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Pedestrian Bridges Monitoring Data for Stochastic Modelling of Human-induced Loads

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ABSTRACT: A model of the human-induced actions, where the consequences of humans unpredictability, together with their response to social and psychological stimuli, are regarded as stochasticity, is developed. After defining a moving grid of nodes in the direction of the crossing, an average action per node is assigned. This value is modified by the following two contributions. A fluctuation, which involves two spatial variables and the time variable, is introduced by stochastic simulation, with a cross-spectral density function which accounts for the spatial dispersion of the single trajectories. A geometric shape function is formulated to account for a non-homogeneous spatial distribution of the pedestrians across the bridge deck.

The procedure of assessing the vibrations serviceability of new footbridges requires to be thoroughly revised in light of the increased slenderness and spans achieved by using innovative construction materials of high strength (Zivanovic et al., 2005; van Nimmen et al., 2014).

Particular attention must be paid to avoid the lock-in phenomenon induced by the crossing of a group of pedestrians. Nowadays, increasing efforts are made to quantify the vibrations due to crowds using the basis of wind engineering theory. Indeed, the correlation between pedestrians at different locations on a structure suggests an approach similar to estimating the dynamic response of structures to turbulent buffeting by wind (Carassale and Solari, 2006).

It is worth noting that the simulation of the time history of a wind field affects at different time instants the same impact surface. Adopting a similar model for pedestrians crossing a bridge also requires that instant after instant the surface of impact moves along the bridge. Furthermore, whereas most studies found in the literature are focused on modelling the crowd load as homogeneous across the bridge deck, there is a lack of investigations concerning the possibility that the synchronization phenomenon occurs among a group of pedestrians which does not fully occupy the spatial domain.

Based on these considerations, a model of the human-induced actions, where the consequences of humans unpredictability, together with their response to social and psychological stimuli, are regarded as stochasticity, has been developed. After defining a moving grid of nodes in the direction of the crossing, an average action per node is assigned. This value is modified by the following two contributions. A fluctuation which involves two spatial variables and the time variable is introduced by stochastic simulation, with a cross-spectral density function which accounts for the spatial dispersion of the single trajectories. A geometric shape function is formulated to account for a non-homogeneous spatial distribution of the pedestrians across the bridge deck.

The deterministic shape function can only be applied on the result of the fluctuation simulation, since this requires a matrix Cholesky decomposition and the matrix properties are influenced by the shape function. In other words, the supposed nature of the eigenvalues of the simulation matrix could go lost if the order of the operations is changed.

The obtained loading realizations are applied to the finite element model of a cable-stayed timber footbridge for which experimental data were collected. It is shown how the availability of experimental data is fundamental to support the selected approach, and to identify the refinements which have still to be implemented.

1. GOVERNING RELATIONS

Pioneering studies on Human Induced Loading (HIL) were developed in (Eriksson, 1994). The basic result of this PhD thesis was the plot in Figure 1, which is also incorporated in the review paper (Zivanovic et al., 2005). Mainly the figure represents a synthesis of experimental results achieved in tests carried out in Sweden.

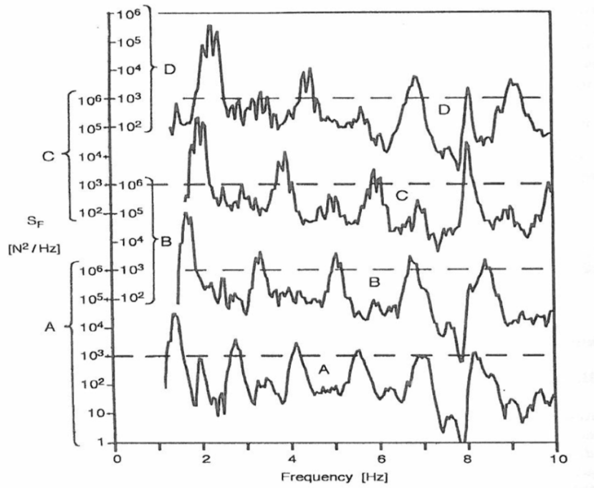

Figure 1: Figure 3-8 of the PhD Thesis by Eriksson (1994). "Spectral densities of the force from a male person (mass 75 kg) walking at different frequencies: A) 1.4 Hz; B) 1.7 Hz; C) 2.0 Hz; D) 2.3 Hz".

This figure is the basis of what can be found in the Setra document (Setra, 2006) which states: "the periodic function *F(t)*, may therefore be resolved into a Fourier series, that is a constant part increased by the sum of harmonic forces. The sum of all the terms returns the total effect of the periodic action.

$$F(t) = G_0 + G_1 \sin 2\pi f_m t + \sum_{i=2}^{n} G_i \sin(2\pi i f_m t - \varphi_i)$$

with:

G_0 : static force (pedestrian weight for the vertical component),

G_1 : first harmonic amplitude,

G_i : i-th harmonic amplitude,

f_m : walking frequency,

φ_i: phase angle of the i-th harmonic in relation to the first one,

n: number of harmonics taken into account".

A mean value of 700 N may be assigned to G_0, i.e., the weight of one pedestrian. At the mean frequency value of a walking pedestrian (which is nearly 2 Hz for the vertical component of the action), three (n=3) coefficients of the Fourier decomposition of $F(t)$ are retained (being the coefficients of the higher terms less than 0.1 G_0) and the coefficient values are the following

G_1=0.4 G_0; G_2=G_3≈0.1 G_0

$\phi_2=\phi_3\approx\pi/2$

Actually, in the applications, a single sine addendum is used, so that:

$$F_v(t) = G_0 + 0{,}4 G_0 \sin(2\pi f_m t)$$

is the vertical component of the single pedestrian action;

$$F_{ht}(t) = 0{,}05 G_0 \sin\left(2\pi\left(\frac{f_m}{2}\right)t\right)$$

is the horizontal transversal component, and

$$F_{hl}(t) = 0{,}2 G_0 \sin(2\pi f_m t)$$

is the horizontal longitudinal component. Indeed, the longitudinal direction is that of the crossing and the transversal direction is normal to it.

It should be noted that, for one same walk, the transverse load frequency is equal to half the frequency of the vertical and longitudinal loads. This is due to the fact that the load period is equal to the time between two consecutive steps for vertical and longitudinal loads, since they exert a force in the same orientation. On the other hand, this duration corresponds to two straight and consecutive right footsteps or to two consecutive left footsteps in the case of transverse load since the left and right footsteps exert loads of opposite orientation. As a result, the transverse load period is two times higher than the vertical and longitudinal loads, and therefore the frequency is two times lower.

2. EXPERIMENTAL EVIDENCE

The authors carried out experimental campaigns on two different timber footbridges located in North-Eastern Italy (Chen et al., 2015). In the specific case of the bridge in Figure 2, several records were collected during the crossing (by walking and running) of groups of persons. A synthetic representation of one of the recorded signals is given in Figure 3. The time frequency analysis is obtained by introducing a moving short time window. The time frequency analysis at the bottom of Figure 3, is better understood by the equivalent 3D graph in Figure 4.

If now the attention is focused on the time where the group of persons reaches and passes the position of the accelerometer (see Figure 5), one detects (in addition to the structure's own frequencies) peaks at multiples of 1 Hz, which is the frequency that characterizes the transversal action. Thus, when modelling the pedestrians load, the problem is to identify if these peaks are characteristic of the action (and, hence, they have to appear in its spectrum too), or they simply appear in the response spectrum. In the latter case, the action spectrum, different from the response spectrum, does not show harmonics but only spikes at the dominant frequencies (1Hz for the transversal component of the force, and 2 Hz for the vertical component).

Figure 2: Suspension timber footbridge located in Fara, North-Eastern Italy, where an experimental campaign under crossing of groups of persons was carried out by the authors.

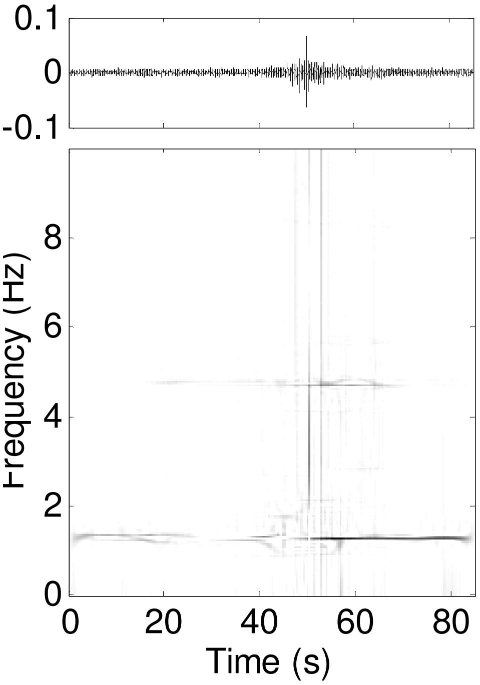

Figure 3: Suspension timber footbridge located in Fara, North-Eastern Italy. At the top, acceleration signal in the transversal direction under the crossing of a group of 6 persons. At the bottom, its time frequency analysis.

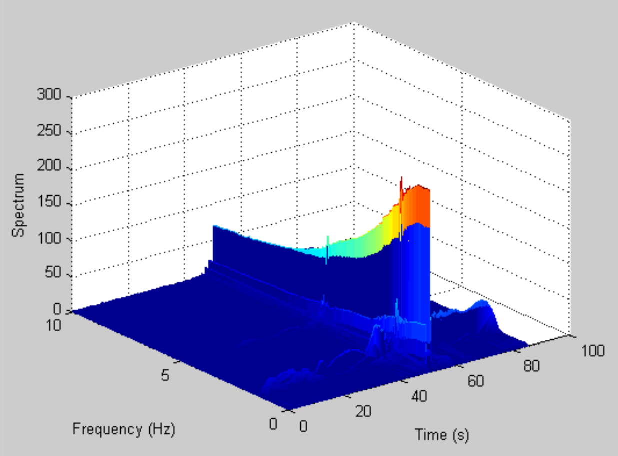

Figure 4: Suspension timber footbridge located in Fara, North-Eastern Italy: spectrum of the acceleration signal in the transversal direction under the crossing of a group of 6 persons.

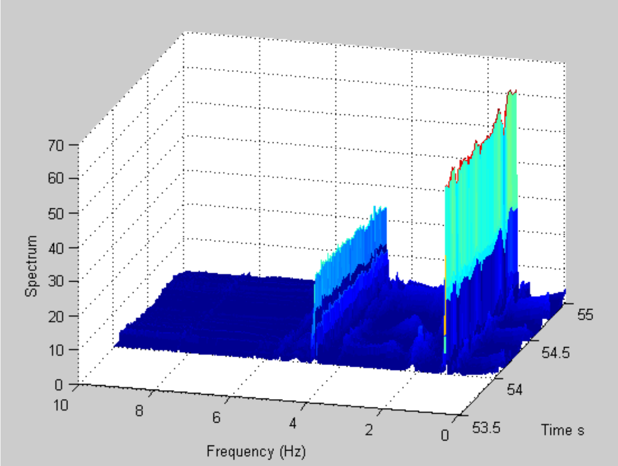

Figure 5: Suspension timber footbridge located in Fara, North-Eastern Italy: detail of the spectrum of the the acceleration signal in the transversal direction under the crossing of a group of 6 persons.

3. THE PROPOSED MODEL

Several attempts to simulate walking and running can be found in the literature (Occhiuzzi et al., 2008; Piccardo and Tubino, 2009; Krenk, 2012).

As discussed in (Casciati et al., 2015), following (Deodatis and Shinozuka, 1989; Faravelli and Bigi, 1990; Fenton and Vanmarcke, 1990; Bruggi et al., 2008), a model quite similar to the one used in wind engineering (Carassale and Solari, 2006) can be adopted for the human induced loading to be considered in the design of footbridges.

For a group of six persons in couples of two, a grid of 24 nodes is conveniently introduced. This grid moves with known velocity v in the direction of the crossing, with the average vertical action being W_0=200 N per node. This average value is modified by two contributions:

$$\boldsymbol{W}(\boldsymbol{x},\boldsymbol{y},t)=\Pi(\boldsymbol{x},\boldsymbol{y})\ [W_0+\boldsymbol{W}'(\boldsymbol{x},\boldsymbol{y},t)]$$

- the fluctuation $\boldsymbol{W}'(\boldsymbol{x},\boldsymbol{y},t)$ (equivalent to the stochastic turbulence in the wind velocity field idealization) which accounts for the spatial dispersion of the single trajectories and,
- a geometric shape function $\Pi(\boldsymbol{x},\boldsymbol{y})$, which accounts for two aspects of the human behavior; namely, the less likely walking close to the borders and the need to maintain a distance between the couples.

The fluctuation part of the force vector $\boldsymbol{W}$ (x_i,y_j,t) in each node (x_i,y_j) is modelled as a zero-mean, Gaussian, stationary random process. Its definition is pursued by the cross-power spectral density function $S_{W_1W_2}(\boldsymbol{r},\boldsymbol{r}';f)$ of the two force components, W_1 and W_2, in any pair of positions $\boldsymbol{r}=(x_i,\ y_j)$ and $\boldsymbol{r}'=(x_i',\ y_j')$ (with 1 and 2 associated with the two geometric horizontal directions of the grid), which is expressed in terms of auto-spectra and coherence function:

$$S_{W_hW_k}(\boldsymbol{r},\boldsymbol{r}';f) = \{S_{W_hW_k}(\boldsymbol{r};f)\ S_{W_hW_k}(\boldsymbol{r}';f)\}^{1/2}\,\mathrm{Coh}_{W_hW_k}(\boldsymbol{r},\boldsymbol{r}';f) \quad \text{for } h,k=1,2$$

f being the frequency and h,k being associated to the two component directions of the action.

The two auto-spectra follow the normalization so that their integral over the positive frequency axis is equal to the variance $\sigma^2{}_{W_k}$ of the force component. The auto-spectrum is conveniently given in a multiplicative form: the variance multiplied by a frequency function, which integrated over the frequency has value 1. The form of this function adopted in wind engineering

$$\Phi(\omega/(2\pi) = f) = a/(1+ a\, b\; \omega/(2\pi))^{5/3}$$

is replaced by

$$\Phi(\omega/(2\pi) = f) = a/(1+ a\, b\; \omega/(2\pi))^{4/3}$$

resulting in spikes at the frequencies typical of the vertical and transversal components.

4. NUMERICAL RESULTS

The model summarized in the previous section is combined with the simulation procedure in (Ubertini and Giuliano, 2010) to generate a realization of the stochastic (in time) random (in space) field. The crossing velocity is assumed to be 1.345 m/s. The moving load is applied to the finite element model (Figure 6) of the bridge in Figure 2. The response in terms of acceleration is achieved in the position where the sensor was located during the test in section 2.

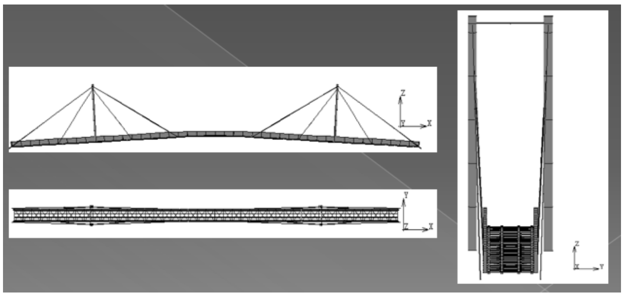

Figure 6: Suspension timber footbridge located in Fara, North-Eastern Italy: finite element model.

From the spectra of the two components of interest of this acceleration, one obtains the spectra in Figures 7 and 8 for the vertical and transversal components, respectively. It is seen that, despite the model of the previous section does not assign any higher harmonics, they are fully present in the response as resulted from the experimental response elaborations.

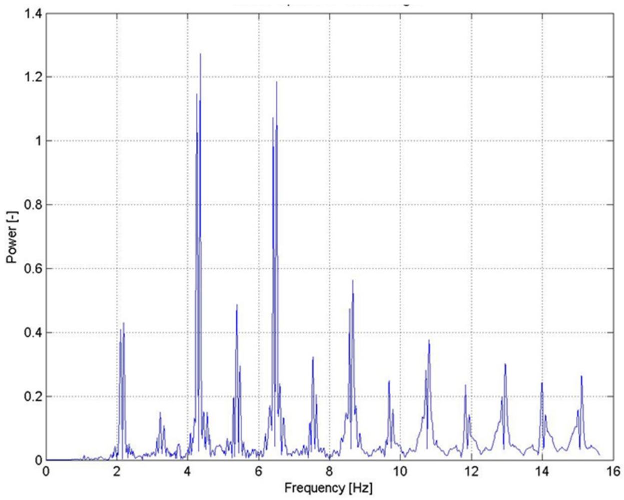

Figure 7: Suspension timber footbridge located in Fara, North-Eastern Italy: spectrum from the acceleration response in the vertical direction under the crossing of a group of 6 persons.

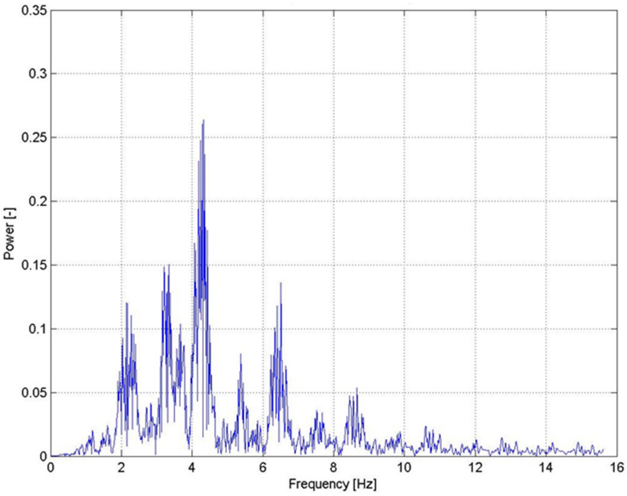

Figure 8: Suspension timber footbridge located in Fara, North-Eastern Italy: spectrum from the acceleration signal in the transversal direction under the crossing of a group of 6 persons.

5. CONCLUSIONS

In this paper, the authors use the result of an experimental campaign on an existing timber footbridge to implement a stochastic model for the so called human induced loading (HIL), i.e., for the source of the human induced vibration (HIV).

It is seen that the harmonics which characterize the spectral representation of the vibration are characteristic of the response and do not appear explicitly in the spectral representation of the load.

6. ACKNOWLEDGEMENTS

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