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A two-step FEM-SEM approach for wave propagation analysis in cable structures

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ABSTRACT

Vibration-based methods are among the most widely studied in structural health monitoring (SHM). It is well known, however, that the low-order modes, characterizing the global dynamic behaviour of structures, are relatively insensitive to local damage. Such local damage may be easier to detect by methods based on wave propagation which involve local high frequency behaviour. The present work considers the numerical analysis of wave propagation in cables. A two-step approach is proposed which allows taking into account the cable sag and the distribution of the axial forces in the wave propagation analysis. In the first step, the static deformation and internal forces are obtained by the finite element method (FEM), taking into account geometric nonlinear effects. In the second step, the results from the static analysis are used to define the initial state of the dynamic analysis which is performed by means of the spectral element method (SEM). The use of the SEM in the second step of the analysis allows for a significant reduction in computational costs as compared to a FE analysis. This methodology is first verified by means of a full FE analysis for a single stretched cable. Next, simulations are made to study the effects of damage in a single stretched cable and a cable-supported truss. The results of the simulations show how damage significantly affects the high frequency response, confirming the potential of wave propagation based methods for SHM.

1. Introduction

Dynamic methods for health monitoring of flexible cable-supported structures have been studied for several decades [1]. The modal parameters of the cables are widely used for cable force identification [2] and damage detection [3], as they can be estimated from ambient vibrations without interrupting the traffic. However, the low-order modal parameters are usually not very sensitive to local damage. For this reason, methods based on wave propagation which involve local high frequency behaviour are investigated for damage assessment [4,5]. Generally, damage leads to the reflection of waves and could therefore be identified from a suitable indicator. For longitudinal guided waves, complex coupling phenomena such as slip occur, complicating the modelling of longitudinal waves as well as the interpretation of physical signals [6]. Such complex coupling phenomena do not occur for transverse waves involving cable bending, as long as the wavelength is much larger than the dimensions of the cross section [7]. An additional benefit of bending waves in nondestructive test is that they are easier to be excited, for example, by traffic loading [8]. For the above reasons, the bending wave response is easier to model and interpret, and is therefore studied

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Free wave propagation in a cable of infinite length was studied by Behbahani-Nejad and Perkins [9], who formulated the wave dispersion relations, considering the coupling between longitudinal and transverse motions. The free vibration response and the forced response of cables considering the cable sag can be analyzed by various numerical methods: finite difference method [10], finite element method [11], boundary element method [12]. Among these methods, the time domain FEM with a central difference method (CDM) for the time discretization is the most popular due to its flexibility and versatility [13]. However, its feasibility for analyzing wave propagation of cable structures is restricted by the following issues:

1) The algorithm is conditionally stable. The integration step ΔT is restricted by the smallest element, leading to a very high number of time steps, especially when the simulation of local damage requires a small element size.
2) The element size is dictated by the maximum frequency. A high frequency analysis will therefore involve a high number of elements.

The above restrictions contribute to an exponential increase of the computational cost, when small elements and high frequencies are considered. Therefore, an attractive alternative approach is the spectral element method (SEM) proposed by Doyle [14]. As the spectral element (SE) matrix is directly derived from the analytical solution, it is unnecessary to further divide a uniform segment into several elements. However, when applying this approach to cable structures, three issues need attention:

1) The transverse stiffness of a cable is mainly provided by the axial force. This should be taken into account in the spectral element;
2) When applying the Fourier transform, the requirement of convergence is quite strict. For lightly damped structures, throw-off elements have to be introduced [14];
3) The geometric nonlinearity of a flexible cable causes a sag effect, which affects the static configuration and the axial force distribution [15].

The first issue can be addressed using the SE matrices of a Euler-Bernoulli Beam and a Timoshenko Beam were derived by Lee [16], considering a constant axial force. When applying these elements, throw-off elements need to be introduced. For the second issue, the SE matrix of the Euler-Bernoulli beam was derived by Lgawa [17], using the Laplace transform instead of the Fourier transform. The integral path is shifted to the right side, and the singularity of the poles can be avoided. This is helpful for time-domain analysis. However, the prestressing by the axial force was not taken into account in this work. In this paper, a two-step approach is proposed to tackle the third issue. Firstly, a static analysis is carried out by a finite element (FE) analysis considering geometric nonlinearity. The static deformation and the element forces are calculated. Based on this, a SE model is established for dynamic analysis. The dynamic response is incremental with regard to the static state.

This paper includes three main parts: First, the spectral element matrix of a 3D Timoshenko beam with axial force is derived in the Laplace domain. Second, the two-step approach is introduced, and the issues for the modelling are illustrated. Lastly, the application of this two-step approach is verified by the dynamic analysis of a single cable and a cable supported truss, and the effects of local damages are studied.

2. Formulation of spectral element matrix

2.1. Transverse motion

For the formulation of the spectral element matrix, we will consider a single cable element without external loading.

A Timoshenko beam with axial force is considered to represent the cable element (see Fig. 1). The axial force is assumed to be constant, with a time-dependent orientation caused by the motion of the cable. In the governing equations of Timoshenko beam theory [18], the additional transverse stiffness caused by the axial force [19] is considered. The equilibrium equations of the free motion can then be written as:

$$\mathrm{d}Q_y + \partial\left(N_x \cdot \frac{\partial v}{\partial x}\right) + f_d \mathrm{d}x + f_I \mathrm{d}x = 0 \tag{1}$$

$$\mathrm{d}M_z + Q_y \mathrm{d}x + m_d \mathrm{d}x + m_I \mathrm{d}x = 0 \tag{2}$$

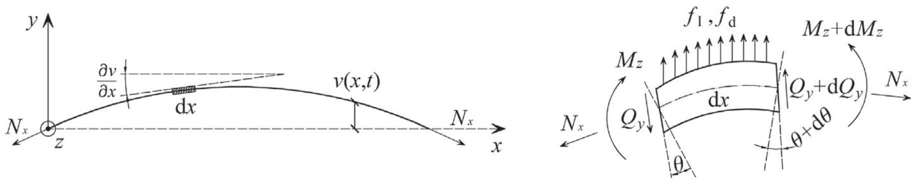

Fig. 1. Model of a Timoshenko beam element with axial force.