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Wave-based vibration control of large cable net structures

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HIGHLIGHTS

- A wave-based boundary control strategy on the large cable net structure is proposed.
- Stability results are given with disturbances coming from the external boundary.
- Dynamic responses of a planar cable net structure are numerically analyzed.
- Structural vibration can be controlled effectively by applying our proposed strategy.

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ABSTRACT

Large cable net structures have been widely applied in aerospace engineering due to the feature of light-weight, high packaging efficiency, and high thermal stability. Structural vibrations induced by a variety of disturbances are inevitable in the space environment, resulting in the requirement of effective vibration control strategies for large cable net structures. Since the large cable net structures have many closely spaced vibrational modes in the range of low frequencies, traditional modal based control may cause modal truncation and spillover problems. In this paper, a wave-based boundary control strategy is adopted and its effectiveness to control the vibration of cable net structures is investigated, by transfer function analysis and numerical methods. It is found that the structural vibration can be absolutely resisted by applying the wave-based boundary controllers onto all the exterior nodes, when disturbances come from the external boundaries of the cable net. Our results in this paper can provide a theoretical basis for the vibration control of large cable net structures.

1. Introduction

Large cable net structures, known as a type of flexible structures, can be easily packaged in a small volume and provide high stiffness when stretched. Besides, cable net structures possess the features of light-weight and high thermal stability, resulting in wide applications in aerospace engineering. For example, the AstroMesh reflector family, fabricated by the Northrop Grumman Corporation, has been used in many renowned projects such as Thuraya, INMARSAT 4, and MBSAT, c.f. [1]. During the usage in the space environment, structural vibrations would be caused by a variety of disturbances, including alternating thermal loads, attitude maneuvers of the spacecraft and impact from space debris [2]. However, the damping of the cable net structures is such low that the introduced vibrations are hard to decay, which will influence the surface accuracy of the reflectors severely. Hence, an efficient vibration control strategy on large cable net structures is required.

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The vibration control of flexible structures can be implemented by active or passive methods. However, passive methods can be sensitive to resonance frequencies, may be bulky, and may not perform well at low frequencies [3]. In comparison, active methods have the potential to overcome the performance limitations of passive methods [4,5]. The most widely used method for active vibration control of flexible structures is based on modal control theory, where the structural dynamic responses are considered as the superposition of all vibrational modes [6–9]. Modal-based active vibration control methods try to attenuate the amplitudes of the modal displacement, and the number of considered vibration modes must be determined before the controller design. With the increasing scale of the cable net structure, close modes of the flexible structure exist in the range of low frequencies [10], making it hard to deal with the modal truncation problem. In addition, dynamic responses of a large flexible structure do not immediately spread to the entire structure under an impact or a disturbance, but in a gradual manner of wave propagation [2]. Consequently, the modal control methods are generally ineffective.

A wave-based theory is proposed to control the vibration of large space structures by Von Flotow et al. [11], where the structural elastic dynamic responses are regarded as the superposition of two traveling waves along opposite directions. Quite a few wave-based active control methods, such as traveling wave control [11], wave-absorbing control [12], active sink method [13], have been proposed since 1986. These active control strategies try to stop the formation of vibrations by wave cancellation. Since the controllers are designed directly based on wave equations, the wave-based methods have shown the abilities to avoid high-frequency spill and modal truncation comparing with the traditional modal control methods [14].

Boundary control has the ability to remove the spillover problem since the control is proposed on the base of the original distributed-parameter systems [15], whose boundary affects all the flexible modes [16]. The wave-based boundary control method has shown great power and simplicity in the vibration control of flexible structures. In Ref. [17], the actuator is located at one end of the structure of the beam-like mass–spring arrays to control its planar position while absorbing the vibration by canceling the outgoing waves. In Ref. [18], the torsional vibrations in drill strings are controlled by decomposing the drill string dynamics into two traveling waves and absorbing the wave traveling in the direction of the top drive. In Ref. [19], the flexural vibration of a slender structure is controlled by the use of an adaptive anechoic termination, which is fulfilled by applying force determined by a feed-forward adaptive control that uses estimates of the incident and reflected waves as reference and error signals. Unfortunately, the wave-based boundary control method on large cable net structures still lacks. This motivates us to find a new vibration control strategy for cable net structures.

In a real cable network antenna reflector, the cable ends are fixed at the ring truss, which is connected to the satellite by a deployable mast. Disturbances are most frequently generated during attitude maneuver or orbit transfer and then transmitted into the cable net from the boundary truss. Thus, in this paper, disturbances are assumed to come from the external boundaries of the cable net. We adopt a wave-based boundary control strategy and its effectiveness to control the vibration of space cable net structures is investigated. The paper is organized as follows. Section 2 presents the motion equations of a planar cable net structure and gives the wave-based boundary control strategy. In Section 3, transfer functions from the disturbance to the displacement of the cables are derived and pole analysis is given to express the stability results of the wave-based boundary control strategy. In Section 4, the Lax–Friedrichs scheme is adopted to analyze the out-of-plane vibration of the cable net structures and numerical simulations are carried out to show the effectiveness of the wave-based boundary control strategy. Finally, the conclusions are made.

2. Problem formulation

2.1. Model descriptions and assumptions

To simplify the study on the proposed wave-based vibration control methods of cable nets, we consider a planar cable net structure with rigid supports, consisting of triangle-faceted mesh in a periodic pattern, as shown in Fig. 1. Note that the network has only one cable at each boundary point since we adopt the boundary control strategy which applies to the end of each boundary cable. The planar cable net structure can be described by a directed graph $\mathcal{G}$ with its edges denoted by $\mathcal{E} = \{\mathbf{e}_1, \mathbf{e}_2, \ldots, \mathbf{e}_{30}\}$, vertices denoted by $\mathcal{V} = \{\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_{25}\}$, and edge orientations illustrated in Fig. 1. We denote $\mathcal{V}_{int}$ and $\mathcal{V}_{ext}$ as the sets of interior and exterior nodes, respectively. Seen from Fig. 1, $\mathcal{V}_{int} = \{\mathbf{v}_1, \ldots, \mathbf{v}_7\}$, $\mathcal{V}_{ext} = \{\mathbf{v}_8, \ldots, \mathbf{v}_{25}\}$. Similarly, $\mathcal{E}_{int}$ and $\mathcal{E}_{ext}$ denote the sets of interior and exterior edges, respectively, where $\mathcal{E}_{int} = \{\mathbf{e}_1, \ldots, \mathbf{e}_{12}\}$, $\mathcal{E}_{ext} = \{\mathbf{e}_{13}, \ldots, \mathbf{e}_{30}\}$.

Some assumptions are first made for the planar cable net structure. All the cables are assumed undamped and the effect of gravity on the structural response is ignored, due to the space environment. We also adopt the same assumptions as Ref. [20]. In order to ensure a high surface accuracy of the reflector, the cables are usually highly pre-stressed to avoid cable slackening after the antenna is deployed. The high pre-tensioning cable nets are considered as weakly nonlinear systems comparing with single cable [14,21]. Giaccu et al. [22] give a malfunctioning measure to evaluate the deviation from a linear behavior of in-plane cable networks in the absence of slackening effect. It is indicated in that reference that for a given vibration amplitude, the minimum pre-tensioning force can ensure the linear dynamic behavior of the cable network. Thus, the planar cable net can be regarded as linear systems under the vibrations with small amplitude and modal coupling between in-plane and out-of-plane vibrational modes is therefore neglected. In the high pre-tensioning cable net, each cable element is in a taut state. Hook's law of the materials in the cable is valid for the linear system with small amplitude. It is pointed out in Ref. [23] that cable flexural stiffness does not greatly affect the response of a taut cable. We therefore consider the taut cable as the string with constant parameters in this study. In addition, the cable ends of a reflector can be