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Human-induced vibrations of a curved cable-stayed footbridge

Elisa Bassoli, Paola Gambarelli, Loris Vincenzi *

Department of Engineering "Enzo Ferrari" (DIEF), University of Modena and Reggio Emilia, Via Vivarelli 10, Modena 41125, Italy

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ABSTRACT

This paper investigates and compares the performances of two simulation models to predict the footbridge response to vertical pedestrian dynamic actions. For this purpose, a rational procedure based on experimental tests, identification, model-updating and simulation is addressed. The object of study is the Pasternak footbridge, a curved cable-stayed footbridge prone to human-induced vibrations. The footbridge dynamic behaviour is investigated thanks to an experimental campaign. Accelerations due to ambient vibrations are recorded and the modal parameters of the structure are identified. The dynamic response to pedestrian actions is investigated performing several experimental tests with different-sized groups of pedestrians. To simulate the dynamic response to pedestrian actions, a Finite Element (FE) model of the footbridge is developed and calibrated so that the numerical dynamic properties match the experimental ones. The structural response to human loads is evaluated through two advanced simulation methods. The first one is based on a periodic walking force and is employed to perform dynamic analyses with the FE model. In the second one, a multi-harmonic force model, which considers the variability of the walking force, is adopted and the dynamic response is evaluated via modal decomposition. Finally, numerical and experimental results are compared with each other.

1. Introduction

Over the last decades, cable-stayed footbridges have reached great importance and popularity thanks to the ease of construction, the economical convenience and the reduction of the deck bending moments due to the benefit of cables [1]. However, due to the upcoming of advanced design methods and high strength materials, footbridges in general are increasingly slender structures. Consequently, they are more and more sensitive to dynamic vibrations induced by pedestrians that can compromise the comfort serviceability conditions [2, 3, 4]. Therefore, the full assessment of the footbridge dynamic behaviour with reference to pedestrian actions is a topical issue in the vibration serviceability analysis [5, 6, 7].

To simulate pedestrian dynamic effects on footbridges, dynamic analyses are to be performed considering suitable pedestrian load models. The reliability of the predicted structural response depends on the capability of a numerical model to represent the structural behaviour as well as on the load model adopted to simulate the pedestrian action. For this purpose, a rational procedure based on identification, model updating and simulation is addressed.

Modelling of human-induced dynamic forces is not straightforward as they depend on many parameters as well as on the pedestrian number and their degree of correlation. In addition, different pedestrians will never produce the same walking force and even a single pedestrian induces a walking force that differs with each step.

Several pedestrian load models, characterized by different level of complexity and refinement, are proposed in literature, such as [8, 9]. Generally, the computational effort and the number of parameters to be defined increase with the model accuracy. Furthermore, pedestrian load models are rarely compared to each other in significant case studies. It is undeniable that models based on different approaches and approximations can produce significant differences when they are applied to complex and comprehensive real case studies.

This paper investigates and compares the performances of two simulation models to predict the response of the Pasternak footbridge to vertical pedestrian dynamic actions. The Pasternak footbridge is a curved cable-stayed footbridge prone to human-induced vibrations. It is about 270 m long and crosses an important freeway in Modena (Italy). Due to its curved shape, the footbridge is significantly more sensitive to vertical vibrations rather than horizontal. To simulate the dynamic effect of a single pedestrian or a stream of pedestrians moving across the footbridge, two advanced simulation approaches are adopted, which are based on different pedestrian load models in the time domain. These models are the single step load model proposed by Li et al. [10] and the multi-harmonic force model proposed by Živanović et al. [11], selected for their specific features. The first one is one of the few models proposed in literature that defines the force exerted by a single footstep. The second model has the advantage of representing the variability of the walking force induced by a single pedestrian. With the first simulation approach, the footbridge response to

* Corresponding author.
E-mail address: loris.vincenzi@unimore.it. (L. Vincenzi).

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pedestrian excitation is evaluated performing dynamic analyses with a Finite Element (FE) model of the structure. The second method relies on the solution of the equation of motion via modal decomposition, based on the experimentally identified mode shapes and frequencies. Dynamic analyses are performed simulating different dynamic loading conditions. Numerical accelerations obtained from the two simulation models are compared with each other and with the experimental ones.

2. Analysis overview

The complex shape of some footbridges and the challenging task of modelling the human-induced vibrations increase difficulties in obtaining an accurate and reliable prediction of the structural dynamic response.

This section presents an overview of the procedure to evaluate the footbridge dynamic behaviour under pedestrian loads through a rational process of modelling, simulation and validation. The procedure includes experimental investigations to identify the footbridge dynamic behaviour and to measure human-induced vibrations, the calibration of structural numerical models and the adoption of pedestrian load models.

The prediction of the structural response to pedestrian actions starts from the characterization of the structural dynamic behaviour. The description of the structural dynamic behaviour is affected by a large number of uncertainties regarding the geometrical and mechanical properties, non-structural masses and effective constraint stiffness values. Because of this, the structural dynamic properties are to be evaluated and characterized based on experimental data. The dynamic behaviour of the footbridge is thus investigated thanks to an experimental campaign performed by means of an advanced MEMS-based measurement system [12]. Starting from the accelerations recorded in operational conditions, the modal properties (frequencies, mode shapes and damping ratios) of the footbridge are identified. In the present study, the classic Enhanced Frequency Domain Decomposition (EFDD) method is adopted [13, 14]. To evaluate the actual dynamic behaviour of the footbridge subjected to pedestrian loads, several experimental tests are performed with different-sized groups of pedestrians crossing the footbridge running and walking freely or in a synchronized manner with different pacing frequencies. The actual response to human-induced loading is assumed as the basis for comparison with the numerical results to evaluate the reliability of the simulated response.

Once the structural dynamic behaviour is characterized, pedestrian load models are to be employed and dynamic analyses are performed simulating different pedestrian loading conditions. This can require the adoption of FE models which have to be calibrated with respect to the identified dynamic properties. Alternatively, numerical dynamic analyses can be performed through the solution of the decoupled equations of motion using the experimentally identified modal parameters. In the first case, model updating procedures are applied to develop reliable models starting from the comparison between the experimentally identified structural dynamic behaviour and the numerical model response [15, 16]. A set of unknown structural parameters is selected and evaluated solving an optimization problem where the objective function is defined as the difference between experimental and numerical natural frequencies and mode shapes [17, 18]. In this respect, model updating techniques based on surrogate-assisted evolutionary strategies have shown advantages in reducing the computational effort in optimization problems. In the present study, the so called DE-S algorithm [19, 20] is applied.

3. Human-induced loading

A pedestrian walking on a structure causes a ground reaction force that is due to acceleration and deceleration of the body centre of mass. This force is a three-dimensional vector that varies in time and space due to the forward movement of the person. Over the years, many studies have been performed to characterize the walking force [21]. The most common model of perfectly periodic human-induced force in the vertical direction is the continuous walking load model [22, 23, 24], which represents the single pedestrian force by a sum of harmonic components:

$$F(t) = G + G\sum_{k=1}^{n}\alpha_k(f_s)\sin(2\pi k f_s t + \Psi_k) \tag{1}$$

where G [N] is the pedestrian's weight, f_s [Hz] is the step frequency, k is the number of the harmonic, Ψ_k [rad] and α_k [−] are the phase shift and the Fourier's coefficient, called Dynamic Loading Factor (DLF), of the kth harmonic. Finally, n is the total number of contributing harmonics.

According to Eq. (1), the walking force is composed of n harmonics characterized by frequencies equal to the step frequency and its integer multiples. However, from the analysis of the force spectrum of measured walking forces, some authors [11, 25, 26] have shown that also some sub-harmonics appear at frequencies between the main harmonics. This is explained as a consequence of more pronounced footfall on one side. In fact, the walking force of Eq. (1) is periodic with fundamental frequency equal to f_s, that is with a fundamental period equal to the time required to take one step. On the contrary, considering that forces exerted by the right and left foot can slightly differ, the fundamental period of the walking force becomes the time required to make two consecutive steps. Hence, the fundamental frequency of the force becomes approximately two times lower than the one for a single step.

Eq. (1) shows that the amplitude of the harmonic component depends on the step frequency through the DLFs α_k. These are to be quantified based on the Fourier spectrum of the experimentally registered ground reaction forces. Over the years, many studies have been conducted in order to quantify the DLFs [27, 28]. Furthermore, some authors have highlighted that all parameters of Eq. (1) should be modelled from a probabilistic point of view to account for the variability in walking forces induced by different pedestrians [11, 29]. This phenomenon is the so-called inter-subject variability, meaning that different pedestrians will never produce exactly the same walking force. For a single person force, which is still assumed periodic, randomness in the walking force is considered via probability-based modelling. This is addressed defining the variables that describe the human-induced force through their probability density function.

Moreover, the walking force caused by a single pedestrian is affected by the intra-subject variability. The latter means that even a single pedestrian induces a walking force that differs with each step. This is because some parameters, such as the step length and the pacing frequency may vary along the path. The naturally present intra-subject variability makes the walking force not a perfectly sinusoidal force, but rather a considerably more complex narrow band random process [30, 31, 32, 33].

The present work focuses on the simulation of the human-induced forces in the vertical direction, adopting the single step load model proposed by Li et al. [10] and the multi-harmonic force model proposed by Živanović et al. [11]. The single step force defined by Li et al. [10] can be directly applied to consecutive nodes of a footbridge FE model to simulate a pedestrian walking. The model proposed by Živanović et al. [11] provides the continuous walking force, i.e. the sum of the forces exerted by both feet, that can be adopted to define the modal force and evaluate the dynamic structural response through modal decomposition.

The adoption of the FE model, once it has been properly calibrated, allows describing the dynamic behaviour of the footbridge accurately. Moreover, as foot forces are applied directly on the FE model, it is possible to account for the effective positions of pedestrians on the structure, without the approximation of them walking on the bridge centreline. Also the different positions of the right and left foot can be represented.