The Prediction of Nonlinear Responses and Active Stiffness Control of Moving Slender Continua Subjected to Dynamic Loadings in a Vertical Host Structure

Stefan Kaczmarczyk and Philip Picton

School of Science and Technology, The University of Northampton, St. George's Avenue, Northampton, NN2 6JD, UK

(Received 21 December 2011, accepted 14 September 2012)

Slender continua such as long ropes, cables, and belts are used as tension and payload-carrying members in various engineering applications. They are deployed in terrestrial mine/underground equipment and high-rise building installations through to tethered offshore tension members, tethered space satellite systems and rotating momentum-exchange tethers in Earth's orbit. The slender continua are inherently nonlinear, leading to large nonlinear responses with passages through resonances taking place when the time-varying natural frequencies of the system approach the frequency of the inertial load resulting from the dynamic loadings. In this paper, the lateral nonlinear dynamic behaviour of long slender continua moving at speed in a tall host structures is analysed. A mathematical model comprising non-stationary, nonlinear ordinary differential equations is used to describe the dynamic behaviour of the system equipped with a multi-modal active stiffness controller. The active control is implemented by an axial motion of the support, which results in substantial reduction of the response.

1. INTRODUCTION

Moving continuous tensioned slender structural elements, such as ropes, cables, belts, and tethers, are pivotal components of many engineering systems. The applications include crane and mine hoists, offshore and marine installations, vertical transportation systems in buildings, and space tether propulsion systems. Due to their relatively low weight, flexibility, and low internal damping, these continua often vibrate at large amplitudes and exhibit a broad range of complex nonlinear dynamic phenomena.

The dynamic behaviour of systems with moving tensioned members has attracted considerable attention. Numerous aspects of their dynamic response characteristics in transport installations, in particular in building elevators, mine hoists and space systems, have been studied.[1–5] A broad range of sources of excitation are present in such systems. These include transient loads as well as periodic forces. The excitations produced by earthquakes and high winds may lead to adverse dynamic behaviour of these tension members installed in large civil structures and tall buildings. Substantial research in the area of rope and cable dynamics has been devoted to the issue of mitigating the effects of their dynamic responses. Various control techniques have been developed to suppress their lateral response, mainly for use in cable civil structures such as suspended bridges and cable-stayed bridges. Passive methods involve the application of viscous dampers placed near the cable support and acting in a lateral direction.[6] Semi-active control strategies include the application of magnetorheological dampers that achieve significant vibration reduction compared to viscous dampers.[7] Active vibration control methods using boundary lateral motion[8,9] or longitudinal motion[10–13] have also been considered. The latter strategy utilizes the fact that the longitudinal elastic stretching of the slender element is coupled with its lateral motion. An actuator is used to produce a longitudinal oscillatory motion of the support in order to cause the time variation of transverse (lateral) stiffness which in turn results in extracting energy from the system. Such an active control method is termed "active stiffness control."

The aim of this paper is to develop a mathematical model to predict the dynamic behaviour of long slender continua deployed in tall host structures. The objectives include to determine the dynamic responses when these continua are subjected to harmonic excitation due to a low-frequency sway of the host structure and to investigate the effectiveness of a suitable strategy to control the effects of the sway. Active stiffness control is considered to mitigate the effects of passage through resonances when a slender continuum, such as a wire rope or cable, moves at speed and comes to rest, exhibiting large dynamic displacements.

2. VIBRATION MODEL AND CONTROL STRATEGY

The planar model of a slender element, representing a rope or cable and modelled as a taut string of time-varying length $L(t)$ moving at speed in a vertical cantilevered host structure, is depicted in Fig. (1). The element has mass per unit length m, elastic modulus E, and an effective cross-sectional area A. It is wrapped around a drum at the bottom end with its upper end attached to a support moving at speed $v(t)$, while the host structure is subjected to bending deformations described by the shape function $\Psi(z)$, with z denoting a coordinate measured from ground level. The bending deformations produce a har-