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Crowd–structure interaction in footbridges: Modelling, application to a real case-study and sensitivity analyses

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Abstract

A mathematical and computational model used to simulate crowd–structure interaction in lively footbridges is presented in this work. The model is based on the mathematical and numerical decomposition of the coupled multiphysical nonlinear system into two interacting subsystems. The model was conceived to simulate the synchronous lateral excitation phenomenon caused by pedestrians walking on footbridges. The model was first applied to simulate a crowd event on an actual footbridge, the T-bridge in Japan. Three sensitivity analyses were then performed on the same benchmark to evaluate the properties of the model. The simulation results show good agreement with the experimental data found in literature and the model could be considered a useful tool for designers and engineers in the different phases of footbridge design.

1. Introduction

Over the last few decades, several footbridges have shown great sensitivity to human induced vibrations in the lateral direction (e.g. Refs. [1,2]). This phenomenon, known as synchronous lateral excitation, can take place any time pedestrians walk on a surface that oscillates laterally with a frequency that is close to the mean lateral walking frequency (around 1 Hz). When a pedestrian walks on a laterally moving surface, in an attempt to maintain balance, he walks with his legs more widespread and adapts his frequency to that of the moving surface, that is, he synchronises to the structure. Hence, the lateral motion of the upper part of the torso increases and the resulting lateral force increases in turn. This phenomenon is amplified if the pedestrian walks in a crowd, since synchronisation among pedestrians increases the effects of pedestrian–structure synchronisation.

The synchronous lateral excitation phenomenon has never caused structural failure since it is self-limited, that is, when the vibrations exceed a limit value, pedestrians stop walking or touch the handrails, and this causes the vibration to decay. Nevertheless, the resulting reduced comfort for the users has often led to a temporary closure of the footbridge, with consequent economic and social repercussions. In order to avoid this kind of problem, an intense research activity was begun after the Millennium Bridge in London was closed

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Nomenclature

a	coefficient for the expression of the pedestrian–pedestrian synchronisation
b	coefficient for the expression of the pedestrian–structure synchronisation
$\mathscr{C}$	damping operator
d_0	body depth of a motionless pedestrian
d_c	characteristic dimension of a cluster of pedestrians
d_s	sensory distance
F	lateral force exerted by pedestrians
F_{pp}	lateral force component due to the pedestrians synchronised to each other
F_{ps}	lateral force component due to the pedestrians synchronised to the structure
F_s	lateral force component due to the uncorrelated pedestrians
$\tilde{F}$	envelope of the lateral force exerted by pedestrians
$\tilde{F_{pp}}, \tilde{F_{ps}}, \tilde{F_s}$	envelope of the lateral force components
$\bar{F}_s$	amplitude of the lateral force exerted by a single pedestrian on a motionless deck
$\bar{F}_{\dot{z}}$	amplitude of the F_{ps} component in phase with lateral velocity of the deck
$\bar{F}_{\ddot{z}}$	amplitude of the F_{ps} component in phase with the lateral acceleration of the deck
f_{pl}	lateral step frequency
f_r	frequency ratio f_{pl}/f_s
f_s	structural natural frequency of interest
g	function that makes the walking velocity sensitive to the deck motion
i	time index
L	length of the footbridge span
$\mathscr{L}$	stiffness operator
m	mass of the crowd–structure system
m_c	crowd mass
m_s	structural mass
n	total number of pedestrians
n_{pp}	number of pedestrians synchronised to each other
n_{ps}	number of pedestrians synchronised to the structure
n_s	number of uncorrelated pedestrians
q	structural displacement
S_{pp}	coefficient of synchronisation among pedestrians
S_{ps}	coefficient of pedestrian–structure synchronisation
t	time
t_s	time at which pedestrians stop because of excessive deck vibrations
v	pedestrian velocity
v_M	mean maximum velocity
X	space coordinate along the footbridge length
Y	vertical space coordinate
$\tilde{\dot{z}}, \tilde{\ddot{z}}$	envelope of the deck lateral velocity and acceleration
$\dot{z}_c, \ddot{z}_c$	thresholds of motion perception
$\dot{z}_M, \ddot{z}_M$	maximum values of the lateral velocity and acceleration of the deck
$\dot{z}_s, \ddot{z}_s$	serviceability limits on the lateral velocity and acceleration of the deck
Z	lateral space coordinate
δ	space dislocation in the crowd density–-velocity relation
Δt	time step
Δt_r	stop-and-go time interval
$\Delta\tau$	synchronisation time delay
ΔX_c	space grid size in the crowd subdomain
ε	half-amplitude of the lock-in triggering region
γ	travel purpose parameter in the crowd density–velocity relation
η	function that describes the deck acceleration effect on S_{ps}
ρ	crowd density
ρ_c	critical density, upper limit for unconstrained free walking
ρ_{ca}	capacity density
ρ_h	maximum density during the crowd event
ρ_M	maximum admissible density
ρ_{sync}	crowd density corresponding to complete pedestrian synchronisation
Φ	shape of the first lateral mode of the deck

because of excessive lateral vibration. The results of these studies, which are reviewed in Ref. [3], represent the scientific background of some recently published design guidelines [4,5].

The most relevant data concerning pedestrian behaviour have been obtained using an empirical approach. Laboratory tests involving a pedestrian walking on both a motionless platform [6] and a laterally moving treadmill [2,7], as well as tests performed on actual footbridges [8], have been carried out to measure the lateral