Structural Safety 66 (2017) 51–61

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

A contribution to the modelling of human induced excitation on pedestrian bridges

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ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form 14 January 2017
Accepted 14 January 2017

Keywords:
Footbridge
Human induced vibration
Random field
Stochastic modelling

ABSTRACT

Human induced vibration is a common problem in the design of planking levels as both flooring or decking. The source of the vibration is the so-called "human induced loading (HIL)". Models are available for a single exciting person and for a dense aggregation of persons. Small groups of persons should also be considered in view of serviceability limit state design. This paper introduces a model for the time variant stochastic fields of forces induced by the walking of a small group of persons. A numerical example is presented dealing with the evaluation of vertical and transversal accelerations at nodes of a finite element model of an existing wood footbridge. The example considers different idealizations of the human induced excitation and the results of these models are compared to actual records.

1. Introduction

Human induced vibrations are generally restricted to those vibrations which are induced by the presence of human bodies on a structural component as the floor of a building [1,2] or the deck of a bridge [3,4]. In the latter case one is generally speaking of pedestrian bridges, since bridges targeted to the crossing of traffic and, even better, rail-services are less sensitive to the human action.

Footbridge serviceability criteria demand for a way to model the loading induced by the human crossing. This is true in the design stage, when the designer has to foresee the human induced vibration, but also in service to interpret the structural monitoring collection of data, in view of possible counteractions when required. Several multi-body dynamics models were proposed, but their use would simulate the behavior of a driven body, rather than that of a human being who mainly responds to social and psychological stimuli.

The movements of a standing human body are generally grouped into three main classes: walking, running (including jogging) and aerobic. Since this manuscript is regarding bridges, the focus is on the first two aspects. Their study is a basic research area in robotics and/or bio-mechanics. Recently a deep historical review since the first Aristotle's steps was published [5], and the author introduces a 17th century book (by Borelli) as the first book never published in bio-mechanics. The same historical review concludes with 2D and 3D models of the human body, conceived as a multi-body of 16 degrees of freedom. The use of these models for loading structural systems [6] would be fascinating, but some ingredients, coming from social sciences and psychology, would make it non-realistic enough. Indeed human beings tend to adapt their behavior to that of the surrounding people and/or, when on a vibrating systems, tends to follow the felt motion. There is an attempt to incorporate such remarks in existing recommendations [7–11], which are focused on the limit cases of a single pedestrian and a dense clustering of persons. Nevertheless, it is worth noticing that from a static point of view the full occupation of the footbridge is the most dangerous scenario, with the human induced vibration source being restricted to the alternate step movements. Added masses are significant for the load intensity, but they also shift the structure own frequencies. By contrast a group of pedestrians, say 4 or 6, with their moving masses, could easily induce resonance with some of the footbridge structure frequencies. This is why this manuscript deals with the modelling of the action induced by a small group of human beings and does it in a stochastic framework involving two spatial variables and the time variable: in other words, the consequence of human unpredictability is regarded as stochasticity.

2. Modelling a time variant stochastic field

Attention is focused on those models of random fields which allow one to simulate [12–14] realizations accurate enough as

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http://dx.doi.org/10.1016/j.strusafe.2017.01.004
0167-4730/

structural excitation. Assume first that the time variability can be neglected. Then one could rely on 2D stationary random field models, in the plane (x, y), usually assigned by a power spectral density matrix with zero mean and Gaussian features. The Gaussianity requirement was recently removed [15], so that any wished probability distribution can be assigned.

Adding the time in a stationary way, one should simply move from a 2D to a 3D spectral specification. However, the main concern, apart the possible non-stationarity in time (which could be included by a suitable shape function), is the non-homogeneity in space. This led wind engineers, wishing to simulate time histories of wind velocity as random field realizations, to conceive a hybrid model accounting the time in a spectral way, while preserving the space coordinates [16]. The reader is referred to the literature for the details, and mainly to a paper by Ubertini and Giuliano [17], which also presents an operational approach to the simulation. Refs. [16,17] inspired the model the authors illustrate in the following of this section. Given a grid on plane surface, the wind engineer needs a time sequence of discrete distributions of wind velocity vectors in each node, being the grid at rest. This paper pursues a time sequence of discrete distributions of force vectors $\boldsymbol{W}$ in each node of a translating grid. The force vectors are actually the local resultant of forces per unit area $\boldsymbol{w}$, which are defined in any point of the continuous surface.

Such a simulation requires that the continuous three-variate function $\boldsymbol{w}(x, y, t)$ be evaluated at the discretization nodes of the 3D domain: $\boldsymbol{w}_{ijh}(x_i, y_j, t_h)$. Under the stationarity assumption, the (constant) mean value of the random field of one of the components of $\boldsymbol{w}$ is drawn in Fig. 1. The shaded region in the bottom plane is drawn in order to emphasize the grid translation at two subsequent time instants. The values at the grid points, representing the mean values, can also be regarded as those associated with a statically (i.e., not in the statistical sense) uniform distribution of the load per unit area. It is worth noticing that the vectors $\boldsymbol{W}$ and $\boldsymbol{w}$ vary in the plane (x, y) as well as in time. However, their components are out-of-plane, i.e., vertical, and transversal, i.e., along y axis. This suggested to denote the components by 1 and 2, vertical and transversal, respectively, in order to avoid conflicts.

When a realization is simulated, the ordinates associated to the grid nodes are generated. As Fig. 1 clarifies, realizations at two successive time discretization steps do not apply to the same deck rectangle, but the rectangle moves at the velocity v, along the longitudinal x direction, by which the pedestrians move. For the reader familiar with continuum mechanics one could say that the grid corresponds to a Lagrangian representation of the load, which moves along the bridge with a given velocity time history.

Due to the narrow width b, in the y direction, of a footbridge of the type discussed below, it can be assumed that the pedestrians proceed by couples. Assuming for sake of clarity, but without loss of generality, that a group of 6 persons is studied, three couples proceed together remaining inside a longitudinal segment of length d: they act over the deck rectangle of area bd. Each couple acts over the deck rectangle $bd/5$, and between two successive couples a distance of $bd/5$ is set. One introduces 4 nodes along each transversal couple position. The grid of Fig. 1 results to be made of 24 nodes ($N_i = 6$ by $N_j = 4$) to cover the rectangle where 3 couples of two persons move along the bridge. The discretization steps are $b/3$ and $d/5$, respectively. In a deterministic context, the single pedestrian is given the nominal mass of 80 kg. For $n = 6$ persons, the total vertical force is 4800 N which can be spread on the area resulting in $4800/bd$ N/m^2 or, equivalently, in a concentrated load of 200 N per node.

Regarding the distributed force as a random variable, the single pedestrian variance can be derived after the introduction of a likely range: for instance, from 35 to 125 kg. This range of 90 kg is regarded as a 6 standard deviation range, i.e., the standard deviation is 15 kg and the variance 225 kg^2. The coefficient of variation (c.o.v.) is 15/80 = 0.1875. For n pedestrians (and statistically independent pedestrian masses) the average global mass becomes 80n kg; the variance is 225 n kg^2; the standard deviation is 15 $(n)^{1/2}$ and the coefficient of variation $0.1875/(n)^{1/2}$.

The random field results from the irregular distribution of the associated global weight divided by the area of the rectangle, but it can also be modelled as the random vector of the concentrated forces at the grid nodes. Let $\boldsymbol{W}(x_i, y_j, t)$ be its symbol, with $W_1(x_i, y_j, t)$ and $W_2(x_i, y_j, t)$ its vertical and transversal component, respectively. The indexes i and j span over the range $(0, N_i)$ and $(0, N_j)$, respectively: writing W_k $(\boldsymbol{x}, \boldsymbol{y}, t)$, $k = 1,2$, one means the vector of the k-th component of the nodal force in all the grid nodes. The vertical components are characterized by the central moments specified above, while the horizontal (transversal) component has zero mean. There is an aspect here which is demanded to further investigation: the standard deviation mentioned above come from the different likely size of the persons in the walking group, but the standard deviations of the components of $\boldsymbol{W}$ also come from the different position within the grid of the single person feet.

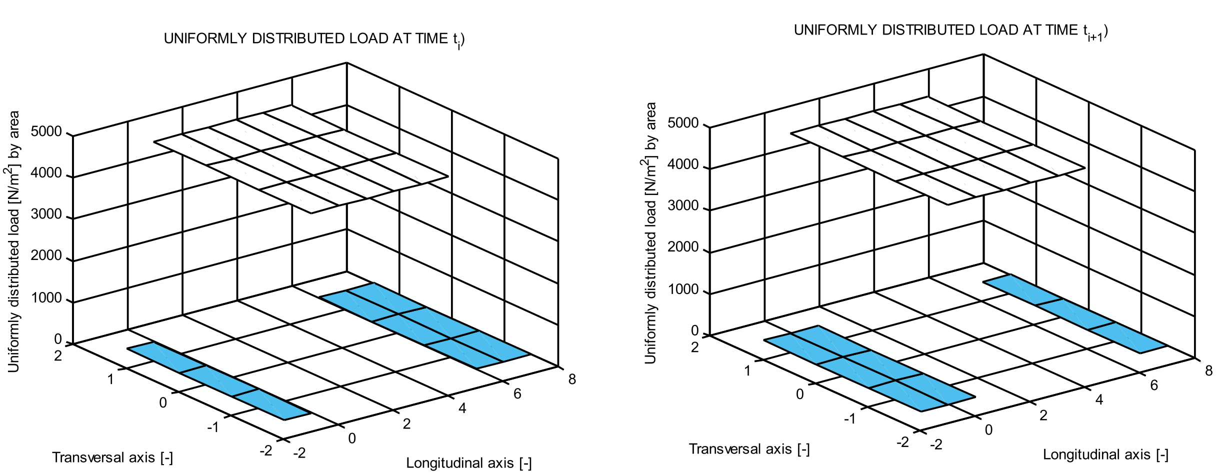

Fig. 1. Within the specified grid rectangle, the spatial random field "distributed load" has to be evaluated at any time t: the shown ordinates provide the mean values around which the vertical component of the random field fluctuates. At two successive times, the grid rectangle moves one step.