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Mathematical model to generate near-periodic human jumping force signals

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ABSTRACT

A mathematical modelling procedure has been developed to generate synthetic vertical force signals induced by a single person jumping. The ability to replicate much of the temporal and spectral features of real jumping loads give this model a definite advantage over the conventional half-sine models coupled with Fourier series analysis. This includes modelling of the omnipresent lack of symmetry of individual jumping pulses and jump-by-jump variations in amplitudes and timing. The model therefore belongs to a new generation of synthetic narrowband jumping loads that simulate reality better. The proposed mathematical concept for characterisation of irregular jumping pulses may be utilised in vibration serviceability assessment of civil engineering assembly structures, such as grandstands, footbridges and concert or gym floors, to estimate realistic dynamic structural response due to people jumping.

1. Introduction

Civil engineering structures, such as grandstands, spectator galleries and floors accommodating sports facilities and concert venues, are expected to be fit for purpose when occupied and dynamically exited by multiple persons and large crowds at special events. There have been numerous high-profile examples of excessive vibration being generated by people dancing, bouncing and/or jumping in unison [1–3]. These problems have clearly indicated shortcomings in the current design guidelines and the level of uncertainty with which civil structural engineers are faced nowadays when designing any of the above-mentioned types of structure which require vibration performance assessment. Of all steps involved in vibration serviceability design, such as establishing acceptance criteria and creating a structural model, determining design loads has the considerable uncertainty and to this end there have been numerous attempts to provide their reliable and practical descriptions [4–6]. Jumping action is generally considered as the most severe loading scenario. Therefore, the aim of this paper is to propose an improved synthetic jumping force model that can be used to simulate more reliably dynamic response, thereby assessing vibration serviceability of civil engineering structures (for which such dynamic excitation is relevant) convincingly at the design stage. The key improvement and added value of the model is its ability to represent dynamic loading from single person jumping as a more realistic near-periodic narrowband process [7],

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rather than a periodic force. The latter model features in all relevant design guidelines worldwide today which are in need of urgent updating to reflect better current state-of-the-art developed over the last 5 years.

Dynamic forces generated by people moving on a structure are commonly determined by direct measurement of the interface forces between the feet and the structure itself, hence they are known as ground reaction forces (GRFs). The typical vertical force time history induced by a single person jumping takes the form illustrated in Fig. 1 and is characterised by a series of single-peak pulses separated by zero-force periods. These periods correspond to the aerial phase of jumping, where both feet leave the ground.

The common engineering practice is to idealise a continuously measured jumping force signal as periodic with the period being the average time between two consecutive jumps, i.e. the average duration of a single jumping cycle [1]. This means that actual forces due to continuous jumping can be recreated by adding a sequence of identical pulses on a cycle-by-cycle basis. Furthermore, a number of investigators [4,5] used a half-sine function to fit morphology (e.g. size and shape) of a single jumping pulse, although no rigorous verification of this approach has been reported. Fig. 2 shows an example of directly measured pulse extracted from Fig. 1 and the associated half-sine model based on modelling parameters suggested elsewhere [5,8]. As illustrated in Fig. 2, the symmetric half-sine pattern cannot fit a typically asymmetric real jumping pulse morphology with visually apparent good accuracy. More recently, Sim et al. [6] made attempts to fit the shape of measured pulses using three analytical functions: the Gaussian distribution function, the half-cosine (equivalent to the half-sine) function and a cosine-squared function, all three symmetrical. For the frequencies higher than 2 Hz, the cosine-squared function gave the best fit and hence was adopted to model the pulse profile. The quality of the fit was frequency dependant: the higher the jumping rate, the cosine-squared function could approximate the shape of the measured pulses better [6]. This is because for jumping in fast motion (typically for the rates higher than 2.5 Hz) people generate landing and launching impulses which are very similar having almost symmetrical pulse shapes. However, attempts to fit reliably pulse shape for slow jumping rates were less successful due to local irregularities and apparent asymmetry in the measured pulses [9].

For dynamic analysis, a set of periodic jumping pulses can be represented more efficiently if expressed in terms of Fourier series with the fundamental harmonic having frequency identical to the jumping rate [4,5]. Such models, utilising

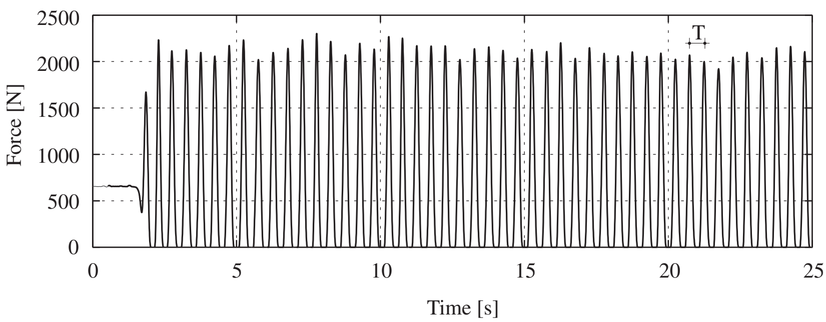

Fig. 1. Example of a vertical jumping force record due to a single person jumping at 2 Hz. $T = 0.5$ s is the average period of a jumping cycle.

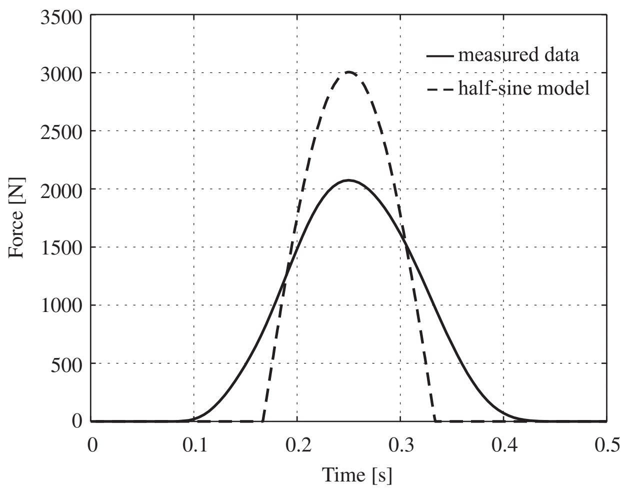

Fig. 2. Measured jumping pulse vs. corresponding half-sine model based on modelling parameters suggested by BS 6399-1 [5,8].