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Coupled analysis of footbridge-pedestrian dynamic interaction

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ABSTRACT

In this work, an analytical formulation for the vibration response of a bridge due to walking pedestrians is proposed to the aim of modelling the human-structure interaction (HSI) in the vertical direction. Bridge and pedestrians are described as mechanical systems having a finite number of degrees of freedom (DOFs). A new single DOF model of a bipedal pedestrian is proposed, that reproduces the alternation of single and double support phases of human gait and the related ground reaction forces. The finite element method is adopted to model the 3D geometry of the bridge. The coupled equations of motion are derived based on the key assumption that contact points between the pedestrians and the bridge deck are massless. However, the structural matrices of the coupled system are time varying due to the pedestrian motion along the bridge. An uncoupled solution strategy is devised to reduce the computational burden, allowing for the separate integration of the bridge and the pedestrian sub-systems. The coupled formulation is uncoupled and associated with an iterative procedure that restores compatibility and equilibrium at contact points. The pedestrian model and the analytical procedure are implemented in a research code where input data are the bridge structural matrices computed with a commercial FE code. The modelling and analysis procedure is applied to a case study, a lively footbridge in Seriate, Italy. A first validation of the code is obtained by comparison with a closed form solution for a 1D beam. For the loading scenarios analyzed here, a maximum of two iterations per step are necessary to achieve convergence within a prescribed tolerance. Loading scenarios encompassing groups of pedestrians in different transverse positions highlight the importance of the 3D bridge modelling. The comparison with a few experimental results clarifies the role of the modelling assumptions. Conclusions discuss novelties, advantages, limits and future developments of the proposed approach.

1. Introduction

In civil engineering dynamics, human-induced vibrations have become a considerable serviceability issue due to the strong trend towards the design of light and slender structures, such as modern footbridges [1–3]. These structural systems often show natural frequencies in the range typical of human activities such as walking, running, bouncing, etc., so that the design requires careful attention to vibration levels [4]. At the design stage, the fulfilment of serviceability prescriptions requires a due consideration of some key aspects [5]. These include expected loading scenarios and dynamic properties of the structures, as well as the accuracy of the models representing dynamic loading and human response to vibration [6].

During footbridge vibration, some form of human-structure interaction (HSI) occurs [7]. HSI is a complex phenomenon in which pedestrians and footbridge interact as coupled mechanical systems in two possible ways: changes in the structural properties lead to changes in the humans' walking and vice versa [8,9]. Structural vibration can affect the human gait and consequently the forces induced by human occupants that, in turn, can change the bridge response [10]. This phenomenon is well documented for lateral vibration only [2,11]. In vertical vibration, the structural response due to pedestrians' motion cannot be predicted from the properties of the empty structure loaded by the pedestrian's forces. Thus, accounting for HSI is fundamental to predict a reliable dynamic response [6].

A large research effort performed over the last 15 years led to the development of human models and analytical procedures able to determine the footbridge response [12]. In a recent work, Caprani & Ahmadi [13] illustrated different literature approaches for modelling both structures and pedestrians. For structures, either a formulation in modal coordinates or the Finite Element (FE) method are used. For pedestrians, dynamic travelling forces, mechanical systems, or a combination of both, are proposed. However, dynamic analyses using force models cannot treat the dynamic effects of the mechanical human body and the consequent HSI [14]. A force model describes only ground reaction forces (GRFs) applied by a pedestrian [15], leading to a

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reduction in the accuracy of estimated bridge response [16]. On the contrary, a mechanical system also represents the mass, stiffness and damping of the pedestrian, all of which can combine with the structural properties [17].

To represent the human body, some authors have proposed simple mechanical systems, in which a complete representation of the human gait is not attempted (Zhang et al. [6,8], Shahabpoor et al. [16], Da Silva & Pimentel [18,19], Van Nimmen et al. [20], Venuti et al. [21], Caprani et al. [13]). Other researchers adopted stiff or compliant bipedal models to simulate the leg-switching behavior of walking (Bocian et al. [22], Geyer et al. [23], Kim & Park [24], Qin et al. [25], Whittington & Thelen [26]).

Caprani & Ahmadi [13] underlined that most of these studies do not present in detail the analytical formulation of the proposed models. In particular, they pointed out that (a) there is a need to provide the detailed formulation of HSI models, particularly under moving crowd scenarios; (b) presently, the models for HSI proposed in the literature are often not complemented with efficient integration procedures for the dynamic equations of motion, which would benefit other researchers in the field. Furthermore, to the best of the authors' knowledge, the literature does not offer examples of full 3D modelling of footbridges within a HSI analysis. In fact, in several works the footbridge is modelled as a simply supported Euler-Bernoulli beam with uniform cross-section (Zhang et al. [6], Bocian et al. [22], Qin et al. [25], Gomez et al. [27], Caprani & Ahmadi [13]). This approach cannot capture the plate behavior of the deck and the effect of coupled torsional-flexural natural modes, which could be excited by eccentric transits of pedestrians. In addition, a 1D-bridge model cannot treat loading scenarios having different spatial distributions in the transverse direction and social force models necessary to include the interaction among pedestrians (human-human interaction).

Since humans transmit a three-component contact force, HSI should be accounted for in the longitudinal, transversal and vertical direction. Even though, as a starting point, the focus of this work is restricted to vertical interaction, HSI remains a multifaceted problem. The high variability of pedestrians' motion, in terms of trajectory, intra-variability and inter-variability, has to be considered when pursuing a comprehensive approach to HSI. The derivation of a complete analytical formulation to compute the bridge response to walking pedestrians, still lacking as pointed out from the above considerations, can be proposed and its applicability investigated. Thus, it is necessary to investigate whether the type of pedestrian's motion modifies the mechanical principles governing the footbridge response. If this is not the case, the two aspects can be analyzed separately.

The derivation of the coupled equation of motion requires the description of the two systems and of their interaction. The bridge model should describe accurately mass and stiffness of the structure, crucial in determining the modal properties, and the effects arising from human activities, as underlined in the European Guideline [28]. To this aim, a 3D FE model of the structure is a straightforward option. The pedestrian mechanical model on one hand should describe the dynamic properties of the human body and, on the other hand, transfer forces to the bridge only through its legs. The interaction between the two systems requires the definition of the compatibility conditions at the interface. A perfect contact can be assumed as in the solution strategy previously adopted for the vehicle-bridge interaction (VBI) problem in [29], taking advantage of analogies between VBI and HSI. The finite area and the mass of feet can be neglected. While the VBI assumptions on contact hold for the HSI as well, the continuous wheel movement is completely different from the human walking or running. Thus, the model must be able to simulate the human gait and the derivation of the coupled equation must account for the real human locomotion and for the simultaneous presence of many pedestrians on the bridge.

The aim of this work is to derive an analytical formulation and a numerical procedure for the HSI, restricted to vertical direction, accounting for the above assumptions. Both systems, bridge and pedestrian, are described by means of discretized linear models. For the former, a 3D FE mesh is developed, with the refinement usual in engineering practice. For the latter, a new bipedal spring-mass-damper (SMD) model that simulates the human gait cycle is proposed. The model transmits contact forces through compliant and damped legs. As a working assumption, a periodic nature of the steps is considered in its first implementation, even though the sequence of footfalls in the human walking is non-periodic [30,31]. The coupled equations of motion are derived under the assumption of perfect contact at massless contact points. A solution strategy overcoming the problems related to the time-varying nature of the coupled matrices is proposed to integrate separately the two systems. This simplifies the representation of the force transfer typical of human gait, characterized by alternate loading applied by the feet.

After the description of the new bipedal pedestrian model in Section 2, Section 3 presents the equation of motion of the pedestrian-bridge coupled system. The equations are subsequently uncoupled and an iterative solution strategy is established in Section 4. The case study in Section 5 is a lively footbridge analyzed in a previous work [32]. Section 6 describes the main features of the research code where the uncoupled formulation is implemented and the results of the analyses. A code validation is performed on a 1D simply supported beam. The performance of the iterative procedure is assessed. Finally, both the numerical response due to pedestrians' different trajectories and a comparison with an experimental test are presented. Conclusions in Section 7 highlight the advantages and novelties of the proposed approach and discuss limits and future developments.

2. Pedestrian model

The model represents a pedestrian who moves with a known motion in the longitudinal direction, along the line at the intersection between his sagittal and frontal planes. Since there is not lateral motion in the pedestrians' transverse plane, it is not necessary to consider degrees of freedom (DOFs) in the horizontal plane. Rigid-body rotations are neglected. The model simulates the typical human gait characterized by a sequence of alternate phases, in which either only one foot (Single Support Phase, SSP) or both feet (Double Support Phase, DSP) are in contact with the ground (Fig. 1a) [33]. Hence, each model's foot transmits a vertical contact force F_i, where $i = 1, 2$ refers to the leading and the trailing leg, respectively. As a working assumption, intra-variability is neglected, and the model follows a deterministic and periodic representation of the human gait. Thus, its steps repeat identically with a period T_e equal to the sum of the duration times of SSP and DSP, T_s and T_d respectively, and both feet transmit the same pattern of force at each step. In the literature, the reference model for the description of the GRFs transmitted by each foot is the one by Li et al. [34]. The position of the single foot force $F_i(t)$ is constant in the interval T_e. Its typical shape is depicted in Fig. 1b. In [34], $F_i(t)$ is the sum of five harmonics, whose amplitudes A_n (or DLF, dynamic load factor) act as multipliers of the pedestrian weight G:

$$F(t) = G\sum_{n=1}^{5} A_n \sin\left(\frac{\pi n}{T_e}\right) \quad 0 \leqslant t \leqslant T_e \tag{1}$$

The coefficients A_n depend explicitly on the step frequency f_s, the inverse of the duration T_s of the SSP. From the statistical results of Ebrahimpour [35], an average value of 4.16 is assumed for the ratio of T_e and T_d. Thus:

$$T_s = \frac{1}{f_s} = T_e - T_d = T_e - \frac{1}{4.16}T_e = 0.76T_e \tag{2}$$

The proposed SMD bipedal mechanical model (Fig. 2) accounts for the above assumptions. The single DOF (SDOF) system has a mass M_h, the total mass of the human being, and is connected to the ground through two vertical spring-damper legs, acting in parallel in the same vertical