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Dynamic performance of existing high-speed railway bridges under resonant conditions following a retrofit with fluid viscous dampers supported on clamped auxiliary beams

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ABSTRACT

This contribution investigates the application of Passive Control techniques to reduce the severe transverse vibrations that railway bridges of moderate lengths may experience under resonant conditions. The proposed solution consists in connecting the slab to a series of auxiliary beams clamped between the bridge abutments through a set of fluid viscous dampers. A particular configuration minimising the space occupied by the devices and the auxiliary beams under the bridge deck is proposed for two typical typologies in the aforementioned lengths: slabs and girder bridges. First, the dynamic response of a double-beam analytical model is obtained in closed-form under harmonic excitation in order to detect the main governing parameters, capturing the essence of the response at resonance of the main beam fundamental mode. Then conditions are obtained for the optimal damper constants that minimise the main beam amplification. Finally the effectiveness of the solution and the adequacy of the expressions derived from the harmonic case are proven under railway traffic excitation taking into account the three-dimensional deformation of the deck. Throughout the study special attention is given to the beneficial effect arising from clamping the auxiliary beam supports when compared to the simply-supported case, analysed by the authors in previous works. Partial rotational restrictions are admitted to take into consideration the expectable deviation from ideally clamped conditions. Two case studies are presented showing that the auxiliary beams size, if partially clamped, could be significantly reduced for the same main beam vibration mitigation level. If the beams are to be installed under a railway bridge deck in a practical application, this is a crucial issue in order to minimise the free space occupied with the retrofit.

1. Introduction

The extensive construction of new High-Speed railway lines and the use of conventional lines for higher operating train velocities require continuous upgrading of railway infrastructure and, in particular, of bridge structures. Even though axle loads of modern trains are not higher than transmitted forces in old-time vehicles, higher design velocities may lead to the appearance of resonance phenomena. Resonance, in a railway bridge, takes place when the exciting frequency of the periodic loading of a train comes close to a natural frequency of the bridge. In this case, the loads enter the bridge in phase with the natural oscillations of the structure leading towards a progressive increase in the deck vibratory response. If structural damping is low, as it usually is in the case of railway bridges [1], and the number of axles is large enough, transverse vibrations at the platform area could build up causing the failure of the Serviceability Limit State of vertical acceleration [2]. In this regard, especially critical structures are short-to-medium-span bridges (up to 25 m), where the main structural elements are simply-supported (S-S) beams or plates. In these structures, resonance phenomena may not only cause impact or fatigue related damage but also, deconsolidation of ballast-beds. This can compromise the running safety of trains, passengers' ride comfort, and ultimately increase bridge maintenance costs [1,3,4].

In existing bridges that experience this kind of behaviour, either as a result of an increase in the Maximum Line Speed at the site or due to structural degradation over time, classical solutions could be applied such as: increasing the deck mass to reduce its acceleration or augmenting its stiffness to raise its natural frequencies and critical velocities. Nevertheless, in many circumstances it is not possible to preserve the original structure, the deck needs to be demolished and replaced, with the subsequent interruption of traffic service. Alternatively, a reduction of the bridge dynamic

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response by artificially increasing the overall damping of the structure is proposed and evaluated in this work, applying Passive Control techniques and, in particular, retrofitting the bridge deck with Fluid Viscous Dampers (FVDs). The installation of the system proposed herein does not require any interaction with the upper side of the bridge. This could allow existing railway bridges to be retrofitted while keeping the line in operation.

Despite the fact that vibration control systems have been applied to reduce the dynamic response of structures since the 1960s, only a few authors have addressed the practical application of these technologies to bridges under the action of moving vehicles. The application of Tuned Mass Dampers (TMDs) to the train-induced vibration problem has been analysed by Kwon et al. [5], Wang et al. [6], Yau et al. [7–9] and Li et al. [10]. These authors investigate the dynamic performance of bridges using planar models retrofitted with single or multiple TMDs. TMDs are tuned to a single frequency of the superstructure (usually the fundamental one) or several frequencies which contributions need to be reduced. From these works it can be inferred that the vehicle passage time on the bridge is, in many cases, too short to build up the needed TMD vibrating regime that effectively mitigates the bridge excessive vibrations; besides, detuning problems may arise if the devices are tuned to the bridge natural frequency, due to the variability of this magnitude over time associated to vehicle-bridge interaction effects, changing environmental parameters, or to the decay of the TMD stiffness with time. Nevertheless this second drawback may be partially overcome with multiple TMDs tuned in a frequency interval [8,10] or with the string-type TMD presented in [9]. Recently Samani and Pellicano [11] has compared the vibration reduction capability of nonlinear TMDs when compared to linear elements connected to simply-supported beams under moving loads concluding that the vibration reduction achieved levels are very similar.

Minsili et al. [12] suggest the installation of supplemental diagonal elements in truss bridges connected to the original braces through Slotted Friction Connections, in order to mitigate traffic and earthquake induced vibrations. The authors point out that structural displacements can be reduced to a great extent with this alternative, but vertical accelerations may exceed their initial values due to the nature of the new forces introduced in the bridge deck. The appearance of residual displacements in the structure after the devices activation is an additional inconvenient of the proposed system.

The use of viscoelastic (VE) materials to improve the dynamic performance of railway bridges has been addressed by a number of researchers. Choo et al. [13] propose the introduction of acrylic rubber patches connected to S-S beams deforming in shear when the main elements bend. The authors carry out an experimental program and adjust a numerical constitutive model for this material. They finally conclude that the proposed design could reduce to permitted levels the structural response of long span bridges which experience inadmissible vertical accelerations. A few authors have investigated the applicability of Continuous Dynamic Vibration Absorbers (CDVAs) combined with viscoelastic materials, to the vibration control of beams under harmonic and moving loads. Aida et al. [14], Vu et al. [15] and Abu-Hilal [16] study the possibility of reducing the dynamic response of a Bernoulli–Euler (B–E) beam connecting it to an identical element through a continuous layer of VE material. Onsiczcuk analyses the dynamic behaviour of double-beam [17,18] and double-plate systems [19,20] linked through continuous Winkler media focusing on the relative properties of the beams and the media that effectively control the oscillations of the main element. Recently, Moliner et al. [21,22] have investigated the dynamic performance of the double-beam system connected by discrete Kelvin elements and have evaluated its applicability in reducing the resonant response of short S-S railway bridges.

A few authors have addressed the use of pure viscous dampers to reduce the amplification in beams traversed by moving vehicles. Oliveto et al. [23] and Greco and Santini [24] solve the dynamic problem of a continuous beam with two end rotational viscous dampers under the circulation of a single load, by using an extension of the complex mode superposition method. Nevertheless, to the authors' knowledge, this type of damper has never been previously applied in the context of High-Speed railway traffic.

FVDs have been selected, as compared to other Passive Control devices for this application, because they dissipate energy at a wide scope of frequency ranges, and not only at narrow ranges like TMDs. As a consequence, they do not present relevant tuning and detuning drawbacks. A further advantage is the fact that dissipative devices based on friction or yielding increase replacement operations and maintenance costs. In contrast, some FVDs are equipped with labyrinth seals which eliminate mechanical friction [25], allowing them to undergo an enormous number of cycles before they have to be replaced. Moreover, since in FVDs the maximum force and maximum displacement are out of phase, additional forces introduced in the structure due to the retrofit are small when compared to other techniques.

The authors of this contribution have investigated in the past the dynamic behaviour of a double-beam system similar to the one shown in Fig. 1, linked through a distribution of pure FVDs under the circulation of moving loads [26,27]. It consists of a *main beam*, which represents the bridge (upper beam in Fig. 1), and an *auxiliary beam* with simply-supported end conditions connected to the bridge by means of the FVDs (i.e. rotational stiffness $K = 0$ in references [26,27]). Closed-form expressions have been provided for the optimal dampers minimising the bridge response, and a methodology for the auxiliary beam design has been developed based on the overall damping needs. This study has been completed taking into account the contribution of three-dimensional modes of the bridge, which cannot be neglected either in multi-track decks or in skewed bridges. To this end, the dynamic performance of orthotropic plates connected to sets of auxiliary beams through FVDs with, again, simply-supported end conditions has been analysed in detail by the authors [26,28,29].

One of the main conclusions derived from these previous works is that in order for the FVDs to effectively reduce the deck vibratory response, the fundamental frequency of the auxiliary beam needs to exceed the bridge or main beam highest frequency, the contribution of which should be controlled. Moreover, as the auxiliary beam frequency increases, the dissipative capacity of the system

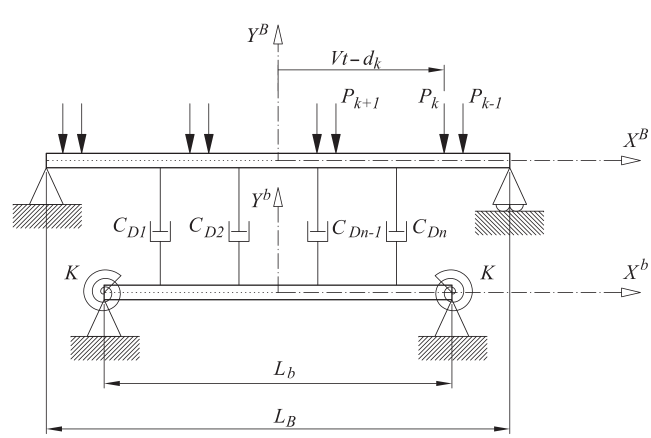

Fig. 1. Simply-supported-partially-clamped double-beam system connected through FVDs.