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Development of a human-structure dynamic interaction model for human sway for use in permanent grandstand design

Varvara Vasilatou[a]*, Rob Harrison[a], Nikolas Nikitas[b]

[a]*Ove Arup and Partners, 6th Floor, 3 Picadilly Place, Manchester, M1 3BN, United Kingdom*
[b]*School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom*

Abstract

This paper details a first attempt to develop a simple human-structure dynamic interaction (HSDI) model for vibration serviceability design of permanent grandstands subject to crowd sway. To date, extensive research has been conducted on vertical crowd-induced vibrations to understand interaction mechanisms and enable engineers to account for them. Similar mechanisms have not yet been fully understood or researched in the lateral plane. This, alongside the limited, verified measured response data has led to incomplete design assessment methods. In this work, an effective two-degree-of-freedom spring-mass-damper-actuator system is developed to represent co-ordinated spectators swaying laterally in the side-to-side direction on a real grandstand. The dynamic properties attributed in the constituents of the model are determined by curve fitting of laboratory-scale human sway data and the modal analysis of the grandstand's finite element model. The comparison of the modelling output against existing serviceability criteria approaches illustrates potential conservatism in current practice. Namely, when the maximum responses and forces were examined as part of the integrated dynamic system a notable drop-out effect was observed. Although further research is required to validate and calibrate the proposed simple human-structure sway model for individuals and crowds, the observations qualitatively determine the significance of explicitly considering human-structure interaction in the design and assessment of permanent grandstands. Such effects may lead to construction cost savings in addition to unwanted limitations on architecture, hospitality areas and spectator circulation.

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Keywords: Crowd loading; stadium design; sway; human-structure dynamic interaction; permanent grandstands

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* Corresponding author. Tel.: +44-161-228-2331
E-mail address: varvara.vasilatou@arup.com

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1. Introduction

Designs of permanent grandstand structures must meet both strength and serviceability requirements including those due to dynamic crowd loading from motions such as jumping, bobbing, dancing and swaying. Such motions can be rhythmic and synchronised in nature leading to the potential for resonant excitation of the structure. In these circumstances, the resulting vibrations can lead to spectator discomfort with the potential for crowd panic.

Vertical spectator motions such as jumping and bobbing are commonly observed at both sports matches and musical events and have in the past led to documented issues for stadium operators. These behaviours are well researched and are covered in various international guidance documents to different levels of detail.

Horizontal spectator motions such as side-to-side and front-to-back sway are less commonly observed and have attracted far less research attention. Some guidance documents do provide limits for use in design, typically in the form of a minimum structural natural frequency above which resonant excitation is deemed unlikely. For instance, guidance by the IStructE in the UK [1] recommends that the first global sway mode be above 1.5Hz.

Such frequency limits are often not met based on strength requirements alone, particularly for high capacity, tall grandstands, and additional stability structure is required in the form of bracing or cores to meet these vibration serviceability criteria. This not only adds substantial material and construction costs to projects but also places structural elements in un-desirable locations from circulation, hospitality and architectural viewpoints. The increase in stiffness may also lead to higher seismic and thermal demands from the structure with associated structural requirements and costs to meet these demands.

The minimum natural frequency route is one way to assess the performance of both new and existing grandstands. An alternative approach, sometimes called performance-based assessment, is to calculate expected vibration levels using a model of the structure and a prescribed loading scenario. There are various performance-based methods for vertical crowd actions including that published by the IStructE [1] which incorporates human-structure dynamic interaction (HSDI) into models of active (those jumping, bobbing etc.) and passive (those standing or sitting) spectators. The HSDI models are intended to recreate the effects that humans can have on the dynamics of the human-structure system when the human to structure mass ratio is relatively high (e.g. changes in system natural frequencies, damping and loading that is applied). Spectators are modelled as mass-spring-damper systems with or without an actuator force for active and passive humans respectively.

To the authors' knowledge, the same HSDI models have never been attempted for horizontal behaviours with the limited number of performance-based methods in the literature prescribing direct load application for active spectators. In this paper, a first attempt at an HSDI model for a single swaying standing person is developed with the focus being on side-to-side sway. The model is then used to demonstrate the potential benefits of using such a model for assessment of an existing permanent grandstand structure over traditional assessment methods (i.e. direct force application). The study uses data currently available in the literature which is described first.

2. Studies into sway loading

Sway forces occur due to the horizontal shifting of a person's centre of mass either front-to-back (FB) or side-to-side (SS) while generally maintaining contact with the ground in the standing or seated position. The differences in the symmetry of the musculoskeletal system of the human body in these two directions affect the characteristics of the resultant loading [2]. Horizontal forces may also be produced due to vertical motions such as jumping and bobbing.

The intention in this paper is to focus on intentional sway of standing individuals in the SS direction as SS movements typically generate higher load components and are a more natural movement for spectators. For tall, permanent grandstands, the first global mode, with lowest natural frequency, is also typically in the SS, or circumferential, direction meaning that achieving minimum natural frequency targets is more onerous.

2.1. Early studies

The first attempts to develop mathematical models for SS sway loading [3,4,5] focused on establishing loads for individuals or groups of 6 or less on rigid structures. First harmonic dynamic load factors (DLFs) in the region 0.05 to 0.25 were measured during these tests with variability observed for different excitation frequencies and for different researchers. Second and third harmonic DLFs were significantly lower.

2.2. Studies at the University of Manchester

Yao et al. [6] were the first to experimentally investigate HSDI in the horizontal plane. Their research involved a single person swaying from side-to-side on a perceptibly moving platform. The platform was configured to have natural frequencies of 1, 2 and 3Hz with the test subject swaying at frequencies in the range 0.7 to 3.5Hz prompted by a metronome.

The results indicated clear evidence of dynamic interaction between the test subject and platform. Notably, a drop-out of applied force occurred when the test subject aimed to sway at or close to the natural frequency of the platform – a finding which was similar to that of similar jumping and bobbing tests – as can be observed in Fig. 1(a) which plots applied first harmonic force normalised to subject weight (DLF) against the ratio of achieved sway frequency to platform natural frequency. The force reduces by around 3 to 4 times at resonance when compared to that away from the resonant region. The resulting measured platform accelerations at resonance were therefore lower than would be expected had loading derived from rigid platform tests been applied.

The force drop-out observed was attributed to the platform displacements and accelerations reaching levels at which the test subject was unable to maintain a significant force level - the test subject essentially began to move with the platform.

2.3. Studies at Oxford University

The most recently published experimental study investigating SS sway forces was conducted by Nhleko [2]. 12 test subjects participated either alone or in groups of 2 or 3 and were asked to sway for a period while standing on force plates mounted on rigid ground. The sway frequencies considered were in the range 0.5 to 1.5Hz with a metronome used as a prompt (set at double the intended sway frequency).

Different styles of swaying, with differing foot positions, were observed and measured DLFs were found to be variable depending on the test subject and target sway frequency. Fig. 1(b) shows the measured frequency spectra of force magnitudes normalised to person weight for all test subjects from which maximum measured DLFs can be established (peaks of the spectra). It can be seen that first harmonic components are notably higher than the second and third harmonics and vary between around 0.1 and 0.2 at maximum depending on sway frequency. The highest measured DLF was at a sway frequency of 1Hz.

Nhleko then used individual force time histories to simulate group behaviour by combining them with random phase lags according to different group sizes. He goes on to note that first harmonic DLFs became asymptotic to 0.05 for group sizes up to 60 people, due to lack of coordination between individuals, representing a 2 to 4 times reduction compared to single person DLFs. This finding is similar to tests for vertical motions by other researchers.

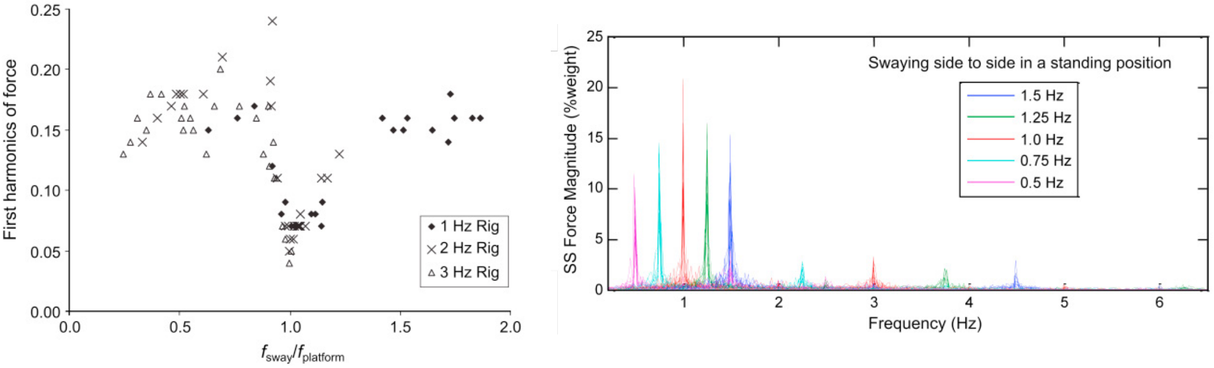

Fig. 1. (a) First harmonic of force normalised to subject weight on a flexible platform for different sway and platform frequencies (from Yao et al. [6]); (b) Spectral force magnitudes normalised to subject weight (%) for different sway frequencies (from Nhleko [2])

3. Human structure dynamic interaction (HSDI) model of a single swaying person

The previous section described research aimed at establishing SS sway loads for humans on rigid and flexible surfaces with some notable differences observed due to the flexibility of the support structure. Similar differences have been observed for bobbing humans and in work by Dougill et al. [7], which went on to be incorporated into the IStructE guidance [1], a spring-mass damper system with an internal force couple (Fig. 2(a)) was used to provide a reasonable approximation to represent these effects. The same approach as used by Dougill et al. will be adopted here but for SS sway.

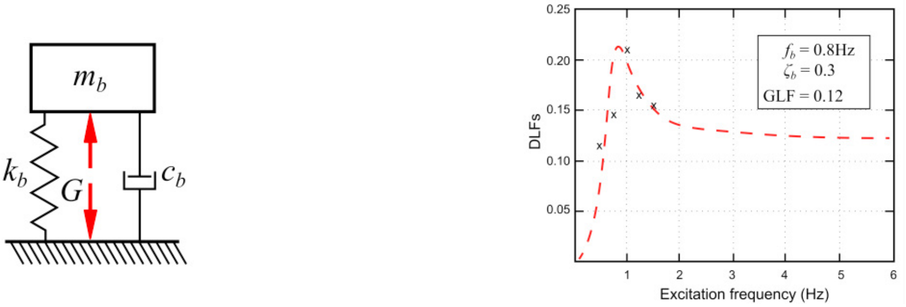

Fig. 2. (a) HSDI model of a bobbing person (from Dougill et al. [7]); (b) Least squares curve fit to Nhleko [2] DLFs using HSDI model

In Fig. 2(a), m_b, k_b and c_b correspond to the mass, stiffness and damping coefficient of the human body respectively. G is a force couple representing the internal force generation within the body and is assumed to be sinusoidal in nature. Following the governing equations of the system, the force, F, applied to the support point can be calculated according to Eq. 1 where ω is the sway angular excitation frequency, ω_b is the angular natural frequency of the body and ζ_b is the damping ratio of the body.

$$F = \frac{G}{-\left(\frac{\omega_b}{\omega}\right)^2\left[1-\left(\frac{\omega}{\omega_b}\right)^2+j2\zeta_b\left(\frac{\omega}{\omega_b}\right)\right]} \tag{1}$$

Using the first harmonic spectral peaks from Fig. 1(b), a least squares curve fit using Eq. 1 has been used to derive body properties for a single person (see Fig. 2(b)). A body natural frequency of 0.8Hz, a body damping ratio of 0.3 and an internal actuator force normalised to body mass, or GLF (Generated Load Factor), of 0.12 provides the best fit to the Nhleko data. The curve fit calculates a lower body natural frequency than derived by Harrison [8] for a single bobbing person (0.8Hz compared to 2.4Hz) as may be expected given the stiffness of the body in lateral direction is lower. The first harmonic GLF is also lower than for bobbing (0.12 compared to 0.42) which would also be expected given that measured vertical forces generated during bobbing are higher than lateral forces during sway. Body damping ratios are relatively similar (30% compared to 25% of critical).

4. Comparison of HSDI sway model to tests on a flexible platform

Using the derived body properties for a single person, it is possible to apply the model to the platform used by Yao et al. and compare forces and accelerations to those measured during the tests. The test data from the 1Hz platform has been used for the comparison as this is within the range of tall grandstands where additional lateral stability (bracing, cores etc.) has not been provided to meet natural frequency limits.

A two-degree-of-freedom (2DOF) model is adopted representing the platform and person as shown in Fig. 3. Here, the platform properties are assigned the subscript s for structure and are taken from Yao et al. [6]. As outlined in Yao, the damping of the platform varied with displacement and so an approximate value of 3% critical has been taken based on displacements presented for a 1Hz platform in the paper.

The person contact force, F, and platform acceleration, $\ddot{U}_s$, can be described by Eqs. 2 and 3 respectively.

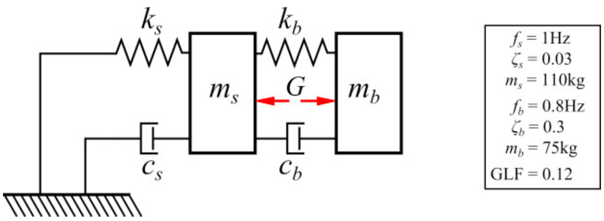

Fig. 3. 2DOF representation of Yao et al. [6] platform with HDSI model

$$F=\frac{G}{1\text{-}\left\{\left(\frac{\omega_b}{\omega}\right)^2\left[1+j2\zeta_b\left(\frac{\omega}{\omega_b}\right)\right]\left[\frac{1\text{-}\left(\frac{\omega}{\omega_t}\right)^2+j2\zeta_s\left(\frac{\omega}{\omega_s}\right)}{1\text{-}\left(\frac{\omega}{\omega_s}\right)^2+j2\zeta_s\left(\frac{\omega}{\omega_s}\right)}\right]\right\}} \qquad \text{where:} \qquad {\omega_t}^2=\frac{k_s}{m_s+m_b} \tag{2}$$

$$\ddot{U}_s=\frac{G\omega^2}{m_s\omega_s\left(\frac{\omega_b}{\omega}\right)^2\left[1\text{-}\left(\frac{\omega}{\omega_b}\right)^2+j2\zeta_b\left(\frac{\omega}{\omega_b}\right)\right]\left[1\text{-}\left(\frac{\omega}{\omega_s}\right)^2+j2\zeta_s\left(\frac{\omega}{\omega_s}\right)\right]\text{-}m_b{\omega_b}^2\left[1+j2\zeta_b\left(\frac{\omega}{\omega_b}\right)\right]} \tag{3}$$

The comparison firstly assumes that the body natural frequency, damping and actuator force remain the same when swaying on the rigid and flexible support structures. It also assumes that these properties remain constant with sway frequency. Fig. 4 compares the applied force (a) and acceleration (b) measured by Yao with the DLFs measured by Nhleko and the accelerations which would be obtained had the DLFs been applied to a SDOF representation of the platform (red lines). It can be seen that the contact force is overestimated in the resonant region and the corresponding accelerations considerably so.

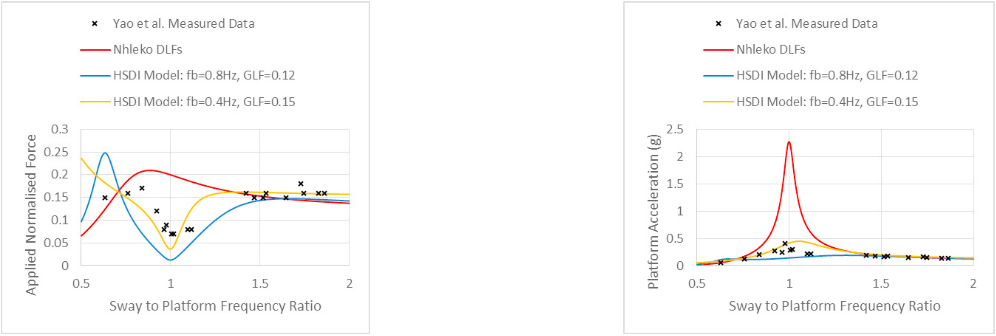

Fig. 4. (a) Comparison of measured applied force normalised to subject weight for different sway to platform frequency ratios from Yao et al. [6] to forces obtained by Nhelko [2] and those predicted using the HSDI model; (b) Comparison of measured to predicted platform accelerations in g

The HSDI model is then used to make the same comparison to the measured Yao data using the body parameters derived earlier in the paper (blue lines). It can be seen that the forces and accelerations are below those measured by Yao with the platform accelerations appearing to be damped in a manner similar to those had a tuned mass damper been added to the platform. In order to understand how to obtain a better fit to the Yao results, parameters were altered, namely the body natural frequency f_b and the GLF. With f_b = 0.4Hz and GLF = 0.15 it can be seen that a much better fit to the data is obtained for both force and acceleration (yellow lines).

As the test subject in Yao's test was different to Nhleko's test subjects, differences are to be expected. Only tests with the same subject swaying in the same style on rigid and flexible platforms can provide a true comparison as the test subject has control over both the stiffness of their legs (and therefore natural frequency) and energy input. It is known that in Yao's work, the subject aimed to excite the platform as much as possible whereas Nhleko's test subjects were given less instruction. That said, the model does recreate the force characteristics observed in Yao's tests (namely the force drop-out) and a reduction in acceleration compared to the case where rigidly derived DLFs are applied.

5. Usage of the HSDI sway model on a stadium structure

In this final section, the HSDI model is used on a real stadium structure shown in Fig. 5(a). The first global mode of the stand is approximately 0.61Hz in the SS direction (below the 1.5Hz recommendation from the IStructE). Loading has been applied by means of first harmonic DLFs given in Fig. 2(a) and according to the HSDI models presented in the previous section. A crowd 'modal mass' is calculated according to the scaling of the mode shape as per the IStructE 'approximate method'. Accelerations are presented in Fig. 5(b) for the worst case top seat positions.

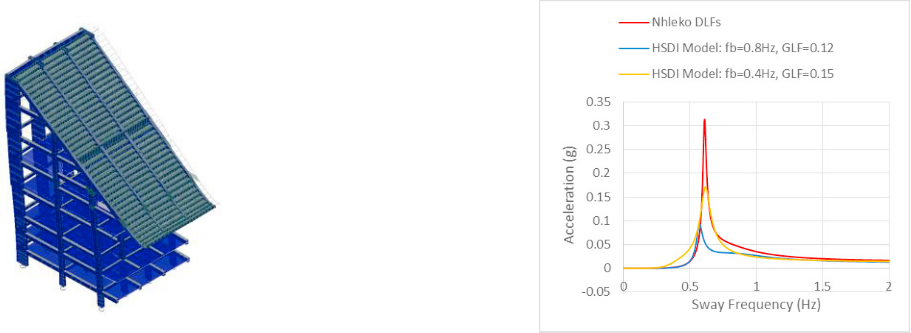

Fig. 5. (a) Grandstand model first global sway mode @ 0.61Hz; (b) Calculated top of stand accelerations due to DLFs and HSDI models

It may be seen that usage of the HSDI model over traditional DLFs results in a reduction in acceleration response. Depending on the body parameters chosen, the response reduces by 2 to 3 times. The results have been generated assuming 100% crowd participation and no allowance for lack of coordination between spectators so are very much upper bound. With these effects included, the response would be expected to reduce further and be closer to acceptable levels of vibration for spectators (noting that Willford [9] proposes 6%g peak as an appropriate limit).

6. Conclusion

This paper presents a first attempt at a human-structure dynamic interaction (HSDI) model for side-to-side sway for permanent grandstand design. People are modelled as a spring-mass damper system with an internal actuator force. The model is able to recreate the important effects of human-structure interaction observed when people sway on flexible structures (e.g. force drop-out / reduction in acceleration response) although further work is required to derive and have confidence in statistically accurate body properties.

The application of the model to a real stadium grandstand indicates that by including HDSI effects, reductions in calculated responses are possible. This, combined with appropriate assumptions for crowd coordination and participation, may lead to high capacity, tall permanent grandstands being shown to be acceptable via performance-based methods without the need for costly and prohibitive stability structure to meet natural frequency targets.

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