Engineering Structures 56 (2013) 95–104

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Mitigation of human-induced lateral vibrations on footbridges through walkway shaping

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ARTICLE INFO

Article history:
Received 18 September 2012
Revised 8 March 2013
Accepted 22 April 2013

Keywords:
Footbridges
Human-induced lateral vibrations
Mitigation measures
Walkway shaping
Crowd flow control

ABSTRACT

In the last decade, the issue of human-induced lateral vibrations on footbridges has attracted an increasing interest due to the construction of several lightweight and flexible structures, which are highly sensitive to dynamic pedestrian action. A new approach to the mitigation of human-induced lateral vibrations on footbridges is proposed. The approach develops from the analogy between crowd- and wind-structure interaction phenomena. The mitigation measure addresses the passive control of the crowd flow and the applied force in turn, in analogy to aerodynamic countermeasures already adopted in Wind Engineering. Crowd flow control is accomplished by shaping the walkway in plan, in order to modify the pedestrian density, speed and walking frequency. A simplified approach to the preliminary assessment of the footbridge and to the conceptual design of the modified walkway is first proposed. A detailed computational analysis is subsequently applied to a test-case to evaluate the effectiveness of the proposed approach.

1. Introduction

The issue of human-induced vibrations on footbridges has become one of the leading research topics in structural dynamics during the last decade. This is due to the recent trend towards increased slenderness and reduced mass, stiffness and damping. Among others, the problem of lateral vibrations induced by synchronized pedestrians – the so-called Synchronous Lateral Excitation (SLE) – has especially attracted the attention of researchers after the closure of the London Millennium Footbridge in 2000 [1]. The SLE phenomenon can occur on any footbridge with a lateral frequency around 1 Hz and crossed by a sufficient number of pedestrians. The SLE is due to the development of synchronization phenomena that enlarge the lateral vibrations until the pedestrians stop walking because they are no longer able to maintain balance (for a review, see [2–4]).

SLE can be ascribed to flow–structure interaction phenomena, such as the ones involving wind and structures, e.g., Vortex-Induced Vibrations (VIVs) and lock-in: the air flow around long-span bridge decks, chimneys and tall buildings in VIV is replaced by the crowd flow along the footbridge in SLE. Crowd and wind streams differ in several key aspects: pedestrians are active agents while air particles are not; crowd flow is compressible and in some circumstances shows granular features, while wind flow is incompressible and turbulent in civil engineering applications. Despite these differences, the occurrence of synchronization and self limitation of the cross-flow structural response is common to the behavior of both coupled systems. This analogy has inspired some authors to adapt models widely used in VIV analysis to SLE. Examples of experimental (see for instance [5,6]), analytical (e.g., [7]) and computational [8] models can be found in the literature. To the best of the authors' knowledge, the VIV-SLE analogy has never been systematically exploited to adapt the full range of VIV mitigation measures to SLE.

In general, the reduction of the flow-induced structural response can be obtained by acting on one of the two components of the coupled system: on the structure, in order to reduce its response by varying its dynamic properties, or on the flow in order to modify/suppress the source of excitation.

Mitigations on the structural side disregard the particular kind of flow (e.g., wind [9,10] or crowd [2,11]), while they are adapted to the structural typology and the structural response threshold value at which they should be effective. In the case of ligthweight and slender footbridges, mitigations generally consist of adding extra damping, since increasing the mass or the stiffness implies high costs and undesired aesthetic impact. Most of the footbridges that have experienced SLE have been subsequently provided with passive dampers such as viscous dampers [1], friction dampers [12], Tuned Mass Dampers [13,14] or Liquid Mass Dampers [15].

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http://dx.doi.org/10.1016/j.engstruct.2013.04.019

Nomenclature

b	variation of the walkway width
B	width of the walkway
B_0	initial width of the walkway
$\mathscr{C}$	damping operator
D	dynamic amplification factor
F	amplitude of the modal force
f_{pp}	force component due to pedestrians synchronized among each other
f_{ps}	force component due to pedestrians synchronized to the structure
f_s	force component due to uncorrelated pedestrians
f_z	pedestrian lateral force per unit length
g	gravity acceleration
$g(\tilde{\ddot{q}}_z)$	function that models the reduction of the walking velocity due to the deck motion
G	average pedestrian mass
L	length of the footbridge span
$\mathscr{L}$	stiffness operator
m_c	crowd mass per unit length
m_r	ratio of the crowd to structure mass
m_s	structure mass per unit length
M	modal mass
n_{pp}	pedestrians synchronized among each other per unit length
n_{ps}	pedestrians synchronized to the structure per unit length
n_s	uncorrelated pedestrians per unit length
$\mathbf{q}$	structural displacement
$\ddot{q}_{z,\mathrm{lim}}$	perception threshold of the lateral acceleration of the deck
$\ddot{q}_{z,M}$	maximum lateral acceleration of the deck
$\tilde{\ddot{q}}_z$	envelope of the lateral acceleration of the deck
$\ddot{Q}_z$	amplitude of the steady state modal acceleration
t	time variable
v	walking velocity
v_M	free walking velocity
w	average width occupied by a walking pedestrian
w_0	average lateral width of the human body
x	space variable along the footbridge longitudinal axis
y	space variable along the footbridge vertical axis
z	space variable along the footbridge lateral axis
α	dynamic load factor of the first harmonic of the pedestrian force
γ	exponent of the speed-density relation
$\varphi(x)$	mode shape
ρ	pedestrian density
ρ_c	critical density below which synchronization does not take place
ρ_ca	capacity density
ρ_in	incoming crowd density
ρ_lim	limit density that induces a lateral acceleration equal to $\ddot{q}_{z,\mathrm{lim}}$
ρ_M	maximum crowd density
$\rho_{M,0}$	initial value of the maximum crowd density
ω_{pl}	lateral step circular frequency
ω_r	ratio of the lateral step frequency to the structure frequency
ω_s	natural circular frequency of the structure
$\omega_{s,0}$	natural circular frequency of the empty footbridge
ζ	damping ratio

Mitigations on the flow side strongly depend on the kind of flow to be modified, so that measures conceived for a kind of flow (e.g., wind) cannot be directly transferred to another one (e.g., crowd flow) or *vice versa*. However, they can serve as a source of inspiration. The conceptual design of these mitigations requires a deep phenomenological understanding and modelling of the source of excitation as well as the structural behavior. A sufficient scientific background has been recently acquired in the field of Wind Engineering, so that a number of aerodynamic devices are presently employed to reduce wind-induced vibrations. Several examples of applications to tall buildings [10,16] and long-span bridges [17,18] can be found in the literature. They are based on the shaping of the overall structure (e.g., elicoidal shape of tall buildings) or on the introduction of punctual elements (e.g., guide vanes around bridge decks). Crowd flow control strategies have been proposed in the fields of applied mathematics, physics and transportation engineering (see e.g., [19,20]), thanks to the development of dynamic models in which the pedestrians are treated as a dynamic system rather than a simple source of load. The control of crowd flow, e.g., in pedestrian traffic or evacuation scenarios, is often accomplished by punctual obstacles (e.g., columns) located in strategic positions, in order to force the crowd flow to follow certain patterns and avoid the formation of jams or ease evacuations (see for instance [21,22]). However, to the authors' knowledge crowd control strategies have never been systematically applied to the mitigation of structural vibrations on footbridges, except for the recent suggestion in [23], where temporary barriers along the footbridge path are expected to modify the crowd flow and to reduce the footbridge response in turn.

This work proposes a strategy of crowd flow control based on the smooth widening/narrowing of the walkway width along the span of the footbridge, with the aim of controlling the structural response. Such a proposal requires a modelling approach where the crowd is not described as a simple load applied to the structure, but as a dynamic system which interacts with the structure.

The paper develops through the following sections: in Section 2 a simplified criterion is proposed to allow the footbridge designer to predict the most suitable shaping strategy, and it is applied to four real world test-cases; in Section 3 the effectiveness of the mitigation measure is assessed more precisely by means of the crowd–structure interaction model previously developed by the authors [24]; Section 4 describes the application of the approach to an ideal footbridge, while the conclusions and research perspectives are outlined in Section 5.

2. Conceptual design of the mitigation measure through a simplified approach

The proposed mitigation measure is based on the walkway narrowing/widening along the footbridge span. The measure is expected to affect the crowd density, and consequently the walking velocity and step frequency, i.e., the load exerted by the pedestrians on the structure. Specifically, the walkway narrowing/widening is set with the aim of reducing the bridge lateral acceleration under its perception threshold value $\ddot{q}_{z,\mathrm{lim}} = 0.1\ \mathrm{m/s^2}$ [25]. As a consequence, synchronization between the pedestrians and the structure does not take place also for incoming crowd density $\rho > \rho_\mathrm{lim}$, where ρ_lim is the density which induces a lateral acceleration equal to $\ddot{q}_{z,\mathrm{lim}}$ [26] on the footbridge in the initial geometrical configuration.

Two remarks should be made. First, the proposed mitigation measure is expected to be ineffective in the so-called unconstrained walking regime, where few pedestrians sparse along the