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Data-driven generator of stochastic dynamic loading due to people bouncing

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ABSTRACT

The latest design guideline relevant to bouncing loads describes bouncing as deterministic and periodic process presentable via Fourier series. However, fitting the Fourier harmonics to a comprehensive database of individual bouncing force records established in this study showed that such a radical simplification of the reality leads to a significant loss of key information. Hence, this study brings the Fourier model to a higher level, where the fitted harmonics are personalised, randomised and the natural variability taken into account, leading to a stochastic generator of near-periodic bouncing force time histories which can simulate reliably the actual measurements.

1. Introduction

In civil engineering dynamics there has been a growing number of reported problems related to excessive vibrations of floors, staircases and assembly structures (grandstands, spectator galleries, etc.) in entertaining venues induced by active people. Significant structural motion felt in 1996 on the Manchester United's Old Trafford Stadium and their London rival Arsenal during pop concerts are the first notable problems in the UK [1]. Five years later the Cardiff showpiece Millennium Stadium needed to be stiffened to satisfy safety regulations for concert events [2], while in 2003 Leeds Town Hall had to be evacuated after only 30 min of a rock concert as a 1000-strong crowd of fans induced vibrations so large that the floor occupied visibly cracked [3]. In continental Europe alarming levels of vibrations estimated above 50%g were observed on Nürnberg football stadium in Germany [4], while on the other side of the Atlantic a similar account was given of the Maracanã stadium in Rio de Janeiro Brazil [5]. More recently, during an aerobic exercise session a group of seventeen people caused the 39-story residential–commercial building in Seoul to shake for ten minutes, prompting hundreds to flee in panic [6]. All these represent a sample of the many cases that indicate the level of uncertainty with which civil structural engineers are faced nowadays when designing entertaining venues, which naturally require vibration performance assessment under human-induced excitation.

The main cause of this unsatisfactory situation is that structures are becoming more flexible. Substantial developments in workmanship and structural materials have enabled daring architects and structural engineers to promote more slender designs than previously. These reduce the mass and stiffness of a structure, hence it is more likely to have a natural frequency within the typical range of rates of repetitive body motion of active occupants (i.e. up to 5 Hz) yielding a large (and often resonant) dynamic response. Moreover, there is a lack of adequate design guidance relevant to crowd rhythmic excitation. BS 6399-1:1996 [7], BRE Digest 426 [8], the User's Guide to the National Building Codes of Canada [9] Commentary D (Part 4 of Division B) and ISO 10137:2007 [10] were shown to be over-conservative based upon observations of real structures [11]. The Institution of Structural Engineers (IStructE), Department for Communities and Local Government (DCLG), Department for Transport, Local Government and the Regions (DTLGR) and Department for Culture, Media and Sport (DCMS) have been closely involved with a number of UK research projects designed to address the problem [12–18] and the results have been fed into two world leading design recommendations [19,20]. Their latest design guidance on crowd dynamic loading of grandstands [20] is a step in the right direction but still not perceived as the final version. The vital

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Nomenclature

f_b	bouncing rate or bouncing frequency	W_j	Gaussian heights (weights)
$F(t)$	force time history	c_j	Gaussian centres
G	body weight	b	Gaussian widths
α_i	dynamic load factors (DLF)	$Z(t)$	template shape
φ_i	Fourier phases	E_i, E'_k	energy of weight normalised cycles
f_s	sampling rate	E_{tc}	energy of template cycle
T_i, T'_k	cycle intervals	ΔE_i	disturbance term
τ_i, τ'_k	normalised cycle intervals	ξ_k	scaling factor
μ_T	mean of T_i	ρ_0, ρ_1	coefficients of linear regression
$S_\tau(f_m), S'_\tau(f_n), S'_\tau(f)$	ASD of τ_i and τ'_k	ρ	correlation coefficient
Δf, $\Delta f'$	spectral spacing	N	number of cycles
$A_\tau(f_m), A'_\tau(f_n)$	Fourier amplitudes of τ_i	T	duration of force signal

refinement should address modelling the actual nature of human activities and the corresponding loads. Although there can be no absolute certainty on the way any random group of people will behave, the guidance is grounded on a conservative deterministic representation of crowd dynamic loading. More adequate models would portray it as a stochastic process suitable for probabilistic performance-based assessment of structural vibration response. This should be done in a similar fashion as modelling wind, wave or earthquake loading has been done for decades, all of them characterised by considerable uncertainty and randomness – the feature this study specifically aims to address.

While it is widely recognised that the most severe crowd-induced loading of entertaining venues comes from jumping, it is often rightly assumed that bouncing loads are more realistic for groups and crowds in the long term. Bouncing is a typical action in response to aural stimulation and has often been described as attempting to "jump" whilst the feet remain in contact with the ground [11]. People find bouncing preferable to jumping due to the lower energy consumption [12], which makes it particularly comfortable during long concert events [20]. The magnitude of the loading is smaller and more regular in comparison to high loads from jumping [21,22], but as the subject remains in contact with the structure they can comfortably achieve a greater activity rate. For instance, Yao et al. [12] reported that bouncing frequencies can be as high as 4.5 or even 5 Hz. For all these reasons, the focus of the present study is on bouncing loads only.

A key ingredient of a reliable load model of bouncing crowds is a reliable model of individual bouncing forces. Measured individual force time histories are characterised by immense inter-subject variability and are invariably near-periodic [23,17], indicating their narrow band nature (Fig. 1). However, to ease design process, they are commonly assumed identical, perfectly periodic and presentable via Fourier series [20]:

$$F(t) = G\sum_{i=1}^{m}\alpha_i \cos(2\pi i f_b t - \varphi_i) \quad (1)$$

Here $F(t)$ is the force magnitude at time t, with G representing the body weight in the same unit (most frequently N). Coefficients α_i and φ_i are the dominant Fourier amplitudes and phase angles corresponding to m integer multiples of the bouncing rate f_b (Fig. 1b). Known as "dynamic load factors" (DLFs), α_i were studied on a limited sample of bouncing force records and the results were reported in the Working Group guideline [20]. However, φ_i have been ignored (i.e. $\varphi_i = 0$) and the values have never been publicised in detail. Section 3 presents results of fitting both α_i and φ_i to the largest database of experimentally measured individual bouncing force signals established in Section 2. In the context of the present study, these results are used in Section 3 to describe morphology of the bouncing force signals.

It is now widely accepted that the modelling strategy based on Fourier harmonics leads to significant loss of information during the data reduction process [24–26,22,27,28]. For example, Brownjohn et al. [25] demonstrated that neglecting the energy around dominant Fourier harmonics (Fig. 1b), which is a result of uneven footfalls, yields up to 50% error in predicted vibration response. More recent study by Van Nimmen et al. [29] showed that precision of simulated resonant vibration response primarily depends on whether variability of timing between successive footfalls is taken into account. A model of variability of successive bouncing intervals is elaborated in Section 4, while variability of the corresponding force amplitudes is presented in Section 5.

The primary objective of the present study is to build a mathematical framework that can generate the correct interface forces between individuals and the occupied structure. Key modelling parameters are carefully selected to enable model calibration against force signals recorded under a wide range of conditions. Here, it is shown how the modelling parameters can be extracted from forces generated on a flat stationary surface, hence discounting the effect of human–structure dynamic interaction [11], while the test subjects were bouncing to an auditory stimulus only. However, there is convincing evidence that environment, vibration level, age, gender and fitness, as well as different combinations of auditory, visual and tactile stimuli exert a strong influence on individuals bouncing and the resulting forces [11]. These still need to be measured and incorporated into the suggested modelling framework.

2. Experimental data collection

The data collection was carried out in the Light Structures Laboratory in the University of Sheffield, UK. A test protocol, approved by the Research Ethics Committee of the University of Sheffield, required all participants should complete a Physical Activity Readiness Questionnaire and a preliminary fitness test (measuring blood pressure and resting heart rate) to check whether they were suited to the kind of physical effort required during the experiment. Measurements of the body mass, age and height were taken for test subject who passed the fitness test. Although different types of footwear affect the force records [30], all participants wore comfortable flat shoes due to health and safety reasons.

Each participant was engaged in twelve bouncing tests, thereby generated twelve force signals. During each test a participant was asked to bounce to a steady metronome beat which was randomly selected from the frequency range 1.2–4.5 Hz with the increment of 0.3 Hz. A test lasted between 25 and 45 s, being shorter for the higher frequencies so the participant would not tire much. Rests were allowed between the tests.