A Comparative Performance Study of Inertial Vibration Controllers for an Ultra-lightweight GFRP Footbridge

Carlos Martín Concha Renedo^(✉), José Manuel Soria, Christian Gallegos,
and Iván M. Díaz

ETSICCP, Universidad Politécnica de Madrid, 28040 Madrid, Spain
`carlos.martindelaconcha@upm.es`

Abstract. Currently, the use of advanced lightweight materials in construction (as aluminium or fibre-reinforced polymer (FRP) composites) are enabling to create aesthetically pleasing structural forms by means of reducing their weight as much as possible. The results of this are ultra-lightweight structures (usually with low both mass and inherent damping) which difficultly comply with the vibration serviceability limit state (VSLS) under human-induced dynamic loading. Moreover, when assessing VSLS, the existing human-structure interaction (HSI) should be considered as it tends to be remarkable. Hence, smart damping strategies can be seen as a good solution to preserve lightweight nature of these structures in the most efficient way. This work aims to investigate whether the efficiency of three types of inertial controllers applied to an ultra-lightweight FRP footbridge degrades or not, when considering the HSI as another inherent element of the dynamic system to be controlled.

Keywords: Vibration control · Lightweight structures · Inertial controllers

1 Introduction

Nowadays, advanced materials with higher stiffness and lower density as fiber reinforced polymers (FRP) or aluminium have enabled to develop even more efficient structures. In this context, strength or stiffness are not constraints for designers to create slender structural forms. However, their low weight and inherent damping have led them to not satisfy the Vibration Serviceability Limit State (VSLS) under human-induced dynamic loading [1].

Usually, vibrations in lightweight structures are due to resonant responses when the first or the second harmonic of the human loading excites the fundamental structural resonance. However, ultra-lightweight structures can also present undesired vibrations due to either non-resonant responses excited by lower harmonics, or due to resonant loading related to higher harmonics.

Furthermore, whilst, in classic steel lightweight structures, the mass of human users is not comparable with the structural modal mass, in ultra-lightweight structures, this relation may be significant. This fact might cause a Human-Structure Interaction (HSI) when the structural acceleration overcome a certain limit. Thus, in order to properly asses the VSLS in ultra-lightweight structures, it is required to use an interactive loading model for the human [2].

Inertial controllers can be a good solution to overcome the vibration problem in ultra-lightweight structures. They can be passive, semi-active or active according to the nature of the feedback control implemented. Passive ones, most commonly known as Tuned Vibration Absorbers (TVAs), are able to damp resonant vibrations when tuned to a single problematic vibration mode. Semi-active versions of the TVA (STVAs) are able to change the properties of the controller in real time, by means of smart dampers, achieving a certain grade of adaptability and making them more robust. Thirdly, active controllers (AVAs) make use of actuators to apply counteract control forces in real time, allowing to mitigate both resonant and non-resonant multi-harmonic responses.

The three inertial controller types can be designed as a feedback system. Up to now, many strategies based on feedback control have been proposed and developed involving both the controller design and its optimal placement in the structure [3]. However, from the authors knowledge, HSI has not been yet considered in the design process. This paper intends to assess whether or not the HSI might play an important role when designing future inertial controllers applied to an upcoming laboratory ultra-lightweight structure which is being designed now.

The remainder of the paper is organized as follows, the second section describes the structural layout of the studied FRP footbridge. Section 3 outlines the closed-loop system model with HSI and an inertial controller. In Sect. 4 the design parameters of three inertial controllers (TVA, STVA and AVA) are provided and some results about their efficiency with and without considering HSI are included. Finally, some conclusions are given in the last section.

2 Structure Description

The footbridge proposed in this study is a simply supported all-GFRP structure. It is 10.0 m long and 1.50 m wide, formed by planks placed onto two main beams that are laterally restrained with square tubes, as shown in Fig. 1a and 1c. All pultruded elements described in Fig. 1b are manufactured by Fiberline A/S [4]. It has been designed according to [5] and [6].

The total weight of the footbridge is 1.66 ton, including handrails and other non-structural elements. A linear elastic FE model of the footbridge was developed in Abaqus software [7], based on the information aforementioned. Figure 2a shows the numerical model developed and Fig. 2b displays the first vibration mode of the footbridge FE model, with a natural frequency of 4.01 Hz. In a recent research, a mean damping ratio of 2.5% was obtained for 8 FRP footbridges located in Europe [1]. Thus, a reasonable damping ratio of 2% was assumed here.

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Fig. 1. Footbridge: (a) frontal view, (b) cross-section of elements, (c) side view.

Fig. 2. FE model of the footbridge.

A deflection design limit of $L/350$ (L being the length of the span) was assumed. According to [8], an uniformly distribute live load of 2.5 kN/m^2 was considered to check deflection. As a result, the total considered load for the analysis was 3.6 kN/m^2 , and the deflection obtained at midspan was 27 mm ($L/370$).

3 Inertial Vibration Controllers and Human-Structure Interaction

Although ultra-lightweight bridges are likely to display at the same time dynamic responses composed of many different resonant and non resonant harmonics, this paper only studies the most responsive first vertical vibration mode, to illustrate the concepts.

The excitation considered is one person bouncing at midspan for 35s for two cases: 1) bouncing at 2 Hz which causes a resonant response due to the second harmonic of the human loading and 2) bouncing out of resonance at 2.5 Hz. Firstly, the dynamic problem is studied assuming that the person does not interact with the structure. Given the high accelerations, it would be reasonable to expect a remarkable human-footbridge interaction. For this reason, the dynamic

analysis is repeated accounting for HSI. The footbridge has been modelled as an equivalent mass-spring-damper system (which represents the vertical dynamic behaviour at midspan) with a mass of 772 kg, a natural frequency of 4.01 Hz, and a damping ratio of 2%.

For the first preliminary dynamic analysis, a non interactive model is used. Here the human is represented just as an external force following the dynamic loading model for bouncing proposed in ISO 10137 [9]. Thus, the human force has been computed as a Fourier series composed of three harmonics with different amplitudes, as Eq. (1) and Fig. 3 displays:

$$F_h(t) = Q \left(1 + \sum_{n=1}^3 \alpha_n \sin(2\pi f t + \phi_n) \right), \quad (1)$$

where Q is the weight of an average human, usually taken as 700 N and α_1 , α_2 and α_3 represent the amplitude coefficients of each harmonic with values of 0.5, 0.25 and 0.15, respectively.

(a) Time domain. Zoom view.

(b) Frequency domain.

Fig. 3. Vertical human force excitation, F_h (N).

The second dynamic analysis accounts for HSI. This model represents the human body dynamics by means of a Mass-Spring-Damper-Actuator system,

(a) Uncontrolled structure.

(b) Uncontrolled structure with HSI.

(c) Controlled structure with an inertial controller.

(d) Controlled structure with HSI and with an inertial controller.

Fig. 4. Simplified control schemes used to evaluate the control performance.

attached to the structure at mid span [10]. Hence, the human's dynamics are defined by body's natural frequency, damping ratio and mass, whilst the force generated by the human legs is applied as a pair of forces acting on both the pedestrian and the footbridge. The human parameters considered are: mass of 66 kg, natural frequency of 2.4 Hz, damping ratio of 20% and an actuator force equal to the one used for the non interactive model.

The inertial controllers (passive, semi-active or active) are designed for the original structure without HSI and considering only the fundamental vibration

modes. Then, the HSI is included and the controller performance is assessed. Figure 4 illustrates the control scheme considered.

The transfer function of the structural model without HSI between the acceleration response and the input force is

$$G_s(s) = \frac{s^2 X(s)}{F(s)} = \frac{1/m_1 s^2}{s^2 + 2\omega_1 \zeta_1 s + \omega_1^2}, \quad (2)$$

where $s = j\omega$, $\omega_1 = 2\pi f_1$ being the circular natural frequency of the structure (rad/s), f_1 its respective natural frequency and m_1 , k_1 and ζ_1 being the mass (kg), stiffness (N/m) and damping ratio of the equivalent structural system described above.

Secondly, both the HSI and the inertial controller are modelled as two separated closed-loops as Figs. 4b and 4c depict. Each one of them feedbacks the structural system response with an interactive force F_{HSI} or F_c . Finally, the overall model shown in Fig. 4d can be seen as two simultaneous closed-loops accounting for HSI and the inertial controller interaction at the same time.

4 Simulations

An overall amount of sixteen different dynamic simulations have been performed. Four different control configurations were studied: uncontrolled structure and controlled via TVA, STVA and AVA. Indeed, each control case was analyzed with and without considering HSI at the two different bouncing frequencies aforementioned. Inertial controller's parameters have been obtained without taking into account the influence of the HSI. This section will cover the design of the proposed inertial controllers.

4.1 TVA

The TVA has been designed using the approximate solution provided by Asami and Nishihara [11], based on H_∞ optimization for primary structural systems with vanishing damping. These expressions minimize the structure acceleration considering a single vibration mode and harmonic excitation:

$$\eta = \sqrt{\frac{1}{1 + \mu}} \quad (3)$$

$$\zeta_\tau = \sqrt{\frac{3\mu}{8(1 + \mu)^3}} \cdot \sqrt{1 + \frac{27}{32}\mu}, \quad (4)$$

$\mu = m_\tau/m_s$ being the mass ratio between the absorber and the primary system. A mass ratio of 2% of the structural equivalent mass has been selected, this is 15 kg. Parameter $\eta = \omega_\tau/\omega_s$ is the frequency ratio between both systems.

4.2 STVA

A phase control strategy for the STVA damping has been considered [12, 13]. The phase control presented has been adopted since this is clearly geared to practical implementation due to the measured real-time parameters employed: the structure acceleration instead of displacement and the inertial mass velocity instead of the relative velocity. The lowest structural response is achieved when the velocity of the inertial mass and structure acceleration have opposing phases, so the semi-active device objective is to bring the inertial mass motion as close as possible to this phase. This is equivalent to a phase lag of 90° between the structure acceleration and the control force. The control law adopted is of the ON/OFF type due to its simplicity. Thus, the adopted control law when ideal viscous damping is assumed is defined as:

$$\begin{cases} \ddot{x}_s \cdot \dot{x}_T \leq 0 & \Rightarrow & c_T = c_{\min} & \text{(normal functioning)} \\ \ddot{x}_s \cdot \dot{x}_T > 0 & \Rightarrow & c_T = c_{\max} & \text{(blocking functioning)}, \end{cases} \quad (5)$$

in which $c_{\max}$ is the maximum damping achieved by the damper, $c_{\min}$ is the optimal damping obtained for the TVA, $\ddot{x}_s$ is the structure acceleration (measured by an accelerometer) and $\dot{x}_T$ is the velocity of the inertial mass (which might be obtained from the integration of an accelerometer signal installed on the inertial mass). Finally, both signals are low-pass filtered in order to avoid control instabilities associated to the ON/OFF control rule. It is important to highlight that the stiffness and mass of the STVA are the same as those calculated for the TVA.

4.3 AVA

Direct Velocity Feedback (DVF) control has been implemented in the AVA. Although DVF is, by its nature, unconditionally stable, when actuator dynamics are included, the closed-loop system becomes conditionally stable and the stability margin has to be studied previously to the implementation. The velocity estimated is multiplied by a control gain K_C producing a command signal to the actuator. Firstly, the limit control gain for stability is derived as $K_{C_{\lim}} \simeq 100$. Finally a control gain K_C equal to $K_{C_{\lim}}/2$ has been chosen providing enough stability gain margin and leading to a safe implementation [14]. The actuator transfer function between the voltage and the force developed can be described as a linear second-order system:

$$G_a(s) = \frac{150 s^2}{s^2 + 4.021 s + 101.1^2}, \quad (6)$$

where the natural frequency of the shaker is $\omega_A = 10.05 \text{ rad/s}$ (1.60 Hz). This model corresponds to an APS 113 Electrodynamic shaker. The AVA has an inertial mass of 13 kg, lightly smaller than the one used for the TVA and STVA.

(a) Uncontrolled.

(b) Passive.

(c) Semi-active.

(d) Active.

Fig. 5. Resonance response structure without HSI.

5 Results

Figure 5 provides the resonant response without HSI at the four cases of study. Three indicators are provided, the acceleration Peak value, the Peak value of the running root mean square acceleration computed using 1 s windows (named as maximum transient vibration value or MTVV) and the cumulative Vibration Dose Value (VDV).

Figure 6 provides a summary for all the cases. The VDV is quite convenient for comparing the vibration controllers performance since it provides an accumulative value of the acceleration over the time.

Fig. 6. VDV of the structural response for all cases.

As Fig. 6 clearly depicts, considering HSI implies to intrinsically change the dynamic characteristic of the system to be controlled, changing its natural frequencies. In the example analyzed here the inertial controllers are a bit detuned reducing slightly their efficiency. To explain the dynamic behaviour of the inertial controllers out of resonance is quite more complex, however it seems to deteriorate also when considering HSI.

6 Conclusions

This research is the first step towards a new way of designing inertial controllers applied to future ultra-lightweight structures excited by human-induced vibrations. The results obtained will lead to further comprehension on how inertial controllers should be designed. Future works should assess whether or not the HSI influence their performance, and how this could be accounted for. In this sense, ultra-lightweight structures are challenging for vibration control due to: multi-modal and non-resonant dynamic responses and the HSI phenomenon.

Acknowledgements. The authors acknowledge the financial support provided by the Ministry of Science, Innovation and Universities (Government of Spain) by funding the Research Project SEED-SD (RTI2018-099639-B-I00). Carlos M. C. Renedo would like to thank Universidad Politécnica de Madrid for the financial support through a PhD research grant.

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