Measurement and Application of Bouncing and Jumping Loads Using Motion Tracking Technology

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ABSTRACT

State-of-the-art facilities for measuring bouncing and jumping ground reaction forces (GRFs) comprise typically equipment for direct force measurement, i.e. single or multiple floor-mounted force plates. Artificial laboratory conditions and constraints imposed by the direct measurement systems, such as small measuring area of a force plate, can have a strong influence on human ability to bounce and jump, naturally yielding unrepresentative force data. However, when dealing with issues like vibration serviceability assessment of real full-scale structures, such as floors, footbridges, staircases and grandstands, there is a growing need to estimate realistic GRFs under a wide range of natural conditions. This paper presents a novel method in the civil engineering context utilising 'free-field' measurement of human bouncing and jumping forces recorded continuously in time using motion capturing technology transferred and adapted from biomechanical research. Results showed that this kind of data can be used successfully in studies of human-structure dynamic interaction, specifically negative cue effect of a perceptibly vibrating structure on GRFs and energy flow and power in the human-structure system, as well as synchronisation between individuals when bouncing/jumping in groups on more or less perceptibly moving structures.

NOMENCLATURE

F_{GR}	ground reaction force	g	gravity
m_i	mass of i-th body segment	s	number of body segments
a_i	acceleration of i-th body segment		

1 INTRODUCTION

In the last decade, there have been rapidly growing numbers of grandstands and entertainment venues that have failed to perform satisfactorily when occupied and dynamically excited by multiple persons and large crowds bouncing and/or jumping in unison [1-3]. These mostly vibration serviceability problems have indicated high levels of uncertainty with which civil structural engineers are faced nowadays when designing any of the above mentioned structures which require vibration performance assessment.

There have been numerous attempts to provide reliable and practical descriptions of human bouncing and jumping loads by measuring the contact forces between the ground and test subjects, hence generally known as ground reaction forces (GRFs). For this purpose Ebrahimpour et al. [4] and Pernica [5] designed a 'force platform', whereas Rainer et al. [6] used the continuously measured reaction of a floor strip having known dynamic properties. Much research into GRFs has been done in the biomechanics community, as GRF patterns provide useful diagnostics in medical and sports applications [7, 8]. Therefore, it is not surprising that the present state-of-the-art equipment for the force measurements, i.e. the 'force plate', emerged from the field of biomechanics of human gait. However, there are a few disadvantages of force plates that make them less suitable in vibration serviceability assessment of civil engineering structures. Firstly, standard dimensions of force plates (typically 0.6x0.4 m) are not large enough to accommodate jumping for some individuals who must control and target their jumps to the relatively small force plate area so as to allow adequate recordings. As a result, this targeting effort can

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affect ability to jump naturally and therefore alter GRF patterns [8]. Secondly, force plates cannot provide accurate measurements when mounted on a flexible structure due to self-inertia. This is because they behave like 'accelerometers' and produce outputs including inertia forces of the moving support surface [9]. Therefore a typical experimental setup includes force plates mounted on a rigid laboratory floor, thus limiting the measurements to laboratory conditions. However, when investigating issues related to vibration serviceability there is a growing need for monitoring many subjects during daily life activities in their natural environment, such as office, sport facility, or a footbridge.

Bearing all this in mind, one way forward is an alternative experimental approach to account for all drawbacks of force plates. Several biomechanical studies designed to estimate the contribution of motion of various body segments to vertical GRFs [10-12] offer a step in this direction. Using these biomechanical studies as a solid foundation, this paper aims to present a reader, conversant with vibration serviceability problems of civil engineering structures, with a novel method, in the context of a civil engineering application, to utilise 'free-field' measurement to obtain bouncing and jumping GRFs in a wide range of conditions. The free-field measurement applies the method to estimate the forces in the real world (i.e. naturally-occurring environments) rather than in a constrained laboratory setting. The method will also enable study of areas of significant interest and lack of knowledge, specifically human-structure dynamic interaction and coordination of movements between a number people bouncing/jumping on more or less perceptibly moving structures.

In the context of this paper, human-structure dynamic interaction aims to address two related key issues. Firstly, how perceptible structural vibrations can influence forces induced by active human occupants, and secondly, how active human occupants influence the dynamic properties (e.g. damping) of a civil engineering structure they occupy and dynamically excite.

2 THEORETICAL BACKGROUND

According to Newton [13], the origin of dynamic forces is in momentum changes, which, for constant mass, means that the force is product of mass and acceleration. As applied to the human body, the vertical force acting upon the body (i.e. vertical ground reaction force F_{GR}) can be defined as [3]:

$$F_{GR} = \sum_{i=1}^{s} m_i (a_i - g) \tag{1}$$

where g is the static acceleration due to gravity (noting that upward accelerations are defined as positive, hence g=-9.81 m/s^2 in the UK), m_i and a_i are mass and acceleration of the centre of the mass of the i-th body segment and s is the total number of body segments. This relation implies that the force a person generates against the surface must react against inertia of their body, so the sum of products of masses and accelerations for all body parts must equal the GRF at all times. Similar to earthquake engineering, the only source of external excitation is the inertial force, which then generates other forces through the human body, being transmitted ultimately to the support of the body and resulting in the GRF. This is the key principle behind the idea of estimating GRFs via measuring motion of the body segments.

In this study, physical parameters associated with each rigid segment, such as mass and position of its centre, are estimated using regression equations proposed by de Leva [14], while measurement of body motion was considered using Coda [15] optical motion capture technology. More detailed explanation of different methods for estimating anthropometry of human bodies and technology for body motion tracking can be found in a comprehensive literature review article published recently by the authors [16].

The strategy for verification of the method described by Equation (1) is as follows:

1) Measure simultaneously motion of test subjects jumping/bouncing and vertical response of a simple structure whose modal properties (of the empty structure) have previously been obtained from modal testing.
2) Perform forward response analysis by utilising the reproduced human induced loading in conjunction with the known modal properties of vertical modes of the empty test structure.
3) Compare these responses with their measured counterparts.

3 DATA COLLECTION

All preparatory steps necessary for the launch of the experiments are explained in Section 3.1. Results of the modal testing of a simple test structure are presented in Section 3.2, while synchronous monitoring of the body motion and structural response due to jumping/bouncing on the structure is elaborated in Section 3.3.

3.1 PREPARATORY PHASE

Two male volunteers (age 27 and 30 years, body mass 70 and 67 kg) participated in the experiment. Using a modelling strategy proposed by de Leva [14], 15 body segments and corresponding segmental masses and positions of segmental mass centres of each participant were defined. The segmentation comprised the pairs of the feet, the shanks, the thighs, the hands, the forearms, the upper-arms, as well as the pelvis, the trunk, and the head. The segmental ends were defined via nine motion tracking markers (also called 'target' markers) stuck to the head and major body joints such as ankle, wrist, knee or elbow, as illustrated in Figure 1b. Because the number of available markers is limited, as well as to reduce the subject's preparatory time and to enable simple and time-efficient experiments, symmetry of motion in the vertical plane between the left and right body segments was assumed.

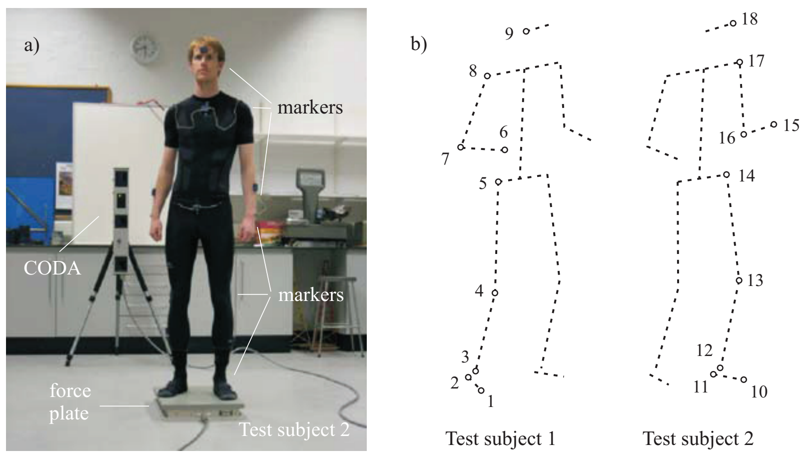

Figure 1: (a) Experimental setup. (b) Human body model and arrangement of markers.

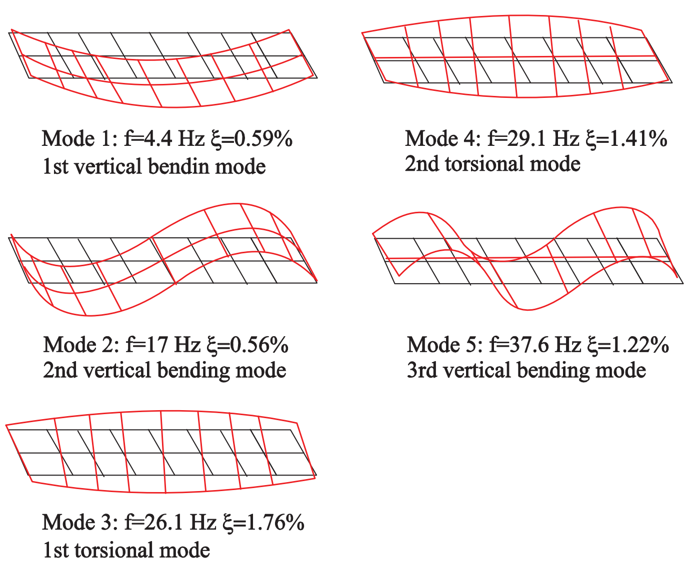

Figure 2: Experimentally estimated modal properties on the test structure (first three vertical bending modes, first two torsional modes).

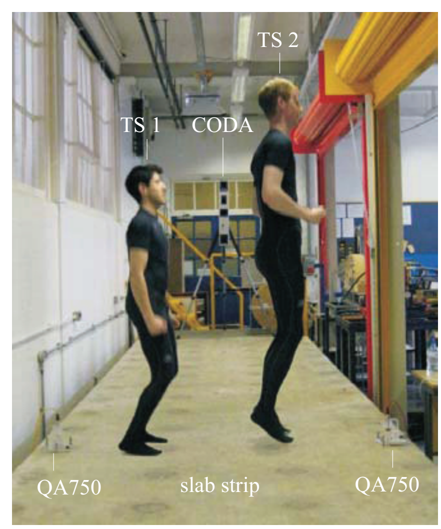

Figure 3: Two test subjects jumping together on the slab strip.

3.2 TEST STRUCTURE AND EXPERIMENTAL MODAL ANALYSIS

The test structure is a 15-tonne pre-stressed concrete slab strip situated in the Light Structure Laboratory of the University of Sheffield, UK. The slab strip is 11 m long and 2 m wide and, structurally, it presents a simply supported beam (Figures 2 and 3).

The natural frequencies, modal masses, modal damping ratios and mode shapes of the structure were determined by shaker modal testing. The modal testing is described in [3] and results are presented in Figure 2.

3.3 BODY MOTION DATA COUPLED WITH RESPONSE MEASUREMENTS OF THE STRUCTURE

Each test subject, fully instrumented with the Coda markers, was asked to either jump or bounce alone in the mid-span of the structure in response to regular metronome beats at three different tempos: 2, 2.2 and 2.5 Hz. Note that jumping and bouncing at 2.2 Hz excited the structure as near to resonance as possible by the second harmonic of the corresponding forces. On the other hand, closely spaced tempos at 2 and 2.5 Hz excited the structure out of resonance. Nominally identical tests were repeated when the two test subjects were jumping/bouncing together (Figure 3).

The Codamotion host computer enabled simultaneous acquisition of vertical movement of the body markers and response of the structure measured in the middle of the span by both a QA750 [17] accelerometer and a tracking marker. Both body motion data and vibration response were sampled at 200 Hz.

The aim was to calculate response of the structure by using the forces reproduced from the body motion data and the modal properties of the first vertical mode determined in Section 3.2. A good match between the calculated and directly measured accelerations should provide a proof that the forces can be reproduced successfully. This is the key aspect outlined in the next section, together with the possibility to use the reproduced forces in a study of human-structure dynamic interaction and synchronisation of people when jumping/bouncing in groups.

4 FORCES INDUCED ON TEST STRUCTURE

Movement of the skin relative to the underlying bone is one of the major sources of error when reconstructing human-induced forces from body motion data [16]. This is known as “soft tissue artefact” and is dominant during highly accelerated movements, e.g. when the feet abruptly hit the ground. Skin markers then oscillate considerably in an unsteady way with respect to the underlying bone, inducing high-frequency noise in the marker data. To filter out the noise, a fourth order low-pass digital Butterworth filter (LPF) having cut-off frequency 15 Hz was applied to accelerations of all markers. Figure 4 illustrates accelerations of the hip marker obtained with and without filtering out the noise above 15 Hz from the displacement data. It can be seen that the main visible features of the markers’ accelerations representing the whole body segment motion remain intact after the filtering.

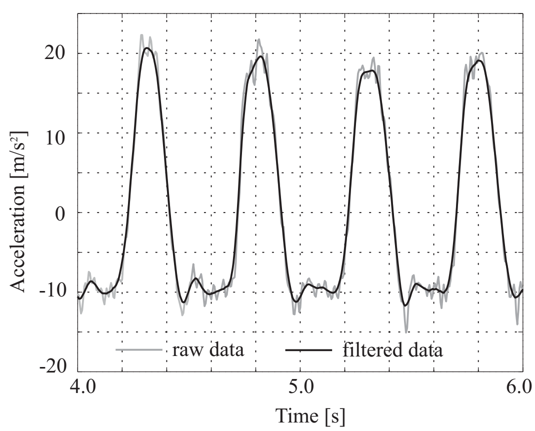

Figure 4: Raw and filtered accelerations (CF=15Hz) of a hip marker due to jumping at 2 Hz.

In the next two sections, filtered acceleration time histories of a kind given in Figure 4 will be used in conjunction with information about the values and locations of the segmental masses (see Section 3.1) to calculate the GRF time histories according to Equation (1).

4.1 SINGLE TEST SUBJECT

The force time histories generated in the mid-span of the structure when test subjects were bouncing or jumping alone in response to the regular metronome beats (at 2, 2.2 and 2.5 Hz) were reproduced from body motion data collected in Section 3.3. As an illustration, the reproduced force signals for Test Subject (TS) 1 bouncing are given in Figure 5a-c. The corresponding Fourier amplitude spectra in the vicinity of the second dominant harmonic are given in Figure 5d-f.

The best way to check if the reproduced forces are correct is to compare responses of the structure measured directly by the accelerometers (Section 3.3) and those calculated from the corresponding SDOF model of the structure. The latter can be obtained using the reproduced forces as the forcing function together with the nonlinear modal properties of the first vertical mode (Section 3.2).

A good match between the calculated and directly measured accelerations in the mid-span of the structure (Figures 5g-i) strongly suggest that the forces have been reproduced successfully. Strong Fourier amplitudes at 4 and 5 Hz and slight ‘spread’ of energy to adjacent spectral lines in Figures 5d and 5f indicate that TS 1 could follow metronome beats well when jumping and bouncing at 2 and 2.5 Hz, respectively. However, for jumping and bouncing at 2.2 Hz, the spread of energy is more prominent around 4.4 Hz (Figure 5e). The same effect was observed for TS 2 as well. This indicated that it was more difficult for them to follow the metronome beat when the structure was dynamically excited in resonance, i.e. they varied more their jumping/bouncing rate when structural responses were greater. As noted elsewhere [18], the most likely explanation for this happening is the influence of large levels of the resonant structural response on the ability of the test subjects to keep jumping/bouncing regularly. This is because the human body is a very sensitive vibration receiver characterized by the innate ability to adapt quickly to almost any type and level of vibration which normally occurs in nature [19].

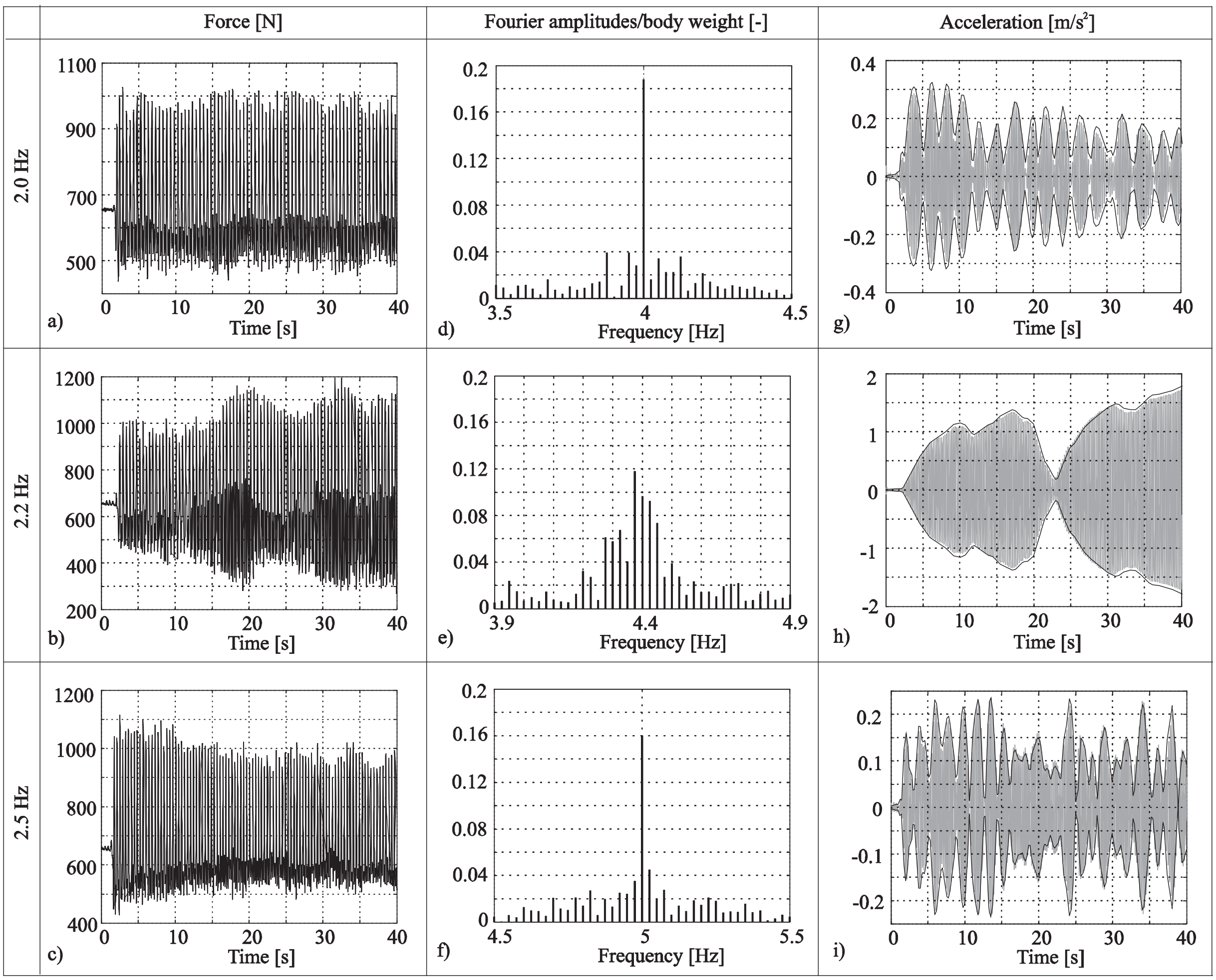

Figure 5: (a-c) Reproduced force time histories, (d-f) the corresponding Fourier amplitudes in the vicinity of the second dominant harmonic, and (g-i) measured (grey) and envelope of simulated (black) accelerations of the structure generated by TS 1 when bouncing on the test structure in response to regular metronome beats at 2, 2.2 and 2.5 Hz.

4.2 TWO TEST SUBJECTS

Following the same logic from the previous section, nominally identical analysis was carried out based on the motion data recorded for both test subjects bouncing and jumping together in the mid-span of the structure in response to regular metronome beats at 2, 2.2 and 2.5 Hz (Section 3.2). As in the case of single test subject, a proof of successful force reproduction for all jumping/bouncing rates is a good matching between the measured vibration responses (Section 3.2) and those calculated from the corresponding SDOF model using the reproduced forces and the modal properties. The results are elaborated in [3].

Although the test subjects were following the same metronome beats when jumping and bouncing together, there was a sporadic lack of coordination between their movements, which is reflected in a lack of synchronisation of the corresponding peak force amplitudes on a cycle-by-cycle basis. Here, one jumping or bouncing cycle corresponds to a period needed to complete one jump or bounce.

In Figure 6, there are cycles for which time instants of individual peak amplitudes match well, indicating a high synchronisation level. Also, this resulted in large peak amplitudes of the total sum force for these cycles. However, because humans are not machines, despite the metronome beat they could not keep moving in synchronisation for a long time, causing peaks to diverge and their sum to decrease. After a while, the process starts to reverse, i.e. the peaks start moving towards each other and finally meet, being synchronised again. Therefore, the lack of synchronisation can be quantified through relative changes of time lags Δt_i between peaks of individual force signals on a cycle-by-cycle basis (Figures 6b and 6d). A summary of mean values and standard deviations of Δt_i values extracted from 30 s duration of all group force signals is given in Table 1.

The largest values of the mean and standard deviation are for the excitation causing near-resonant response for both bouncing and jumping indicating that the synchronisation was most affected by the large structural vibrations. Also, for both resonant and non-resonant rates, synchronisation during jumping was better compared with the bouncing counterparts.

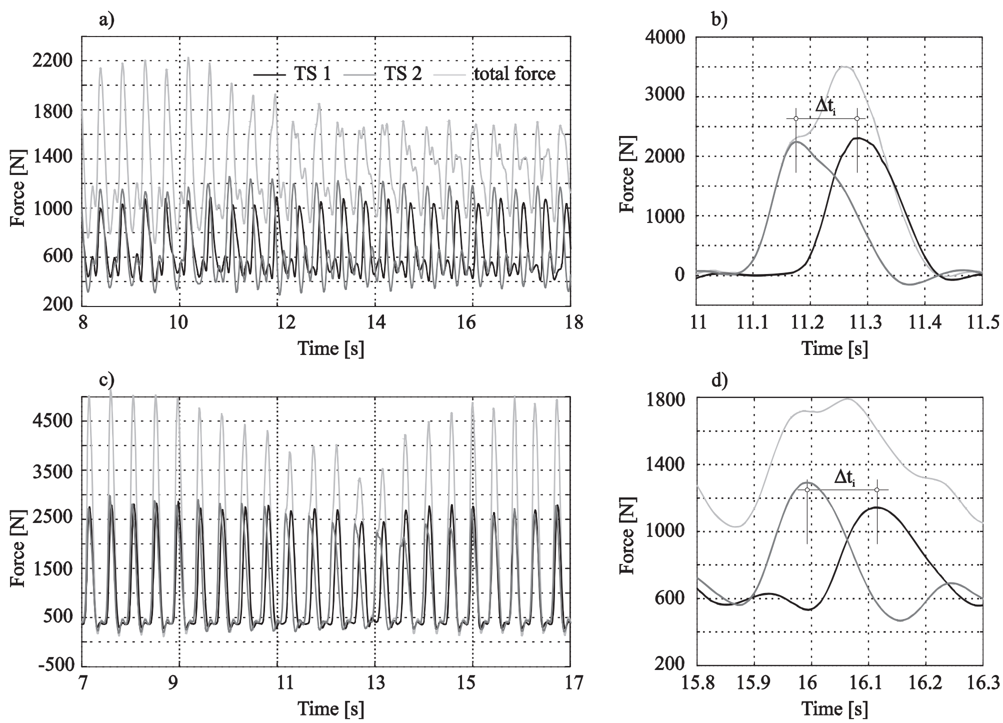

Figure 6: Synchronisation of (a-b) bouncing and (c-d) jumping forces. **Error! Reference source not found.** and 17 illustrate the same data.

Table 1: Summary of statistics (mean ± standard deviation) of Δt_i:

Frequency [Hz]	bouncing [s]	jumping [s]
2.0	0.052 ± 0.036	0.039 ± 0.020
2.2	0.076 ± 0.076	0.073 ± 0.036
2.5	0.049 ± 0.024	0.022 ± 0.012

5 ENERGY FLOW AND POWER

A useful technique for studying human-structure dynamic interaction involves analysis of the power developed by human occupants moving on a structure and the power represented by the rate of internal energy dissipation in a structure conceptualised via damping forces [20]. Energy, with the units of Joules [J] or [Nm], is the time integral of power and is a more familiar quantity whose flow is easy to visualise. However graphical representation using power, with units of Watts [W] or [Nm/s], is simpler to study for comparative purposes.

For the slab strip, supply of energy to the structure at the point of contact is the instantaneous product of velocity $\dot{x}(t)$ and contact force f(t). The contact force f(t) could be obtained either directly by a load cell or reproduction from the marker motion, while velocity could be obtained by integrating accelerometer signals or differentiating contact point marker displacements. Here, the contact force is measured indirectly using Equation (1) and the velocity is obtained from displacements of a marker attached to the middle of the span where the activity was happening.

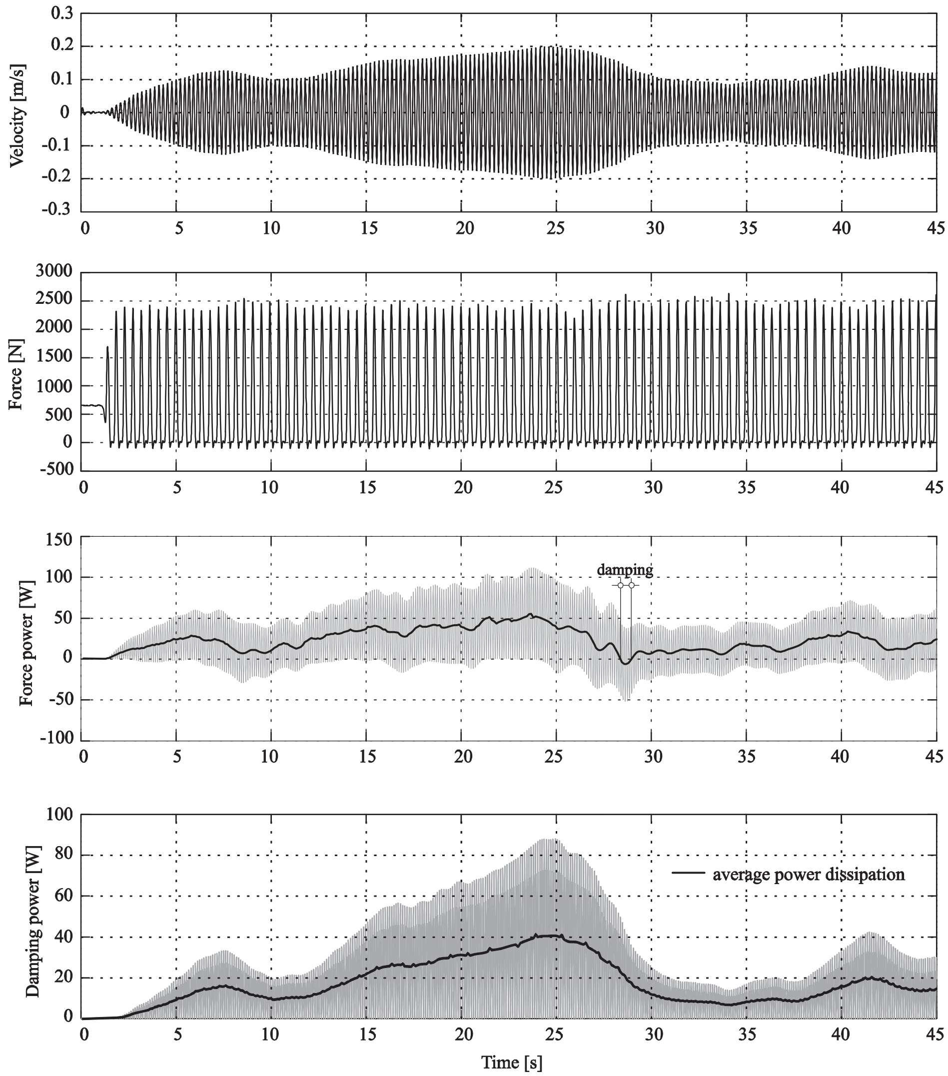

Figure 7:Energy flow and power due to TS 1 jumping in the middle of the span at resonant rate of 2.2 Hz.

Consider an equation of motion of a SDOF system, e.g. the first mode of vibration of the slab strip excited by a jumping force at the midpoint (antinode). If the mode shape is unity scaled at the midpoint then modal and physical displacements at the mid-point are identical and can both be represented by x(t) which is a solution of the following well known differential equation [21]:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \tag{2}$$

Here, m, c and k are the modal mass, damping and stiffness, respectively. Multiplying by the modal/physical velocity $\dot{x}(t)$, the equation of motion can be used to calculate instantaneous power $f(t)\dot{x}(t)$:

$$m\ddot{x}(t)\dot{x}(t) + c\dot{x}(t)\dot{x}(t) + kx(t)\dot{x}(t) = f(t)\dot{x}(t) \tag{3}$$

Here, $m\ddot{x}(t)\dot{x}(t)$ is kinetic power, $c\dot{x}(t)\dot{x}(t)$ is damping power and $kx(t)\dot{x}(t)$ is potential power.

In resonance it is well known that the inertia and stiffness forces are perfectly balanced with the interchange of kinetic and potential energy resulting in a constant value of energy and no net supply to either of them. Simultaneously, the external force simply provides positive power to compensate for the energy dissipated internally via damping (damping power):

$$m\ddot{x}(t)\dot{x}(t) = kx(t)\dot{x}(t)$$
$$c\dot{x}^2(t) = f(t)\dot{x}(t) > 0 \qquad (4)$$

Away from resonance in steady state the damping power is always positive (due to the square term in $c\dot{x}^2(t)$) but the external power has a zero-mean oscillating component which supplies and withdraws power during a cycle due to the imbalance of inertia and stiffness forces. During build up of response towards resonance the external force only supplies and never withdraws power to build up the constant level of total (i.e. kinetic plus potential) energy.

In the case of a single TS jumping, Figure 7 shows positive power as response levels build up, with corresponding increasing damping power. The jumping human power cycles below zero, sometimes because the response is off-resonance, but also sometimes because the TS is actually out of synchronisation with the motion, resulting in net removal of energy. The cycle-by-cycle average power, represented by the heavy line, shows whether the human is active (driving) or passive (damping) overall. In [3], the same effect is illustrated for bouncing.

For the two TSs bouncing/jumping together (Figure 8), the individual cycle-by-cycle average power plots show that TS 1 was supplying energy to the system most of the time during the tests, while TS 2 was often acting as the strong damping element. This clearly explains why the resonance was very difficult to maintain for both activities. These tests also confirmed findings elsewhere [22] that the humans are characterised by huge inter-subject differences between their abilities to induce dynamic loads, to change the dynamic properties and to respond to nominally the same vibrations of the structure they occupy and dynamically excite.

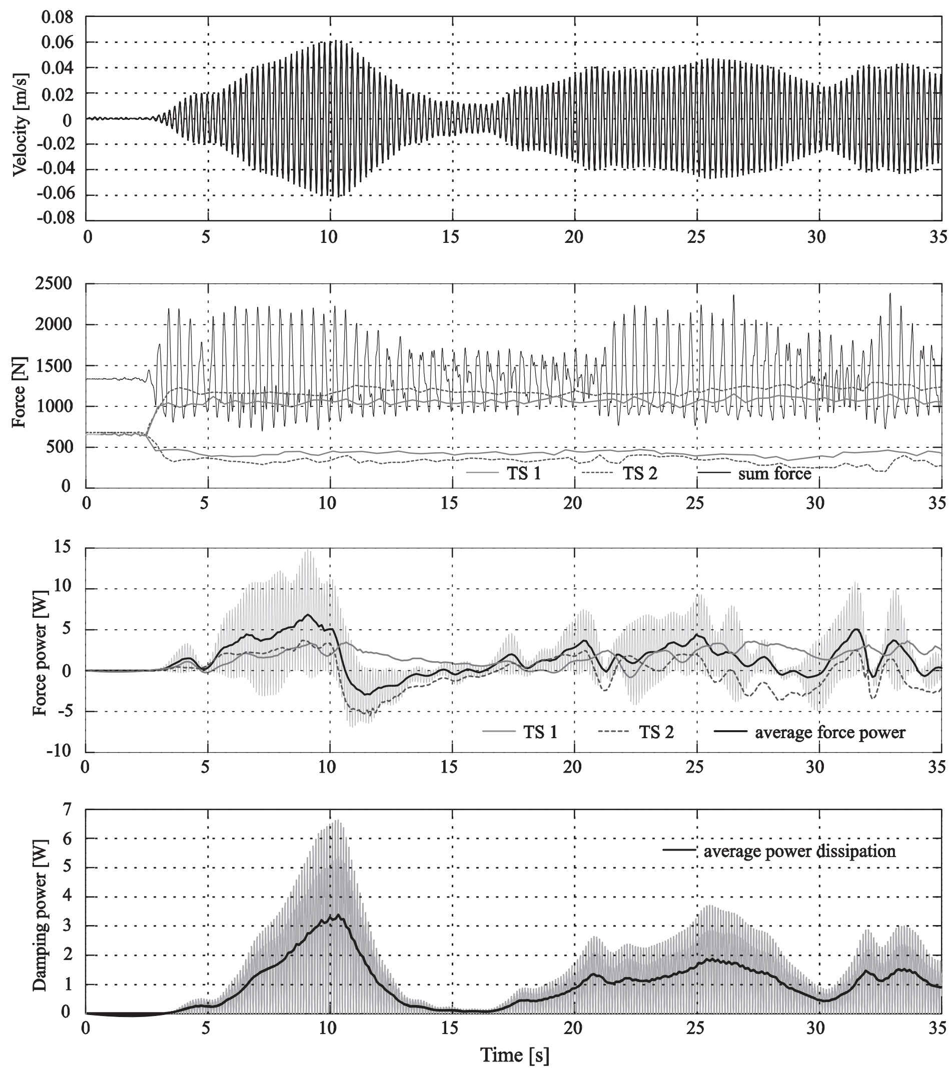

Figure 8: Energy flow and power due to both TSs bouncing together in the middle of the span at resonant rate of 2.2 Hz.

6 CONCLUSIONS

This paper presents a novel method in the civil engineering context to measure indirectly bouncing and jumping GRFs by combining human body motion tracking data and known/assumed body mass distribution. When compared with the traditional direct force measurements on floor-mounted force plates, a key advantage of the method proposed is utilisation of 'free-field' measurement of continuous bouncing and jumping GRFs. As demonstrated, indirect force measurements enable monitoring of people performing rhythmic activities in their natural environments, such as footbridges, grandstands, staircases and open-plan floors. Moreover, the method enables study areas of significant interest and uncertainty, specifically human-structure dynamic interaction and synchronisation between occupants when bouncing and jumping on flexible structures. Measurements have been able to show the negative cue effect of perceptible vibrations on the GRFs. Also, they indicated that in the joint human-structure dynamic system an active human can not only be the source of energy but they can also act as the strongest damping element. This happens either because the response is off-resonance or because they are out of phase with the structural motion resulting in net removal of energy. The effect is even stronger for multiple occupants due to the lack of synchronisation of their movements.

The method piloted in this paper has been validated using two male participants, who were jumping or bouncing either individually or as a pair on a realistic test structure. This means that there remains a requirement to carry out similar tests for single individuals and multiple occupants moving on a number of different, more or less vibrating real-life structures. Measurements can be used to develop and calibrate a new generation of badly needed models of rhythmic crowd loads. Therefore, this approach presents a timely opportunity to advance the whole field of vibration serviceability assessment of structures predominantly occupied and dynamically excited by bouncing/jumping humans, such as grandstands and entertainment venues.

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