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Probabilistic criteria for lateral dynamic stability of bridges under crowd loading

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ABSTRACT

Probabilistic conditions for lateral stability of bridges are proposed, based on output from the inverted pendulum pedestrian model from the field of biomechanics. Statistical variations of the parameters defining the model are studied based on real statistical data of the English population. Variability of the self-excited forces is quantified for crowds of different velocities and critical conditions are identified for bridge natural frequencies below 5 Hz. Allowance is made for the influence of the bridge mode shape and number of pedestrians in the crowd and their spatial distribution. This allows realistic worst case conditions among different loading scenarios for a particular structure to be found.

1. Introduction

The problem of pedestrian-induced lateral vibrations is especially pertinent to bridges, which, due to the trend of building lighter and longer structures, have become increasingly vulnerable to dynamic pedestrian loading. Among well documented cases of bridges susceptible to excessive lateral vibrations are the London Millennium Footbridge (LMF) [1], the Singapore Airport's Changi Mezzanine Bridge (CMB) [2], the Clifton Suspension Bridge (CSB) [3] and the Pedro e Inês Footbridge (PIF) [4]. The measured responses of these bridges to crowd actions are characterised by divergent amplitude lateral vibrations which develop rapidly with a small increase in the number of occupants, which cannot be explained considering pedestrian forces exerted on stationary ground only, thus suggesting the existence of self-excited (or 'motion-dependent') forces arising from bi-directional human–structure interaction. (Excessive vibrations of bridges due to pedestrian loading can also occur in vertical direction (e.g. [5,6]) and human–structure interaction is also likely to occur on vertically oscillating ground [18], but this problem is outside of the scope of this paper.)

The origin of the self-excited forces has most commonly been explained as the pedestrians synchronising to the movement of the structure, adjusting the frequency and phase of their footsteps in a manner to increase its motion ('lock-in'), a phenomenon allegedly reinforced by interpersonal synchronisation occurring unintentionally in crowds. However, many loading models based on these propositions stand in direct contrast to some recent observations. Specifically, no evidence of synchronisation was detected from measurements on the CMB [2] and CSB [3], yet rapid increases of lateral displacement amplitudes were clearly observed. Interestingly, the measured responses of these two bridges are compatible with the model based upon a linear relationship between the local velocity of the deck and the lateral pedestrian force, derived by Arup from the tests on the LMF [1], although the values of the pedestrian negative damping parameter (the coefficient of proportionality) differ in each case. Moreover, a lack of synchronisation was found from the latest experimental campaign aimed at measuring forces from pedestrians walking on a laterally oscillating instrumented treadmill [7]. However, self-excited forces were identified, with the most important component centred at the treadmill vibration frequency, which was generally different from the walking frequency. Therefore, the model derived by Arup seems to be valid (although the nature of the underlying mechanism, at least in the case of small amplitude vibrations, might have been misunderstood at the time), but it requires further generalisation.

For that purpose a fundamental biomechanically-inspired inverted pendulum pedestrian model (IPM) has been applied to study lateral pedestrian–structure interactions [8,9]. In this model, while supported on one leg, the pedestrian acts passively under the influence of gravity and any acceleration of the supporting surface, which can be considered as an external perturbation. Lateral

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balance is maintained by means of a foot placement control law at the transition from one foot to the other (without assuming synchronisation of footstep timing to the bridge motion), whereby the foot is placed further or less far out to the side on each step to stabilise the pedestrian's lateral balance depending on the their lateral velocity at the time it is placed (e.g. if falling too fast to the right, the foot is placed further to the right). Experimental evidence was recently presented by Hof et al. [10] showing this is the primary response to lateral perturbations while walking. Outputs of the IPM have been found to be consistent with the measured lateral forces of pedestrians on stationary ground [8], the self-excited forces identified from the laboratory tests by Ingólfsson et al. [7], and the measurements on the LMF, CMB and CSB [9].

To put the findings from the IPM in the context of existing modelling approaches, formalised design recommendations and other proposed models are briefly reviewed and some of their shortcomings highlighted. Utilising real statistical data, the distributions of the parameters defining the IPM are then analysed. Taking these into consideration, probabilistic dynamic stability criteria are derived for a given number of pedestrians on a bridge, accounting for their spatial distribution with relation to the mode shape.

2. Existing design recommendations and modelling approaches

Elementary recommendations for the design of structures for the actions of pedestrians are included in Eurocodes 0 and 5 [11,12] and ISO 10137 [13], dealing with the evaluation of serviceability against vibrations of walkways for human occupancy. All these standards propose some design parameters expressed in terms of acceleration for lateral frequencies typically below 2.5 Hz. However, measurements on the CMB [2] and CSB [3] have revealed that quantifying the acceleration alone may not capture the potential for instability, since when certain conditions are met the acceleration amplitude can grow rapidly from very low levels. Eurocode 1 [14] acknowledges the complex nature of pedestrian action and states that appropriate loading models and comfort criteria may be defined in the National Annexes. In broad terms, a periodic force with a frequency range between 0.5 and 1.5 Hz is to be assumed in the lateral direction.

A lateral pedestrian load model is presented in the reports from two major European research projects focusing on human-induced vibrations: Human Induced Vibrations of Steel Structures (HIVOSS) [15] and Advanced Load Models for Synchronous Pedestrian Excitation and Optimised Design Guidelines for Steel Footbridges (SYNPEX) [16]. However, this model ignores the influence of the feedback from the movement of the structure on pedestrian behaviour and instead, for calculation of the structural response, it suggests application of the first harmonic load contribution only, characteristic of walking on stationary ground (0.04 fraction of body weight), and application of an increased first harmonic load factor when synchronisation with the vibration occurs (0.055 or 0.075 fraction of body weight for acceleration amplitudes lower or higher than 0.5 m/s^2, respectively). Synchronisation lies at the centre of the guidelines from the French Ministry of Transport and Infrastructure (Sétra) [17]. An acceleration limit of 0.1 m/s^2 is proposed, beyond which the probability of synchronisation increases and large amplitude lateral vibrations can develop. However, the negative damping model proposed by Arup is consistent with the data collected on the LMF, CMB and CSB down to very low vibration levels, well below this proposed limit. (Synchronisation may however occur for larger vibration amplitudes, which is beyond the scope of the current paper, which deals only with the initiation of the lateral instability.) A number of other modelling approaches have been proposed in which synchronisation and parametric resonance are employed as driving mechanisms of lateral vibrations, which are reviewed in [18–22]. However, these models are often based on uncertain forcing assumptions and parameters are often chosen to fit the data.

An alternative source of the additional self-excited forces was suggested by Barker [23] who formulated a pedestrian model comprising a lumped mass, equal to the whole pedestrian body mass (at the centre of mass, CoM), moving along the bridge in a straight line, from which the lateral forces are derived by resolving its action through an inclined massless leg. He found that, without assuming synchronisation, averaged over all possible phase angles, pedestrians put energy into the vibrating bridge, even for pedestrian pacing frequencies different from the bridge frequency. The results from this model, calibrated by the Arup model [1], constitute the basis of the recommendations in the UK National Annex to Eurocode 1 (UKNA) [24] for avoidance of unstable lateral responses due to crowd loading [25], shown in Fig. 1.

The stability boundary (grey curve) is defined in terms of the pedestrian mass damping parameter (similar to the Pedestrian Scruton Number proposed by McRobie & Morgenthal [26] and equivalent to half the Pedestrian Scruton Number adopted by Newland [27]) relating the modal mass of the bridge, M, the modal mass of pedestrians, M_p, and the structural damping ratio, ζ:

$$D = \zeta \frac{M}{M_p}, \tag{1}$$

where M_p is defined as:

$$M_p = \int_0^L m\phi^2 \mathrm{d}s, \tag{2}$$

where m is the mass of pedestrians per unit length, L is the length of the bridge, ϕ is the lateral mode shape and s is the distance along the bridge. To avoid dynamic instability in a given lateral vibration mode, the pedestrian mass damping parameter for that mode, with the relevant pedestrian mass, should lie above the stability boundary. For comparison, also presented are estimates of values on the stability boundary from the LMF [1], for bridge natural frequencies of 0.5–1 Hz, the CMB [2] and CSB [3] (two unstable modes), derived for these three bridges through inverse dynamics (by identifying the forces from the motion of the bridge and finding the constant of proportionality with the velocity). Also shown is a value on the stability boundary from the PIF [4], derived from crowd loading tests which validated the critical number of people necessary for the onset of instability, N_{cr}, as specified by the formula established by Arup [1] for a uniform distribution of pedestrians:

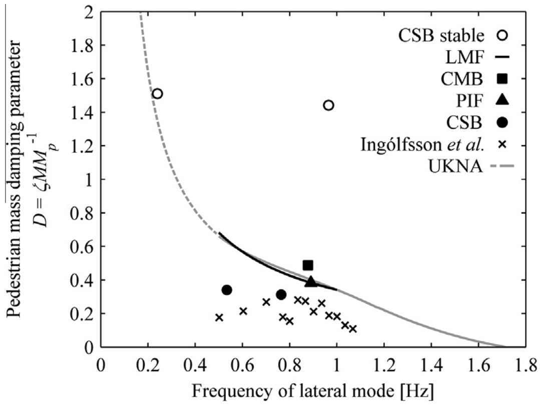

Fig. 1. Lateral stability boundary taken directly from UKNA (grey curve whose dashed part indicates uncertain values). Also presented are the results from site measurements on four bridges: the LMF [1] (for frequency range of 0.5–1 Hz – black curve), CMB [2] (■), CSB [3] (● – unstable modes, ○ – stable modes) and PIF [4] (▲), and results of laboratory investigations [7] for amplitude of 4.5 mm (×).