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Procedia Engineering 190 (2017) 645 – 652

Procedia Engineering

www.elsevier.com/locate/procedia

Structural and Physical Aspects of Construction Engineering

Modelling of Synchronized Jumping Crowds on Grandstands

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Abstract

Synchronized jumping is considered to be the most significant dynamic load on grandstand structures induced by humans. In order to accurately predict reliability and serviceability at the design stage, computational models with proper characterization of these kinds of external loads are required. In this contribution, we will focus on categorization and description of load, providing thus an overview of various approaches to simulate forces induced by a synchronized jumping crowds. Standard models, such as equivalent static load or simple approximations in time and frequency domain, will be recalled. Because the true load induced by a crowd is inherently random, more advanced models will be discussed as well. These are based on Monte Carlo generators or semi-analytical probabilistic models. Finally, all discussed approaches will be demonstrated on a simple test example.

Peer-review under responsibility of the organizing committee of SPACE 2016

Keywords: Grandstands; active crowd; jumping spectators; dynamic response

1. Introduction

Sport stadia recently found a wide palette of utilization, serving as entertainment centers that host various kinds of events and large numbers of spectators. Requirements for clear views and increasingly large demands on capacities led to cantilever upper tiers, relatively flexible and light-weight, requiring thus accurate modelling techniques.

Because crowds on grandstands are lively and energetic, they may cause serious problems from serviceability and reliability point of view. This applies especially to pop concerts when aural stimuli are present, resulting in

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Peer-review under responsibility of the organizing committee of SPACE 2016
doi:10.1016/j.proeng.2017.05.392

highly synchronized movements of majority of the spectators. Although the problem is rather actual, cf. e.g. [1 – 3], available guidelines, [4 – 7], indicate that the problem is not resolved satisfactorily. Let us quote EUROCODE 1: „*Where the danger of significant structural response to synchronized rhythmical movement of people, dancing or jumping exists, then in dynamic analysis the relevant load model should be considered, efficient for the verification of relevant structural response*".

A simplified flowchart of a typical design process of grandstand structures is shown in Fig. 1. Upon distinguishing between active part (being in motion) and a passive part (being at rest) of a crowd, the main difficulties emerging due to the presence of spectators on structures are:

- The passive part of a crowd is capable to significantly modify physical properties of the underlying structure
- The passive part of a crowd is able to absorb a significant amount of kinetic energy
- Crowds are inherently random, i.e. induced effects are unpredictable up to some extent

Because the above-listed effects depend on time and level of excitation, it is challenging to develop accurate yet reliable mathematical models. Certain approximations are needed.

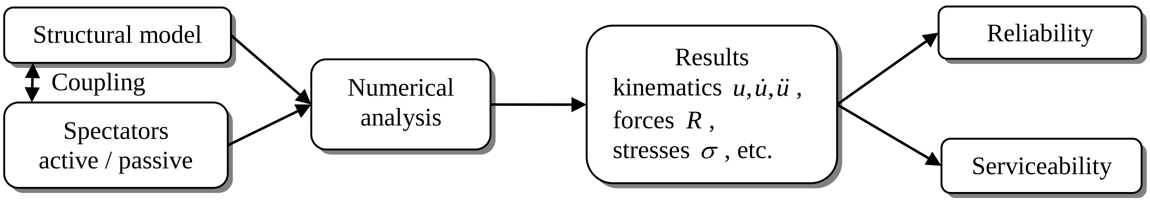

Fig. 1. Simplified flowchart of a design process of grandstand structures.

After Jones et al. [8], loads induced by an active crowd can be categorized as follows:

- Walking and running
- Jumping
- Bouncing (bobbing, jouncing)
- Swaying
- Foot-stamping and hand-clapping
- Abrupt rising
- Rhythmic exercise loads

The most significant load is usually considered jumping, cf. e.g. [10], discussed in Section 2. Sections 3 and 4 briefly discuss response measures and passive crowd models. Computational aspects follow in Section 5, short demonstration in Section 6, and present contribution closes in Section 7.

2. Forces induced by jumping spectators

This section provides an overview of various models that can be used to approximate vertical forces due to jumping individuals or groups of people. Typical frequency ranges are listed in Tab. 1.

Table 1. Frequency ranges for jumping spectators (Hz).

	Ginty et al. [9]	Littler et al. [10] & ISO 10137 [4]	Bachmann and Ammann [23]
Individuals	1.2 – 2.8	1 – 3.5	1.8 – 3.4
Small groups	1.5 – 2.5	1 – 3.5	1.8 – 3.4

Large groups	1.8 – 2.3	–	–

Jumping is characterized by an intermittent contact of spectators with structure. If the length of this contact is sufficiently short, cf. e.g. [30], induced effects can be modeled simply through time dependent forcing terms. When contact period prolongs, models for bouncing, such as actuators, become more convenient [32].

2.1. Equivalent static load

Initially, active spectators were described using equivalent static load. This technique aimed on evaluation of reliability rather than serviceability. Apart from prescribed load, requirements for natural frequencies were included to avoid resonance effects. Several values, reported in [8], are partly reproduced in Tab. 2.

Table 2. Equivalent static loads on grandstands.

	Tuan and Saul [11]	Ebrahimpour et al. [12]	Moreland [13]
Load (kN/m^2)	4.50	8.14	3.23
Load (kN/person)	–	2.85	1.13
Frequency (Hz)	2.2	4	–

2.2. Time domain approximation

Next kind of approximation relies on time description, consisting of a series of half-sine pulses. Initially, it was introduced by Bachmann and Ammann, [23], in the following form

$$F(t) = \begin{cases} k_p G \sin\left(\dfrac{\pi t}{t_p}\right), & 0 \le t \le t_p \\ 0, & t_p \le t \le T_p, \end{cases} \tag{1}$$

where t denotes time variable, G static human weight, $k_p = F_{\max}/G$ impact factor, $F_{\max}$ peak dynamic load, t_p contact time, T_p jumping period, and $\alpha = t_p/T_p$ contact ratio. Note that $k_p = \pi/2\alpha$. Several values of contact ratios are specified in Tab. 3.

Table 3. Contact ratios for time domain approximation.

	Bachmann and Ammann [23]	Yao et al. [24]	BS 6399 [25]
Contact ratio α	0.25 – 0.60	0.50 – 1.00 (flexible structures)	0.25 – 0.67 (1/3 typical)

Although Eq. (1) uses half-sine pulses, Fig. 2 suggests that for lower jumping frequencies, more sophisticated shapes are required. For instance, Sim in [22] uses Gaussian or cos^2 pulses, whereas Nhleko et al. [26] suggest a framework based on a variable mass model, allowing for a more complicated, double-peaked pulse shapes.

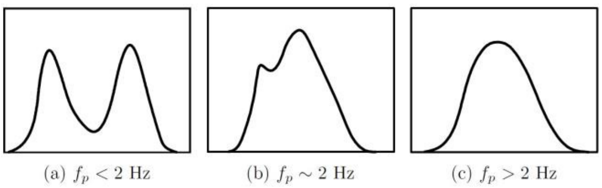

Fig. 2. Three characteristic pulse shapes after Sim [22]: (a) double-peaked, (b) merging, (c) single-peaked.

2.3. Frequency domain approximation

Employing Fourier series, expression in Eq. (1) can be transformed to frequency domain, cf. [23, 27]. Upon using n lowest harmonics (usually $n = 2$ or 3), one obtains

$$F(t) = G\left[1 + \sum_{k=1}^{n} r_k \sin\left(\frac{2k\pi t}{T_p} + \varphi_k\right)\right], \quad t \in R, \tag{2}$$

where r_k denote Fourier coefficients (also Dynamic Load Factors, or DLFs for short), φ_k are phase shifts, and R denotes a set of real numbers. Specifying r_k and φ_k, one defines the model, cf. Tab. 4 and [29, 30].

Table 4. DLFs and phase shifts corresponding to various authors.

	Pernica [31]	Ellis et al. [28] (normal jumping, α = 1/3)
r_1, φ_1	1.60, –	9/5, π/6
r_2, φ_2	0.60, –	9/7, –π/6
r_3, φ_3	0.20, –	2/3, –π/2

2.4. Monte Carlo generated loads

When randomness becomes important, Monte Carlo (MC) generators can be used. Load function is then described as a parametric process

$$F(t,\omega) = h(t; \boldsymbol{Y}(\omega)), \quad t \in R, \tag{3}$$

where $\boldsymbol{Y} \in R^n$ represents a random variable, and ω explicitly indicates any kind of randomness. For instance, models in Sections 2.1 – 2.3 can be randomized by taking jumping frequency, contact ratio, or phase lag as random variables.

Ellis and Ji in [33] investigate randomness in jump height, jumping frequency, and phase lag, cf. also [35]. Sim [22] introduces model that reflects delays in individual pulses using auto-regression time series. Typical weight-normalized realizations for various jumping frequencies are shown in Fig. 3. Generator developed by Racic and Pavic [35] simulates individual histories using electrocardiogram techniques, and time lags in individual pulses are described as random series with prescribed spectral density. Pulses are specified through a linear combination of a number of Gaussian shape functions.

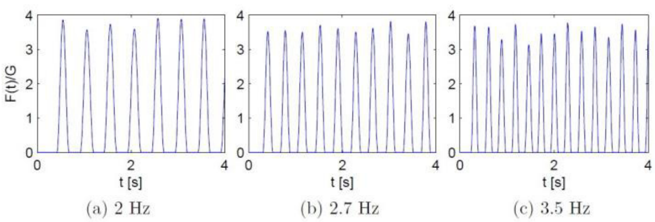

Fig. 3. Typical MC realizations after Sim [22] for normalized load histories.

2.5. Approximations using random processes

The next option relies on the theory of random vibrations, cf. e.g. [36, 37]. Loading history is specified as

$$F(t,\omega) = \mu(t) + \tilde{Y}(t,\omega), \quad t \in R, \tag{4}$$

where $\mu(t)$ is a deterministic mean value, approximated as a truncated Fourier series (similar to Eq. (2)), and $\tilde{Y}(t,\omega)$ is a colored Gaussian noise, possibly modulated. This description allows for analytical derivations; for instance, spatial interactions between spectators (intra-personal coordination) can be introduced and analyzed, cf. [38, 39].

2.6. Loading due to groups of people

So far, only the loads induced by single spectators have been discussed. Grandstand structures are, however, occupied by entire crowds and hence, extensions to groups of people are required. When a group of people coordinately jumps, their resulting force would ideally be a sum of their load histories. Nevertheless, due to a lack of synchronization (intra- and inter-personal), their overall load reduces, namely for deterministic models in Sections 2.2 and 2.3.

Concerning deterministic models, ISO 10137 [4] reduces the resulting force function $F(t)$ by applying a coordination factor $C(N)$ of N spectators as follows

$$F_N(t) = C(N)F(t), \quad t \in R, \tag{5}$$

cf. Table 5. Note that $C(N)$ depends on harmonic in certain cases.

Table 5. Various coordination factors $C(N)$.

	ISO 10137 [4] (medium coord.)	Ellis and Ji [40]	Bachmann [23]	Ebrahimpour and Sack [41]
1st harm.	0.67	$N^{-0.082}$	0.75	0.65
2nd harm.	0.50	$N^{-0.24}$	0.75	0.65
3rd harm.	0.40	$N^{-0.31}$	0.75	0.65

Concerning stochastic models, they account for a lack of coordination automatically through their randomness. Resulting load due to a group of people can be expressed as a sum of individual histories. For instance, the model described in Eq. (4) assumes that spectators synchronize in the mean, i.e. $\mu_N(t) = N\mu(t)$ whereas $\tilde{Y}(t,\omega)$ reflects uncorrelated noise.

3. Note on response measures

Response measures, according to Fig. 1, relate either to reliability or serviceability. The reliability limits are dictated by a bearing structure, i.e. by maximum forces, stress amplitudes, number of cycles, etc. The serviceability limits depend on many conditions such as duration, frequency content, or crowd density. It has been determined, however, that humans are capable to detect accelerations as low as $0.005g$ in vertical direction [20], where g denotes the acceleration due to gravity. Upper comfort limits were observed to be 10% g of 10 sec floating RMS for comfort, and 20% g of 1 sec RMS for panic, cf. [21].

4. Note on passive spectators

Human body is a complex, spatial, and nonlinear dynamic system with variable parameters depending on posture, physical condition, or level of excitation. It is standard to adopt biodynamic models with one or several degrees of freedom acting only in the vertical direction. Although such models are simple, they are capable of capturing the major effects. Further description and details can be found, e.g., in [14 – 19].

5. Computational aspects

Equivalent static load is clearly the least demanding kind of loading from the computational standpoint. It amounts to solving the following system of linear equations in order to obtain the response $\boldsymbol{u}$

$$\boldsymbol{K}\boldsymbol{u} = \boldsymbol{F}, \tag{6}$$

where $\boldsymbol{F}$ is the vector of external static load, and $\boldsymbol{K}$ is the stiffness matrix.

The time domain approximations amount to solving a system of the second order Ordinary Differential Equations (ODEs). Assuming that grandstand is a Linear Time Invariant (LTI) system, associated ODEs read as

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + \boldsymbol{C}\dot{\boldsymbol{u}}(t) + \boldsymbol{K}\boldsymbol{u}(t) = \boldsymbol{F}(t), \tag{7}$$

and can be integrated using various schemes, cf. e.g. [42]. These usually require assembly of algorithmic stiffness matrix, its factorization, and repetitive solutions for numerous right hand sides.

The model defined in Eq. (2) is computationally efficient especially for steady state response. Assuming periodicity in the right hand side of Eq. (7), one can perform Fourier transform to obtain

$$\left[-(2\pi\xi)^2\boldsymbol{M} + i2\pi\xi\boldsymbol{C} + \boldsymbol{K}\right]\hat{\boldsymbol{u}}(\xi) = \boldsymbol{D}\sum_{k=0}^{n} Gr_k e^{i\varphi_k}\,\delta(k/T_p - \xi), \tag{8}$$

i.e. the solution amounts to n factorizations of the Frequency Response Function (FRF) for various harmonics; note that ξ (Hz) denotes frequency, $\hat{\boldsymbol{u}}(\xi)$ Fourier transform of $\boldsymbol{u}(t)$, $\delta(\xi)$ the Delta function, i is the complex unit, and that $r_0 = 1$ and $\varphi_0 = \pi/2$. In Eq. (8), $\boldsymbol{D}$ spatially distributes applied load over the structure.

The MC simulation requires to generate N_r realizations and to solve Eq. (7) N_r times. Then, all responses can be statistically analyzed to provide relevant descriptors. This approach becomes particularly expensive when high accuracy is required because N_r grows rapidly.

For the model in Eq. (4), the additive colored noise is obtained by filtering the Gaussian white noise. For LTI systems, the mean value $\mathrm{E}\boldsymbol{u}(t)$ solves Eq. (8), whereas covariance matrix $\boldsymbol{c}(t,t) = \mathrm{E}[(\boldsymbol{u}(t)-\mathrm{E}\boldsymbol{u}(t))\,(\boldsymbol{u}(t)-\mathrm{E}\boldsymbol{u}(t))^T]$ satisfies

$$\dot{\boldsymbol{c}}(t,t) = \boldsymbol{a}\boldsymbol{c}(t,t) + \boldsymbol{c}(t,t)\boldsymbol{a}^T + \boldsymbol{b}\boldsymbol{b}^T \tag{9}$$

when Gaussian approximation is adopted. Above, matrices $\boldsymbol{a}$ and $\boldsymbol{b}$ describe the system and associated filters in Cauchy form, see [38] for further details.

Note that in all discussed cases, Reduced Order Modelling techniques such as modal superposition or proper orthogonal decomposition can be used to save significant computational efforts while maintaining accuracy.

6. One simple example

In this example, all models described in Section 2 are demonstrated on grandstand structure depicted in Fig. 4 (left). This structure hosts 630 active spectators. Equivalent static load is considered by the value 8.14 kN/m^2 from Tab. 2 [12], the time domain approximation considers α = 1/2 from Tab. 3 [25] with coordination factor 0.65 from Tab. 5 [41], the frequency domain approximation is adopted with values from Tab. 4 [28] and coordination factor from Tab. 5 [4] applied to various harmonics, MC simulation is employed with the model after Sim [22] and 1,000 realizations, and the random processes are chosen to approximate the model after Sim, cf. [38]. Jumping frequency is set to 2.67 Hz. Because the first three lowest natural frequencies of the structure associated with the vertical modes are 3.08, 5.53, and 5.37 Hz, the response is expected to be close to the state of resonance. The weight of individual spectators is set to 86 kg. Resulting vertical displacements, associated with individual models for the node highlighted by red arrow in Fig. 4 (left), are shown in Fig. 4 (right).

The first thing we notice in Fig. 4 (right) is that all models predict comparable responses. Note that for the time domain approximation, when the typical value $\alpha = 1/3$ is chosen, associated response slightly overestimates results of other models. Second, a good agreement between probabilistic models is achieved, as expected. These models provide not only the mean value responses, but also other statistics such as standard deviation (shown in Fig. 4 (right) in black and cyan). Although the result corresponding to the equivalent static load match well, it deteriorates considerably when material properties, and hence natural frequencies, change.

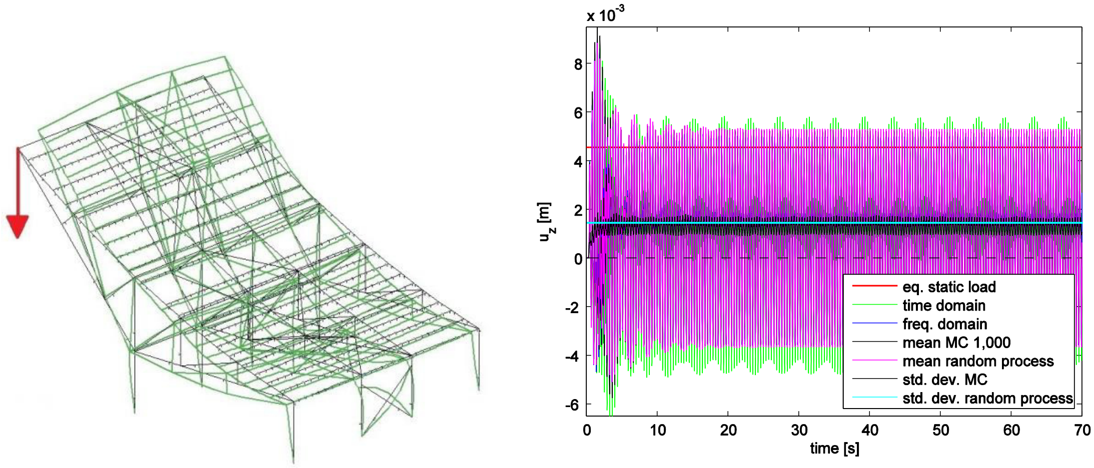

Fig. 4. Geometry of employed structure (left), and vertical displacements in highlighted node (right).

7. Summary and conclusions

In this contribution, a brief overview of models available in the literature for modelling of synchronized jumping spectators on grandstands was presented. Their advantages and limitations were briefly discussed along with their computational complexities. Finally, a simple numerical example demonstrated use of these models along with discussion of obtained results.

Acknowledgements

Financial support of this work from the Czech Science Foundation (GAČR) under project No. 15-15728S is gratefully acknowledged.

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