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Wave-based transfer matrix method for dynamic response of large net structures

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ABSTRACT

Wave-based method for dynamic responses of net structures can provide analytic out-of-plane responses in full frequency range, helping to avoid the problem of control spillover, comparing with traditional modal analysis. However, as the scale of the net structure increases, more computing resources are required. Here, a wave-based method inspired by transfer matrix method is proposed for both orthogonal and non-orthogonal symmetric net structures. According to the symmetric characteristics of the net structure, we first divide the whole structure into several periodic elements and calculate the transfer matrix of the periodic element by using the basic wave-based method. Then by multiplying transfer matrixes of the periodic element and using all the boundary condition of net structure, the out-of-plane displacments of the net structure can be finally obtained. Our proposed wave-based transfer matrix method is proved to be more accurate and efficient than the finite element analysis for large net structures.

1. Introduction

Cable-mesh deployable antennas with flexible net structures are widely used in reconnaissance and space exploration due to their excellent characteristics, including large diameter, light weight, small stowed volume and good reflector surface precision [1,2]. During the service of the antennas, the adjustment of the spacecraft's attitude and the impact of the space debris can cause the out-of-plane vibration of the net structures, which has a negative effect on the precision of the antenna and even leads to the destruction of the structure [3]. As a result, the vibration control of net structures becomes a quite urgent issue to deal with in the space engineering. To figure out the control law, the dynamic analysis of the structure need be carried out first [3].

The modals of large and flexible net structures are so dense that it is difficult to use the traditional modal truncation technique [4]. Therefore, there have been some other methods to conduct the dynamic analysis of net structures. Singh et al. [5] used membrane analogy to study net structures. Gambhir and Batchelor [6] adopted a finite element model to study the free vibration of a single sagged cable hanging freely from two supports. Zingoni [7] took advantage of group theory to decompose the characteristic equations of net structures into lower dimensions. Kaveh [8] used the graph theory to deal with the vibration analysis of net structures. Dhoopar et al. [9] developed a method based on transfer matrix to derive its natural frequencies of orthogonal net structures. Comparing with the other methods, the wave-based method considers the

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propagation of disturbance in the structure in the form of wave. By using this method, the dynamic response of the structure can be achieved without the effect of the modal truncation. Inspired by Mace's work [10], Mei et al. [11] investigated the wave vibration, derived the transmission and reflection matrices for various discontinuities on an axially loaded Timoshenko beam. Mencik and Ichchou [12] discussed the guided wave propagation and diffusion in periodic elastic structures. Kang et al. [13] used wave-based method to present a systematic approach for the free vibration analysis of a planar circular curved beam system. Kang et al. [14] further got transfer functions of one-dimensional distributed parameter systems. Mei and Sha [15] applied wave-based analytical method to study vibrations in simple spatial structures and investigated the coupled bending, axial, and torsional vibrations. Unfortunately, the wave-based method for dynamic response of large net structures is not yet reported. In fact, the basic wave-based method is not available for dynamic properties of large two-dimensional net structures due to very low computational efficient. New method needs to be exploited for large net structures.

In addtion, the transfer matrix method has high computing efficient for the dynamic analysis of periodic structures and has been applied for one dimensional phononic crystal [16], periodic beam [17], drill string system [18], orthogonal net structures with small size [9]. Inspired by the transfer matrix method, as an improved wave-based method, wave-based method combined with the transfer matrix method is proposed to improve the computing efficient for dynamic response of net structures. Our method can not only derive the natural frequencies and displacement responses but also be more accurate and efficient than the finite element method (FEM). Furthermore, it can help to figure out all the traveling waves and energy flow in net structure, which contributes to determining the control law of the net structure's vibration [19–22] and offering new approach for manipulating the traveling waves [23] and isolating vibration [24].

2. Method

2.1. Basic wave-based method

The basic wave-based method (BWM) is firstly introduced in this section. It is assumed that the displacement responses of the net structure are quite small, resulting in the approximately constant tensions of any continuous string [25], permitting a linear analysis of the net structures [7]. Furthermore, high levels of cable pretensions can also mitigate the large initial deflections, which ensures that the cable net structure is always considered as weakly nonlinear systems. Essentially linear techniques may be used to overcome the non-linear effects [26–28]. Such an idealized string has a negligible Young's modulus and cannot transmit longitudinal waves along its length [29]. Therefore, the uncoupled modes are adopted. The basic wave-based method is based on the one-dimensional linear wave equation. Structural deformation caused by gravity is also ignored because of the absence of gravity in space. Considering the string structure, the displacement simulations and responses involved here are all transverse, which means that longitudinal or in-plane responses of structures are not considered in our study.

For a single string, its predominant flexibility leads to transverse deflection, $u(x,t)$. This behavior is well described by the wave equation:

$$T\frac{\partial^2 u}{\partial x^2} = \rho\frac{\partial^2 u}{\partial t^2}, \tag{1}$$

where T and ρ are the pretension and mass per unit length of the string, respectively; x and t is the space ordinate along the string and time, respectively.

Eq. (1) can be transformed into a homogeneous equation in frequency domain by using Fourier transformation, whose solution can be considered as the sum of a leftward and rightward traveling wave modes in the frequency domain,

$$U(x,\omega) = W_l(\omega)e^{ikx} + W_r(\omega)e^{-ikx} = u_l(x,\omega) + u_r(x,\omega), \tag{2}$$

where the amplitudes $W_l(\omega)$ and $W_r(\omega)$ may be complex. The wave number k is given by $k = \omega/c = \sqrt{\rho\cdot\omega^2/T}$ and is real and positive in the absence of the damping, and $c = \sqrt{T/\rho}$ is the wave speed. $u_l(x,\omega)$ and $u_r(x,\omega)$ are the waves traveling toward the left and right along the string, respectively. The idea of traveling wave components derived from Eq. (2) can be directly used to describe the responses of a single string instead of solving the corresponding differential equation.

Considering the single string under the excitation, external displacement U_1, as shown in Fig. 1, its boundary conditions can be expressed as

$$\begin{cases} u_{A1} + u_{A2} = 0 \\ u_{B1} + u_{B2} = U_1 \end{cases}. \tag{3}$$

According to traveling wave continuous condition, the four wave components in the string with length L will have the following relationship as