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Robust vibration serviceability assessment of footbridges subjected to pedestrian excitation: strategy and applications

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ABSTRACT

The present paper proposes a strategy for the robust vibration serviceability assessment of footbridges. The response of the footbridge to vertical walking loading is predicted by simulating continuous flows of pedestrians on the structure. In the calculations, both variability in the walking characteristics and human-structure interaction effects are accounted for. Uncertainty in the modal parameters of the footbridge is considered in a multi-interval approach. The resulting range in predicted response levels is subsequently compared to vibration comfort criteria. A case study serves as illustration of the procedure. First, the response of the footbridge is evaluated in a multi-interval assessment showing how the predicted vibration levels are affected by uncertainties. The multi-interval approach allows understanding how uncertainties in the modal parameters of the structure affects the response. Second, the procedure is applied for the design of Tuned Mass Dampers (TMD). The TMD parameters are tuned by solving an optimisation problem such that an effective reduction of the accelerations under realistic walking scenarios is ensured. The total TMD mass is minimised, considered as the determining factor for the cost of the TMD. A higher TMD mass is needed to satisfy the vibration serviceability constraints for higher levels of uncertainty, showing the trade-off between cost and robustness.

1. Introduction

The development of high-strength materials and advanced calculation techniques allows architects and engineers to design and build ever more slender footbridges. The slenderness of the structure often results in low natural frequencies in the range of the loading frequencies of human-induced excitation. As these light structures are generally also lightly damped, they are sensitive to human-induced loading. A vibration serviceability assessment of footbridges is therefore required to evaluate the dynamic response of the footbridge to human-induced loading.

Simplified procedures for the vibration serviceability assessment of footbridges are presented in guidelines such as Sétra [1], HiVoSS [2] and Willford and Young [3] or in standards as Eurocode 5 [4] and ISO 10137 [5]. In these methods, resonance of one mode of the structure with the first or second harmonic component of the walking loading is assumed. The obtained acceleration level is multiplied by a reduction factor for frequencies which deviate significantly from the expected loading frequencies. By upscaling the load models of single pedestrians, the load of a group of pedestrians crossing a footbridge is represented. Other methods such as those proposed by Brownjohn et al. [6], Piccardo and Tubino [7,8] and Krenk [9] are based on an equivalent spectral load model. In all these methods, a simplified load model is used and a single mode is assumed to dominate the response. However, for footbridges, multiple modes are often excited simultaneously and the contribution of all these modes must be accounted for. Besides, more advanced models describing the crowd behaviour consider two other important aspects: human-human interaction (HHI) effects and human-structure interaction (HSI) effects [10]. HHI models try to describe the interaction among pedestrians. Generally, the average walking velocity decreases for higher pedestrian densities. Detailed models such as the widely used social force model [11,12], describe the behaviour of each pedestrian in a crowd individually (microscopic model). The pedestrian behaviour is governed by a driving force depending on the intention of the pedestrian, an interaction repulsive force due to other pedestrians and a repulsive force due to physical barriers such as sides of the bridge. By this microscopic modelling, the location and velocity of each individual pedestrian can be calculated and used to determine its position and step frequency at each moment in time. Alternatively, a macroscopic model such as the Kladek relation

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Nomenclature

A_n	Fourier coefficient of the single foot force load model
$c_{TMD,n}$	damping constant of n-th TMD
d	pedestrian density
f	natural frequency
f_s	pedestrian step frequency
$\bar{f}_s(d)$	average step frequency
G	pedestrian weight
$k_{TMD,n}$	stiffness constant of n-th TMD
m_j	modal mass of mode j
$m_{TMD,n}$	mass of n-th TMD
T	time window for response evaluation
T_c	time duration of contact between foot and ground
T_{cross}	time that a pedestrian needs to cross the footbridge
T_s	step period
v_s	pedestrian walking speed
$\bar{v}_s$	average free walking speed
α	level of uncertainty
β	multiplication factor
$\Delta_{\mu_{f_s}}$	variability on the mean step frequency
μ_{f_s}	mean step frequency of the flow
$\mu_{TMD,n}$	mass ratio of n-th TMD
$\mu_{\ddot{u}_{max}(T)}$	mean value of the instantaneous peak response
$\rho_{TMD,n}$	frequency ratio of n-th TMD
σ_{f_s}	standard deviation of the step frequency of the flow
$\sigma_{\ddot{u}}$	standard deviation of the acceleration response
$\sigma_{\ddot{u}_{max}(T)}$	standard deviation of the instantaneous peak response
ξ	damping ratio
ϕ	mass-normalised mode shape
$\square_H$	subscript referring to human body parameter
$\square_j$	subscript referring to mode j
$\square_{TMD}$	subscript referring to TMD parameter
$\widetilde{\square}$	referring to the membership function

[13,14] can be used to link the pedestrian density and average step characteristics (walking velocity and step frequency). In addition to HHI effects, human-structure interaction (HSI) affects the response as well. In vertical direction, the added damping due to the pedestrian bodies must be accounted for [15–18] while in lateral direction, synchronisation of the pedestrian step frequencies may lead to lock-in [19,20]. Recently, in [21] the impact of vertical HSI was investigated by means of simulations using a detailed crowd model. It was found that the effective damping due to the pedestrians is significantly higher than the modal damping of the empty footbridge. To account for the stochastic nature of the walking loading, variability in the load characteristics must be considered.

As the outcome of the vibration serviceability assessment is highly sensitive to the modal parameters, uncertainties in these modal parameters should be accounted for. The natural frequencies and modes of the footbridge can be calculated by a finite element model (FEM) while the modal damping can be estimated based on experience with similar structures such as the values proposed in [1,2]. It has been shown in [22] that small deviations in predictions of the natural frequency or assumptions for the modal damping significantly affect the response predicted according to established guidelines [1,2]. Briefly, two types of sources of uncertainty are distinguished. The first source deals with the effective stiffness of the footbridge that may be uncertain due to small deviations in the assumed material properties or support conditions. The second source encompasses uncertainties in the natural frequency and modal damping due to daily or seasonal and environmental changes like temperature. Shifts in the natural frequency and modal damping during the structure's life-time are reported in [23–25]. In [26], it was found that natural frequencies predicted by a detailed FEM of a structure may be up to 10% off from the actual measured values. In [27], large variations of the modal damping are reported depending on the amplitude of the acceleration. Up to now, this uncertainty in the modal parameters of the structure is not accounted for in any of the conventional methods presented for vibration serviceability assessment of footbridges.

Therefore, this paper proposes an approach for the robust vibration serviceability assessment of footbridges that takes into account uncertainties in the modal parameters of the structure as well as the stochastic nature of the loading. In state-of-the-art load models such as in [10,28,29], variability in the walking characteristics is considered by stochastic load models. In this case, a probabilistic approach is used while realistic walking scenarios are generated for different pedestrian densities based on Monte Carlo simulations. The peak acceleration is computed, considering the contribution of multiple modes in the calculation of the response. To account for uncertainty in the modal parameters, a range of values is determined using scarce information available in the literature. Different levels of uncertainty are considered in a multi-interval approach to gradually evaluate the effect of uncertainties in the modal parameters. The simulated flows consider a realistic distribution of step frequencies for all considered pedestrian densities accounting for variability in the walking characteristics of the pedestrians. HSI effects are accounted for following [21] and a macroscopic model is applied to account for HHI [13,14]. The robust assessment then consists of an evaluation of the ranges of the calculated response to vibration comfort criteria. A similar approach with a simplified load and response model was followed in [22] for the robust design of a tuned mass damper (TMD).

The remainder of this paper is organised in five sections. First, the strategy of the robust vibration serviceability assessment is presented in Section 2. Second, the Avelgem footbridge is introduced as a case study in Section 3. Next, the approach for the robust response prediction is demonstrated for the footbridge considering multiple pedestrian densities (Section 4). It is verified to what extent the response differs when all modes are considered as opposed to an approach in which only the dominant mode is accounted for. Then, in Section 5, the robust design of a TMD is considered by solving an optimisation problem where constraints for vibration serviceability are imposed according to the proposed strategy. Finally, in Section 6, a number of conclusions are drawn summarising the main findings and advantages of the presented approach.

2. Methodology for robust response prediction

In the robust vibration serviceability assessment, both uncertainties in the modal parameters of the structure and the stochastic nature of the loads are considered. The section is organised as follows. First, the methodology to deal with uncertainties in the modal parameters is discussed. Second, a summary of the state-of-the-art load models is given. Third, it is explained how to extract the instantaneous peak acceleration and to perform the assessment considering multiple levels of uncertainty.

2.1. Uncertain modal parameters

Since the dynamic behaviour of the structure is determined by its modal parameters, the effect of uncertainties in the modal parameters on the response must be accounted for.

To deal with uncertainties in the natural frequency and modal damping of the structure, a multi-interval approach is proposed which allows assessing the sensitivity of the vibration serviceability assessment to a change in the modal parameters of the structure [22]. The uncertainty is characterised by a multiplication factor β which is