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Vibration-based cable condition assessment: A novel application of neural networks

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ABSTRACT

Vibration-based cable tension estimation methods demand complex computations especially when usage of comprehensive cable models is required. Avoiding mathematical calculations, this paper proposes a simple novel framework to estimate the cable tension based on Artificial Neural Networks (ANNs). Employing a comprehensive cable model, a set of data including cable length, cable mass per unit length, cable axial stiffness, cable bending stiffness, cable tension and the corresponding cable natural frequencies is generated for training, validation, and testing of the ANNs. The acquired ANNs are then used to estimate the cable tensions in new Ironton-Russell Bridge and the results are compared against the cable tensions directly measured by lift-off test. It will be shown that for new Ironton-Russell Bridge, using cable length, cable mass per unit length, cable axial stiffness, and first two cable natural frequencies as input features to ANNs, the cable tensions can be accurately estimated.

1. Introduction

Consistency of cable tension over time is considered as one of the health indicators for both cables and superstructure of cable structures [1–3]. Cable tension can be measured directly [4] or it can be estimated by measuring different parameters of the cable such as stress [5], strain [6], or natural frequencies [7]. The methods that use cable natural frequencies to estimate the cable tension are called vibration-based tension estimation methods [8–11]. Vibration-based tension estimation methods have been extensively employed to estimate the cable tension in many cable structures around the world [12–14]. In a vibration-based cable tension estimation method, a cable model is usually used to create an error function representative of the difference between the measured natural frequencies of the cable and the analytical natural frequencies (coming from the cable model). Minimizing the error function, the cable tension can be identified [15]. Kim and Park also suggested a different approach to estimate the cable tension using cable natural frequencies [16]. They employed a frequency-based sensitivity-updating algorithm to identify the horizontal component of cable tension, cable bending stiffness, and cable axial stiffness in a finite element cable model. Suggesting adaptive sparse time-frequency analysis method to identify the time-varying cable natural frequencies using cable acceleration, Bao et al. allowed the vibration-based cable tension estimation methods to identify the time-varying cable tension [17]. In this paper, a novel vibration-based approach based on ANNs is presented to estimate the cable tension in cable structures avoiding complex calculations. Using normalized strain and displacement along the cable, ANN has already been employed to estimate the cable tension in

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bridges [18]. However, the method requires the measurement of strain and displacement values at several points along the cable which is experimentally expensive. An easily measurable set of cable properties including cable length, cable mass per unit length, cable axial stiffness, and in-plane natural frequencies of cable are suggested in this paper to train ANNs for estimating the cable tension in cable structures.

First, the unified finite difference cable model [19] is reviewed and used to generate a set of 1000 data points of cable length, cable mass per unit length, cable axial stiffness, cable bending stiffness, cable tension and the corresponding in-plane natural frequencies of cable. Second, the acquired dataset is employed to train, validate and test the ANNs with a single hidden layer that take cable properties as input features and output the cable tension force. Finally, the trained ANNs were used to estimate the cable tensions in new Ironton-Russell Bridge (a newly built cable-stayed bridge between Ironton, Ohio and Russell, Kentucky) and the results were compared against the tension forces measured by Lift-off test.

2. Finite difference cable model

Knowing cable length L, cable mass per unit length m, and cable tension force H, taut string model is the simplest cable model that can be used to estimate the cable natural frequencies [20]:

$$f_n = \frac{n}{2L}\sqrt{\frac{H}{m}} \tag{1}$$

where f_n is the n^{th} natural frequency of the cable in Hz. Employing the vibration equation of an axially tensioned beam is a common approach for considering the bending stiffness of the cable [8,9]. Irvine and Caughey [21] considered the sag and extensibility of the cable for the first time. They introduced the dimensionless parameter λ^2 (sag-extensibility parameter) as:

$$\lambda^2 = \left(\frac{8d}{L}\right)^2 \frac{L}{(HL_e/EA)} \tag{2}$$

where d is the cable sag, EA is the axial stiffness of the cable, and L_e is calculated as,

$$L_e = L\left(1 + 8\left(\frac{d}{L}\right)^2\right) \tag{3}$$

Assuming a parabolic static profile for the cable, the non-dimensional parameter λ^2 can be written as below [22]:

$$\lambda^2 = \frac{\left(\frac{mgL}{H}\right)^2 LEA}{HL_e},\ L_e \cong L\left(1 + \frac{\left(\frac{mgL}{H}\right)^2}{8}\right) \tag{4}$$

Supposing that the angle of inclination of cable cord relative to the horizontal is defined as θ (See Fig. 6), for cables with small sag, the in-plane natural frequencies of cable in Hz can also be calculated using Equation (5) [23]:

$$f_n = \frac{n}{2L}\sqrt{\frac{H}{m}}(1 + \varkappa_n) \tag{5}$$

where $\varkappa_n$ is calculated as below:

$$\varkappa_n = \left(\frac{\lambda_\theta{}^2}{\pi^4 n^4}\right)(1 + (-1)^{n+1})^2 \tag{6}$$

$$\lambda_\theta{}^2 = \frac{EA}{H}\left(\frac{\gamma LA}{H}\right)^2,\ \gamma = \rho g cos\theta \tag{7}$$

and ρ is density of the cable. Introducing the dimensionless parameter ζ (bending stiffness parameter), Zui et al. considered both cable sag-extensibility and cable bending stiffness [10]:

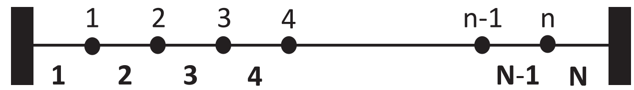

Fig. 1. Discretized cable with N elements and n internal nodes (n = N − 1).

$$\zeta = L\sqrt{\frac{H}{EI}} \tag{8}$$

where EI is the bending stiffness of the cable. Employing the dimensionless parameters ζ and λ^2, Ren et al. [11] classified different types of cables and proposed formulas to estimate the cable tension considering sag-extensibility and bending stiffness of the cable separately. Ricciardi and Saitta [24] developed a continuous cable model capable of considering sag-extensibility and bending stiffness simultaneously. Mehrabi and Tabatabai [19] introduced a finite difference cable model that also considers variation in cross sectional area along the cable, end conditions, and intermediate springs and dampers. Fig. 1 shows a discretized cable with N elements of length a and n internal nodes (n = N − 1):

According to the finite difference cable model, the in-plane natural frequencies and mode shapes of the cable can be calculated using the eigenvalues and eigenvectors of the following eigenvalue equation:

$$\bar{\mathbf{K}}\bar{\mathbf{w}} + p\bar{\mathbf{M}}\bar{\mathbf{w}} = 0 \tag{9}$$

where

$$\bar{\mathbf{w}} = \begin{Bmatrix} \mathbf{w} \\ p\mathbf{w} \end{Bmatrix} \bar{\mathbf{K}} = \begin{bmatrix} \mathbf{K} & 0 \\ 0 & \mathbf{I} \end{bmatrix} \bar{\mathbf{M}} = \begin{bmatrix} \mathbf{C} & \mathbf{M} \\ -\mathbf{I} & 0 \end{bmatrix} \tag{10}$$

$\mathbf{w} \in R^{n\times 1}$ is a vector representing the mode shape components of the cable at internal nodes, p is the complex-valued natural frequency of the cable:

$$p = -\delta\omega + i\omega\sqrt{1-\delta^2} \tag{11}$$

where ω and δ are the undamped natural frequency and damping ratio of the cable and $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K} \in R^{n\times n}$ are the mass, damping, and stiffness matrices of the discretized cable (defined in Appendix A). Having the cable properties: cable length, cable mass per unit length, cable axial stiffness, cable bending stiffness, cable tension and employing the finite difference cable model, natural frequencies of the cable can be calculated.

3. Training data set

For most stay cables used in cable-stayed bridges around the world, non-dimensional parameters λ^2 and ζ (Eqs. (4) and (8)) fall within the intervals $\lambda^2 < 3.1$ and $\zeta > 50$ [19,25–27]. Based on the range of cable properties in new Ironton-Russell bridge, 1000 cables with properties randomly chosen from the intervals $50 < \zeta < 650$, $0.1 < \lambda^2 < 3.1$, 30 m < L < 170 m, 15 kg/m < m < 60 kg/m, 500 kN < H < 3000 kN are selected. Knowing ζ, λ^2, L, m, H, and E = 196.5 GPa (modulus of elasticity of stainless steel), the corresponding cable cross-sectional area A and cable second moment of inertia I can be calculated as below (using Eqs. (2)–(4), and (8)):

$$A = \frac{\lambda^2 H^3 L_e}{m^2 g^2 L^3 E} \tag{12}$$

$$I = \frac{L^2 H}{E\zeta^2} \tag{13}$$

where L_e is calculated as Eq. (4). The acquired cable properties are then fed into the finite difference cable model (with element length a = 0.1 m) to calculate the first 10 in-plane natural frequencies of each cable. It is worth mentioning that although some combinations of cable properties (Cable length, cable mass per unit length, cable axial stiffness, cable bending stiffness, and cable tension) and the corresponding