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A parametric multi-body section model for modal interactions of cable-supported bridges

Marco Lepidi [a,*], Vincenzo Gattulli [b]

[a] DICCA - Dipartimento di Ingegneria Civile, Chimica e Ambientale, Università di Genova, Via Montallegro 1, 16145 Genova, Italy
[b] DICEAA - Dipartimento di Ingegneria Civile, Edile-Architettura e Ambientale, Università dell'Aquila, Via G. Gronchi 18, 67100 L'Aquila, Italy

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ABSTRACT

A parametric section model is formulated to synthetically describe the geometrically nonlinear dynamics of cable-stayed and suspended bridges through a planar elastic multi-body system. The four-degrees-of-freedom model accounts for both the flexo-torsional motion of the bridge deck and for the transversal motion of a pair of hangers or stay cables. After linearization around the pre-stressed static equilibrium configuration, the coupled equations of motion governing the global deck dynamics and the local cable motion are obtained. A multi-parameter perturbation method is employed to solve the modal problem of internally resonant systems. The perturbation-based modal solution furnishes, first, explicit formulae for the parameter combinations which realize the internal resonance conditions and, second, asymptotic approximations of the resonant frequencies and modes. Attention is focused on the triple internal resonance among a global torsional mode of the deck and two local modes of the cables, due to the relevant geometric coupling which maximizes the modal interaction. The asymptotic approximation of the modal solution is found to finely describe the multiple veering phenomenon which involves the three frequency loci under small variation of the most significant mechanical parameters, including terms of structural coupling or disorder. Moreover, the veering amplitude between any two of the three frequency loci can be expressed as an explicit parametric function. Finally, the disorder is recognized as the only parameter governing a complex phenomenon of triple modal hybridization involving all the resonant modes. The entire hybridization process is successfully described by an energy-based localization factor, presented in a new perturbation-based form, valid for internally resonant system.

1. Introduction

The parametric formulation of synthetic structural models may capture the essential aspects which characterize the dynamic behavior of many complex engineering systems. If sufficiently representative, synthetic models may also highlight, and sometimes quantitatively assess, the risks associated with exceeding limit states of collapse and serviceability due to unacceptable vibration levels. In particular, the development of high-amplitude oscillations can often be related to the

* Corresponding author.
E-mail addresses: marco.lepidi@unige.it (M. Lepidi), vincenzo.gattulli@univaq.it (V. Gattulli).

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modal properties of a structure. Indeed, many relevant dynamic phenomena can be attributed to either the occurrence of internal resonance conditions among the natural frequencies or the localization of the modal shapes. In such cases, the systematic analysis of how the modal properties depend on a few significant parameters may be a crucial issue of theoretical and technical interest, and a minimal representative model may help to conveniently express this parametric dependence in the simplest possible, though eventually approximate, analytical form.

Cable structures are encountering a growing success in the modern engineering due to technical, economic and aesthetic reasons, which justify their actual competitiveness for covering free spans in an increasingly wide length-range. The structural and architectural design of suspended and cable-stayed bridges, in particular, has been fine-tuned over the last few decades to conjugate efficient geometric shapes, optimal material usage, and appreciable visual pleasantness. Focusing on the structural viewpoint, the virtuous synergy among the load-bearing capacity of beams (or arches) and the force-transferring ability of cables has been optimally exploited in a variety of collaboration schemes (Fig. 1a). Nonetheless, this optimization trend often ends up over-stressing the inherent properties of slenderness and flexibility of cable-supported bridges and footbridges. Such structural features, combined with low damping capacities and associated with rising performance demands due – among other things – to the increase of live loads, make these structures particularly vulnerable to dangerous dynamic phenomena, including for instance the aeroelastic instabilities due to wind actions, or the dynamic bifurcations due to the direct or parametric excitation of pedestrian or vehicular traffic.

The non-negligible influence of the cable vibrations on the free and forced full-bridge dynamics is a key-issue, well-recognized since the early nineties of the past century [1]. Consequently, a variety of continuous and discrete formulations [2–6] have been proposed to overcome the inherent shortcomings of traditional models, coarsely describing the cables as tendon elements with Ernst equivalent elastic modulus [7,8]. The matter tends to become determinant in the newest structural realizations, considering that the modern design trend is to prevent the risk of stress localization in the suspension system (main cables, arch, towers) by increasing the total number of suspending cables. In this respect, several numerical and experimental studies confirm that cable-supported bridges typically possess a dense spectrum of natural frequencies, in which internal resonant conditions among *global modes*, dominated by the flexural and/or torsional dynamics of the deck (Fig. 1b), and *local modes*, dominated instead of the lateral dynamics of one or more cables (Fig. 1c), are practically unavoidable [2,3,9–13]. As a remarkable engineering-oriented result in the linear dynamic field, the cable-deck modal interactions have been proved to appreciably affect the full-bridge response to limit and service loads [11,14].

In this challenging scenario, it may be worth devoting some theoretical research efforts to develop structural models able to well-balance the competing requirements of synthesis and representativeness, with expected positive spillovers in a variety of engineering applications, including vibration control and health monitoring systems. Indeed, a synthetic but representative model formulation can effectively be focused on the deepest investigation of a single or a few peculiar aspects of the complex dynamic behavior of cable-supported bridges. According to this leading idea, the present paper illustrates a four-degree-of-freedom parametric model governing the linearized dynamics of a minimal elastic multi-body system, still able to effectively simulate the complex sectional behavior of a suspended or a cable-stayed bridge. As a fundamental peculiarity and major novelty, the model captures the internal global–local coupling between the flexural/torsional deck motion and the transversal oscillations of a pair of pretensioned suspender cables (which may represent the hangers in suspension bridges, or the stays in cable-stayed bridges), by virtue of an accurate description of the geometric contributions to the stiffness terms.

In comparison with the current state-of-the-art, the present model intends to originally address some open issues which can be recognized in the existing scientific literature on the topic. On the one hand, a massive well-established bibliography concerns the so-called elastic section models, which typically consist of elastic springs suspending an undeformable mono-body system. Its rigid components of motion can represent the generalized flexural (vertical and lateral) and torsional displacements of the bridge deck in the cross-section plane. The employment of elastic section models is traditionally

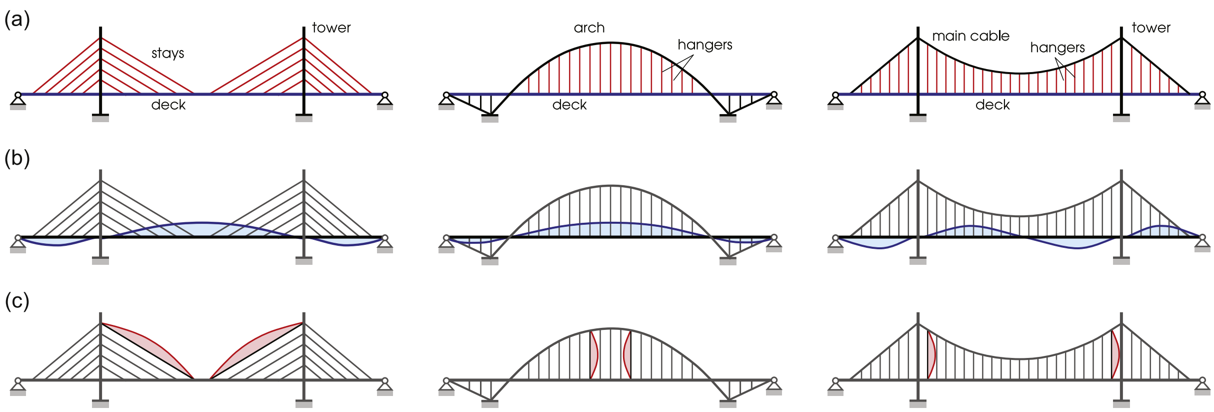

Fig. 1. Cable-stayed bridge (left), through-arch bridge (center), suspended bridge (right): qualitative examples of (a) cable-beam collaboration schemes, (b) deck vibration shape in global modes, (c) cable vibration shapes in local modes.