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Numerical and experimental dynamic analysis and control of a cable stayed bridge under parametric excitation

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ABSTRACT

In cable-stayed bridges, the occurrence of parametric excitation is very probable due to the presence of many low frequencies in the deck or tower and in the stay cables. When a local (cable) and a global (structure) mode are coupled, even very small motion of the deck or tower may cause dynamic instability and extremely large vibration amplitudes of the stay cables. This paper presents a nonlinear dynamic study of a three dimensional cable stayed bridge in construction phase under parametric excitation. A nonlinear inclined cable with small sag which takes into account the quadratic and cubic nonlinear couplings between in-plane and out-of-plane motion, is coupled with a finite element model of a cable stayed bridge. Active damping is successfully added to the structure using collocated displacement actuator–force sensor pairs located on each cable and a robust control strategy based on decentralized collocated Integral Force Feedback. The effect of the amplitude of excitation as well as the added active damping on the steady state response of the stay cable under parametric excitation is studied numerically and experimentally. A phenomenon of energy transfer between the cable and the deck is observed. The experimental results are qualitatively in good agreement with the numerical ones.

1. Introduction

In the past few decades, cable-stayed bridges became very popular especially when designed to cross valleys and wide rivers. This fact is a consequence of their structural efficiency, economical construction and aesthetic shape. These structures are very flexible and light and because of the strength of high performance materials used in their construction, their stiffness increases faster. Such structures are very sensitive to traffic, wind and rain-wind induced vibrations as well as flutter instability and seismic excitations. Thus, stay cables are prone to vibrate locally both in-plane and out-of-plane. Furthermore, cable vibrations can be accompanied by pylon or deck motions, called global vibration. The coupling between the local and the global modes may give rise to parametric excitations [1]. In fact, small periodic vibrations of the deck (or pylon) excite the cables through the axial motion of their support and large spectacular oscillations of the cables arise given that the tuning process converges to certain conditions. Reasonably small amplitudes of anchorage oscillations may lead to important steady state-cable response. This may occur when the frequency of the anchorage motion is close to the first natural frequency or twice the fundamental frequency of the cable [2].

Linear free and forced oscillations of elastic cables with a small sag-to-chord-length ratio based on the parabolic equilibrium approximation were first developed by Irvine and Caughey [3,4]. Wu et al. [5] improved the expressions for the in-plane natural frequencies of an inclined cable derived by Irvine [4]. Ren et al. [6] proposed empirical formulas to estimate cable tension based on its fundamental frequency only. The obtained tension was validated through comparison to results available in the literature; and to experimental results carried out on a stay cable mockup. Based on a single-degree-of-freedom model for in-plane vibrations of a cable, Hagedorn and Shafer [7] extended the linear theory considering the effect of quadratic and cubic non-linearities on Eigen frequencies. The existence of the quadratic and cubic non-linear terms makes the in-plane cable motion couples with that of the out-of-plane and induces modal interaction [8].

Wang and Zhao [9] applied the shooting method and the continuation technique to investigate the large amplitude motion and non-planar motion characteristic of an inclined cable subjected to support motion. An investigation on accurate finite element modelling of large-diameter sagged cables taking into account flexural rigidity and sag extensibility was carried out by Ni et al. [10]. As the flexural rigidity has an effect on the natural

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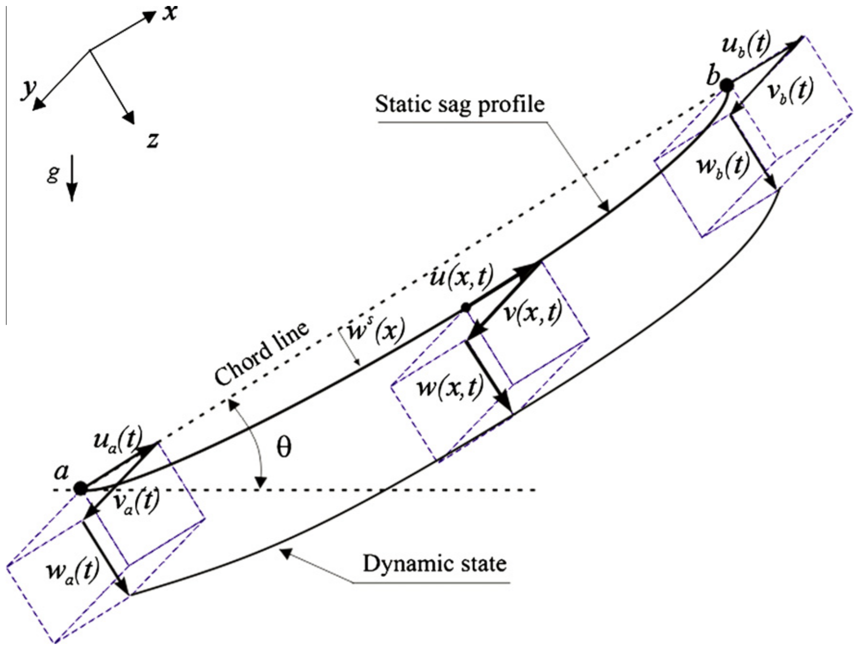

Fig. 1. 3D-model of an inclined cable with support motions.

frequencies in the case of suspended cables with large diameters, it can be neglected in the case of stay cables with smaller diameter.

Kovàcs [11] introduced the concept of parametric excitation in cable stayed bridges. Based on a linear assumption, he derived expressions for the maximum amplitude of cable oscillations as a function of the ratio between the natural frequencies of the stay cable and the bridge.

Fujino et al. [12] distinguished local vibrations from global vibrations and studied the nonlinear interaction between them. Warnitchai et al. [13] developed a nonlinear model for cables and its application to a cable-structure system. Gattulli et al. [14] deeply investigated a non-linear interaction mechanism called cable end angle-variation through an analytical model of a simple cable-stayed beam and a consistent experimental set-up corroborated by numerical finite element analysis. Based on the Floquet theory, Fourier series and generalized Eigenvalue analysis, Ying et al. [15] developed a direct numerical approach to study the parametrically excited instability of a stay cable system with multi-degree-of-freedom under general parametric excitation. They analyzed the effects of each mode of vibration and parameters of an inclined stay cable with sag on the unstable regions, under periodic two-support-motion excitation. Abdelghaffar and Khalifa [16]

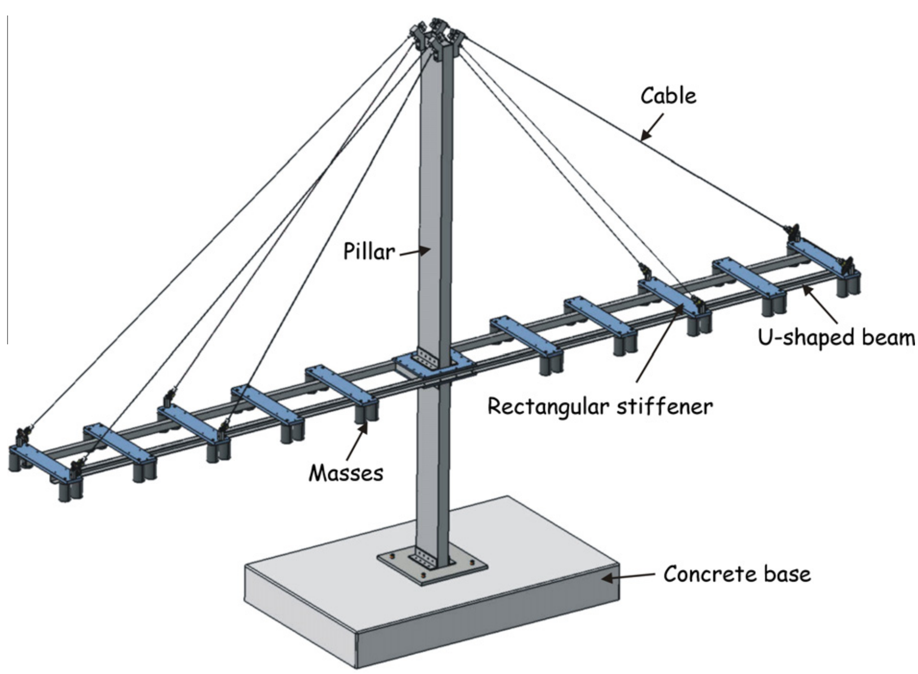

Fig. 2. The smart bridge: description of the main components.