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Probabilistic assessment of the dynamic interaction between multiple pedestrians and vertical vibrations of footbridges

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A R T I C L E I N F O

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The effect of human-structure interaction in the vertical direction for footbridges is studied based on a probabilistic approach. The bridge is modeled as a continuous dynamic system, while pedestrians are schematized as moving single-degree-of-freedom systems with random dynamic properties. The non-dimensional form of the equations of motion allows us to obtain results that can be applied in a very wide set of cases. An extensive Monte Carlo simulation campaign is performed, varying the main non-dimensional parameters identified, and the mean values and coefficients of variation of the damping ratio and of the non-dimensional natural frequency of the coupled system are reported. The results obtained can be interpreted from two different points of view. If the characterization of pedestrians' equivalent dynamic parameters is assumed as uncertain, as revealed from a current literature review, then the paper provides a range of possible variations of the coupled system damping ratio and natural frequency as a function of pedestrians' parameters. Assuming that a reliable characterization of pedestrians' dynamic parameters is available (which is not the case at present, but could be in the future), the results presented can be adopted to estimate the damping ratio and natural frequency of the coupled footbridge-pedestrian system for a very wide range of real structures.

1. Introduction

Vibration serviceability assessment of footbridges is commonly based on simplified procedures (e.g. Refs. [1–8]) which neglect human-structure interaction.

Human-structure interaction could significantly affect human-induced vibrations of footbridges. Many models have been introduced in the literature in order to model lateral synchronization, which may lead to instability problems (see Refs. [9,10] for a review). Dealing with vibrations in the vertical direction, experimental measurements on real structures seem to demonstrate that human-structure interaction is beneficial, providing an equivalent additional damping to the footbridge [11–13]. Thus, experimental tests in laboratory conditions were carried out on scaled footbridges, confirming the results on real structures [14,15]: an extensive review can be found in [16]. Analogous findings were reported for staircases [17,18].

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Nomenclature

$\mathbf{C}$	damping matrix of the coupled structure-pedestrian system
c_i	velocity of the i-th pedestrian
c_j	j-th modal damping of the structure
c_{pi}	viscous damping of the SDOF system equivalent to the i-th pedestrian
f	external force
$\mathbf{f}$	external force on the coupled structure-pedestrian system
$\mathbf{G}$	state matrix of the coupled structure-pedestrian system
$\mathbf{H}$	complex response matrix of the coupled structure-pedestrian system
H	Heaviside step function
$\mathbf{K}$	stiffness matrix of the coupled structure-pedestrian system
k_j	j-th modal stiffness of the structure
k_{pi}	stiffness of the SDOF system equivalent to the i-th pedestrian
L	bridge deck span length
$\mathbf{M}$	mass matrix of the coupled structure-pedestrian system
m_j	j-th modal mass of the structure
m_{pi}	mass of the SDOF system equivalent to the i-th pedestrian
m_s	structural mass per-unit-length
n_{pm}	mean value of the natural frequency of the pedestrians' equivalent SDOF system
N_p	average number of pedestrians contemporarily present on the footbridge
p_j	j-th principal coordinate of the structure
$\mathbf{q}$	degrees of freedom of the coupled structure-pedestrian system
q_{pi}	displacement of the SDOF system equivalent to the i-th pedestrian
q_s	vertical displacement of the bridge
t	time
$\tilde{t}$	non-dimensional time
V_{mp}	coefficient of variation of the mass of the pedestrians' equivalent SDOF system
$V_{\omega c}$	coefficient of variation of the natural circular frequency of the coupled structure-pedestrian system
$V_{\omega p}$	coefficient of variation of the natural circular frequency of the pedestrians' equivalent SDOF system
$V_{\xi c}$	coefficient of variation of the damping ratio of the coupled structure-pedestrian system
$V_{\xi p}$	coefficient of variation of the damping ratio of the pedestrians' equivalent SDOF system
x	abscissa along the deck
$\tilde{x}$	non-dimensional abscissa along the deck
x_i	position of the i-th pedestrian
$\mathscr{C}$	damping operator
$\mathscr{L}$	stiffness operator
δ	Dirac Delta function
φ_j	j-th mode shape of the structure
μ_{pi}	non-dimensional mass of the SDOF system equivalent to the i-th pedestrian
μ_{pm}	mean value of the mass of the pedestrians' equivalent SDOF system
τ_i	arrival time of the i-th pedestrian
$\tilde{\omega}_c$	non-dimensional natural frequency of the coupled structure-pedestrian system
$\tilde{\omega}_{cm}$	mean value of the non-dimensional natural frequency of the coupled structure-pedestrian system
ω_j	j-th natural circular frequency of the structure
ω_{pi}	natural circular frequency of the SDOF system equivalent to the i-th pedestrian
$\tilde{\omega}_{pi}$	non-dimensional natural frequency of the SDOF system equivalent to the i-th pedestrian
$\tilde{\omega}_{pm}$	mean value of the non-dimensional natural frequency of the pedestrians' equivalent SDOF system
ξ_c	damping ratio of the coupled structure-pedestrian system
ξ_{cm}	mean value of the damping ratio of the coupled structure-pedestrian system
ξ_j	j-th damping ratio of the structure
ξ_{pi}	damping ratio of the SDOF system equivalent to the i-th pedestrian

Different models have been proposed in the literature to deal with human-structure interaction in the vertical direction. Pedestrians have been schematized as equivalent Single-Degree-of-Freedom (SDOF) or Multi-Degree-of-Freedom (MDOF) systems [19,20], as an inverted pendulum [21], or as a bipedal walking model with damped compliant legs [22,23]. In the analysis of grandstands and stadiums occupied by humans, sitting or standing humans were modeled as SDOF or MDOF