

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

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Received 23 May 2008; received in revised form 3 December 2008; accepted 3 December 2008

Handling Editor: C.L. Morfey

Available online 20 January 2009

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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.

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

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