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Numerical analysis of a synchronization phenomenon: Pedestrian–structure interaction

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ABSTRACT

The pedestrian–structure interaction is considered by developing a non-linear double pendulum model, representing the lateral walking of the pedestrian and the horizontal vibration mode of the structure. To understand the synchronization phenomenon, the two oscillators were considered in their phase spaces, and a ring-dynamics approach was applied. As synchronization occurs, pedestrian motion becomes in phase quadrature with a quarter-of-period in advance of the bridge motion: this ensures stability of walking conditions on a moving deck, but causes random cancellation of forces typical of an incoherent crowd. Correspondingly, the lateral force transmitted to the structure increases its value, approaching resonance conditions.

1. Introduction

The soil reaction demanded by a pedestrian when walking on a slippery surface generally has three orthogonal force components and three orthogonal moment components. Which one of these, or in what combination, might be relevant to the definition of dynamic load, which is not only a function of the walking posture, but also of the characteristics of the surface and substructure below: i.e. a rigid pavement, a dance-hall, a stadium, a grandstand, a footbridge, etc. Effects may, in fact, vary from the incoherent case (for which no correlation exists between the footfall times of the walker and the base motion), to vertical resonance with the base, and to lateral synchronization, i.e. lock-in.

Fields of research in pedestrian dynamics are therefore various: Biomechanics and Robotics (e.g. [1]) are more interested in defining loads transmitted to the body from a rigid pavement; Neurosciences (e.g. [2]) in studying spatial paths of the body in the search of equilibrium, while Structural Engineering – which began to consider pedestrian dynamic loads only with the advent of lightweight structures – is more increasingly interested in studying the relationship between pedestrian action and the motion of the structure below, as testified by the wide scientific literature published in last few decades, and recently reviewed in [3].

In fact, the literature has identified human-induced load as one of the most important sources of vibration for lightweight structures, in particular for new innovative footbridges. Actually, such slender footbridges, due to the new technology and application of light weight and high strength materials, often have low stiffness, low mass, low damping and therefore are susceptible to vibration induced by human activities. Nevertheless, modeling of the crowd-induced dynamic force is not clearly defined yet, despite some serious attempts to tackle this issue in the last few years.

It was noted very early that this type of dynamic excitation could cause excessive vibrations and in extreme cases even the collapse of the structure. However, it is generally accepted that vibration produced by human-induced loads is usually a serviceability rather than a safety (i.e. ultimate limit state) problem for modern slender footbridges [3]. Severe vibration serviceability problems can arise, particularly in the lateral direction since pedestrians are much more sensitive to low-frequency lateral vibration when walking or running than to the vertical vibration, and slender footbridges have a much weaker structural stiffness in the lateral direction than in the vertical direction [4,5].

Research concerning structural and pedestrian dynamic interaction can be generally classified in two ways: by working domain analysis, which is frequency and time domains, and by the scale of the phenomenological observation of the system, which is single pedestrian and crowd action. It is worth noting that while single pedestrian action can hardly affect structural response, crowd action has repeatedly forced the closure of newly conceived footbridges, failing with respect to acceleration limits compatible with pedestrian comfort, e.g. Millennium Bridge in London [6], T-Bridge in Japan [7], and Solférino Bridge in Paris [8]. In most of these cases, the excitation of the structure was caused by the lateral dynamic force produced by the zigzag movement of pedestrians. Once the

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base started to vibrate, some of the pedestrians synchronized with the structure vibration, which further increased the structure response.

Therefore, the key to predicting the actual structural response, and to give some more indications in the design phase, is the correct evaluation of lateral dynamic forces of pedestrians when they walk on a vibrating deck. Usually, the theoretical description of such a phenomenon (i.e. the synchronization or lock-in) has been carried out by defining the "crowd action", considered as a whole entity and not as a "sum" of single pedestrian effects. In such a way, the synchronization is dealt with at a "macro" level, allowing the proper capture of the crowd effect but losing the meaning and the phenomenology of the actual mechanisms which produce lock-in.

In this paper, the synchronization phenomenon is approached from the single pedestrian level, regarded as element of crowd, and the treatment of pedestrian–structure interaction is carried out by means of an original two-degree freedom model of interface, where coupling between pedestrian and structure is explicitly taken into account, introducing the concept of a pedestrian "phase" variable, in the general case of an oscillator (e.g. pedestrian) perturbed by external action (e.g. structural motion). The proposed model has been developed by exploiting the existing analogy with another synchronization phenomenon typical of civil engineering: the interaction between the bell tower dynamic motion and the oscillation of the bells. In particular, the proposed coupled model has been developed starting from the bell-tower formulation proposed in [9].

With such an approach, the synchronization phenomenon can be tackled at a "micro" level, i.e. pedestrian level, thus allowing the clarification of the actual mechanisms driving entrainment (i.e. the tendency for two oscillating bodies to lock into phase so that they vibrate in harmony) and coherence of pedestrians on a moving deck. In fact, the resulting crowd force, in serviceability failure cases, is determined by single pedestrian lateral motions strongly coherent with common base oscillation, thereby making it mandatory to account for the real stiffness of the supporting structure. On the contrary, while walking on a rigid (or nearly rigid) surface, single pedestrians cannot be coherent to any oscillating common support, the resulting crowd force thus being a sum of randomly deleted components of minor importance.

2. Pedestrian–deck interaction model

2.1. The frontal plane

There is some evidence in the literature that the component of walking forces governing pedestrian–structure interaction is the force acting in a lateral direction with respect to the frontal plane. Firstly, ISO 10137 concerning serviceability of buildings and pedestrian structures against vibrations, reports that moving humans are about 4 times more sensitive towards lateral than vertical accelerations, e.g. [10].

Moreover, the well known phenomenon of resonant effects on bridges from vertical motion caused by marching soldiers was controlled in the past by simply warning troops to break step when crossing: actually in the case of pedestrians no natural synchronization phenomenon with the vertical modes of the bridge is present.

Rather obviously then, longitudinal modes recalling significant axial stiffness are not interested in the case of pedestrian bridge decks.

In real structures, lateral modes and the frequent lateral–torsional coupled modes are the ones experiencing crowd action response, as shown by a review of the experimental results in the literature (e.g. Auckland harbor bridge back in 1979, T-footbridge in Japan in 1992 [11], London Millennium footbridge in 2000 [6], Paris Solférino footbridge in 2000 [8]). Moreover, different justifications from Biomechanics and Neural Sciences allow us to concentrate our research on the pedestrian frontal plane. In particular, in human walking dynamics literature, e.g. [12], the lateral eigenvector (i.e. roll angle) is the only one whose stability of limit cycle is not assured against external small perturbations (e.g. transverse deck motion). This means that the periodic motion of the system in the frontal plane is not passively stable at local limb level as in fore–aft stability, but requires active control by pedestrian brain. Neural feedback control is likely to involve higher centers such as brain stem and cerebellum, with integrated input by visual, vestibular, proprioceptive and other sensors.

Crowd action lateral response characterizes interaction on the structure side, and neural feedback control in roll angle characterizes interaction on the pedestrian side. This is why the proposed approach for the interaction simulation assumes the frontal as reference plane, and therefore only lateral walker forces will be relevant in the coupled study.

2.2. Walking model

As previously stated, we are interested in a walking model able to describe roll angle oscillations in the frontal plane. In biomechanical literature, the classical theoretical model is the inverted pendulum with reference to quiet standing [13] or to a single free-falling step [2]: extending it to continuous walking for pedestrian–structure interaction is not straightforward, because the model involves discontinuity in step change, and evaluation of the ankle and hip equilibrating torques, which have not only mechanical but also neural components, e.g. [14]. On the other hand, experimental measures in [1,3] show that continuous walking lateral forces and accelerations of the center of mass CoM are a nearly-square wave curve, Fig. 1a, and lateral displacements a nearly-sine wave, in-phase and with the same period, Fig. 1b: each semi-wave corresponds to a change in position of the center of pressure CoP, located on the sole of the foot leaned on the ground (according to the inverse pendulum model, see Fig. 1c).

For the pedestrian–structure interaction scope, this suggests the possibility to model the walking process as a simple oscillator, Fig. 1d: in particular note in Fig. 1d the possibility to maintain both CoM, and CoP change concepts. In fact, to model the interaction of a pedestrian with a moving surface, it could be sufficient to record the instant in which the pedestrian changes his CoP, and analyze how this change occurs with respect to a undisturbed sequence of CoP changes on rigid surface. In other words, to study synchronization, it would be sufficient to check the oscillator frequencies or rhythms, neglecting shape and amplitude variations in wave.

Dynamical systems that fit such simplified framework of interacting in rhythms belong to the category of "ring dynamics" [15]. In ring dynamics, the pedestrian roll angle oscillation is considered as a point traveling around its limit cycle at the walking frequency, and the structure external force can push this point backward or forward along the cycle, neglecting slight changes happening in radial direction, i.e. "off the ring". Therefore, in our research the roll angle model is represented as a simple oscillator, so the pedestrian oscillator can be schematized only by its fundamental harmonic, as shown in Fig. 1b. The criterion to prove the validity of the ring dynamics scheme will be clarified further in Section 2.5.

Fig. 2 describes how to move from a distributed mass pedestrian, to the classical inverted pendulum model, to the equivalent simple oscillator adopted in our research: the pedestrian masses $m_{p1} + m_{p2} + \cdots + m_{pi} + \cdots + m_{pn}$ in the inverted pendulum model (Fig. 2a) are classically concentrated at pelvis level, in a CoM assumed near m_{p2}. To define the simple oscillator describing