to stochastic jumping loads due to groups and crowds.

1. Introduction

Civil engineering structures like footbridge, cantilever grandstands and long-span floors may experience severe vibrations when subjected to human-induced dynamic loads, such as walking, jumping, running. When the activity's frequency is equal or close to the natural frequency of the structure, resonant or near-resonant vibrations can be perceptible to occupants. These vibrations can also cause discomfort or even panic to occupants if excessive, leading to the so-called vibration serviceability problem [1,2].

Jumping action is generally considered as the most severe loading scenario. If the vibration serviceability problem is not well considered at the structural design state, large resonant structural vibrations may occur, making people feel uncomfort-

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able [3,4]. In a 1985 concert held at Nya Ullevi Stadium in Sweden, excited audiences jumped along with the beats of the music and caused damage to the foundation of that stadium [5]. In 1994, during a pop concert in London the temporary grandstand collapsed due to the audience's rhythmic motions, including jumping, and 50 people were injured [6]. More recently in July 2011, a 39-story building in Seoul Korea vibrated for ten minutes causing occupants to flee in panic. The reason was later identified as a group of people exercising at an aerobics center in the 12th of the building [7]. Similar events were also reported in [8–12].

Comfort of occupants in a structure exposed to vibration is usually assessed by the acceleration amplitude experienced. Therefore, the vibration serviceability of a structure is generally evaluated by an index related to its acceleration response to human-induced load, e.g., peak value [13], root mean square value [14] and vibration dose value [15]. In this connection, a reliable load model is a prerequisite for prediction of a structure's response at its design stage. Mathematical models of human-induced load can be broadly classified as either deterministic or stochastic. Where jumping load is concerned, deterministic jumping load models are widely used in current design practice [16–18]. These models treat jumping activity as a periodic process and accordingly represent the jumping load by the Fourier series function. However, significant differences exist between structural responses due to real jumping loads and equivalent periodic simulations [19]. Actually, during jumping activities, he/she can't duplicate each jumping pulse to assure that each jump is identical. This makes the jumping load process stochastic. In view of the shortcomings of deterministic model, several stochastic models have been proposed recently to represent a more realistic jumping load. For individual jumping loads, Sim et al. [20] used a half-cosine-squared function to fit the measured jumping pulses. Key parameters, i.e., jump timing, impact factor and relative contact ratio were assumed to be random variables whose probability distribution functions were determined from experimental records. Based on a large number of experimental data, Racic and Pavic [21] pointed out that a more complex model is necessary to simulate the local temporal and spectral random features of a jumping impulse. They thus employed more than 100 Gaussian functions to fit the shape of each jumping impulse. Chen et al. [22] proposed that jumping pulses should be fitted by a half-sine function during low beat jumping, and the pulses would be better fitted by a half-sine-squared function during high beat jumping. In both cases, controlling factors: jumping frequency, contact ratio (relative jumping time) and peak factor, were taken as random variables. It is clear that all the above stochastic models share the same feature in that they focus on modeling single jumping pulse. A continuous jumping force is thereby constructed on a pulse-by-pulse rule. The key challenges to this rule are how to model (1) the shape, especially the local irregularities, of each jumping pulse and (2) the timing/energy variation between consecutive jumping pulses.

Based on a feasibility study by the authors [23], we suggest using wavelet analysis to tackle the above problems. The goal was to describe the time-frequency localization characteristics in jumping pulses and to develop a wavelet analysis method to represent jumping pulses. Wavelet analysis is probably the most important development in signal processing in the past decades. Since its first appearance in 1984 [24], wavelet analysis has been widely used in signal processing, image processing, noise reduction, structural health monitoring and many other areas. Wavelet analysis is known as a mathematical 'microscope' since it can capture the local irregularities of signals [25]. It is thus worth investigating the application of wavelet analysis to describe the time-frequency localization characteristics in jumping pulses and to develop a wavelet-based method to simulate jumping load. To this end, this paper first collected individual jumping load records from three experiments. Experimental details and data pre-processing are summarized in Section 2. Statistical analysis were conducted on the experimental data, the results are presented in Section 3 with focuses the probability feature of jumping cycle period and contact ratio of each jump pulse. Section 4 describes the usage of wavelet analysis to decompose measured jumping records to develop a database consisting of decomposition coefficients. The inverse wavelet analysis to generate new jumping pulse is also discussed in this section. Section 5 summaries the procedure of the data-driven wavelet-based approach for generating jumping loads. Application of the approach is presented in Section 6. Main findings of this study and limitations of the proposed method are discussed in Section 7.

2. Data collection and analysis

2.1. Jumping experiments

A sufficiently large database of high-quality jumping force records, which also have a fine resolution of measured jumping rates, is a prerequisite for investigating the time-frequency feature of jumping loads. In this study, we developed such a database using individual jumping load records mainly from three experiments: two conducted at Tongji University, China, and one at Sheffield University, UK.

The first experiment was performed in a gait laboratory (Fig. 1a). A total of 67 healthy adults participated in the experiment and they were students and staff of Tongji University. Each test subject was asked to complete five test cases on a fixed force plate (AMTI OR6-7, USA), including four cases with fixed jumping rates (1.5, 2.0, 2.67 and 3.5 Hz) that were timed by a metronome and one free jumping case without sound instruction. A detailed description of the experimental arrangement can be found in Chen et al. [22]. The second experiment conducted at Tongji University involved 25 volunteers, who were all students. The wireless dynamometer pressure-insole sensor technology, Novel Pedar system (Novel Co., Germany) was chosen for the test (Fig. 1b). The Pedar system is an accurate and reliable pressure distribution system for monitoring local loads between the foot and the shoe, which has been widely used in sport biomechanics and kinetic analysis of free gait. This time