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Finite element-based analyses of natural frequencies of long tapered hollow steel poles

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Abstract

Long tapered poles are commonly used to support Closed Circuit Television Cameras (CCTV) for security and traffic monitoring. Images received from CCTV are normally distorted due to the camera's wind-induced vibration. To minimize the vibration experienced by the CCTV through development of a damping device to be placed at the interface between the pole and the camera, identification of the poles' different frequencies as functions of poles' geometric variables is essential. Thus, this study presents the development of natural frequency equations for long tapered hollow poles as functions of their geometric variables based on three-dimensional finite element model (FEM) analyses by taking into account the couplings between material, contact and geometric nonlinearities. The FEM results are compared and verified with the experimental data obtained from the instrumentation of a 60 ft pole. Sensitivity study is performed to identify the effect of different geometric parameters on the overall natural frequencies of the pole. Using the results from the parametric study, empirical formulae between the geometric parameters and the first, second and third mode natural frequencies for the long tapered hollow steel poles are obtained.
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Keywords: Finite element; Natural frequency; Steel pole; CCTV; Non-linear; ABAQUS

1. Introduction

Long tapered steel poles are generally used for the installation of Closed Circuit Television (CCTV) cameras to obtain real-time live images of ongoing traffic, which depend on the intensity of wind-induced vibrations. This will result in serious problems for capturing clear images when loading frequencies meet the natural frequencies of the pole. To develop a customized mechanical damping device (not the subject of this paper) to be placed at the interface between the pole and the camera, the information about the pole's natural frequencies is essential. Thus, in order to identify the natural frequencies of poles commonly used by the State departments of transportation with different geometric parameters, empirical equations are needed.

The information in the literature with regard to the dynamic characteristics of the long hollow tapered poles is limited. However, there are some codes [1], reports [2] and publications (Jones and Caracagolia [3], Pagnini and Solari [4]) regarding the dynamic behaviors of road signs, signals and light poles, but there has not been any essential work done on poles containing CCTV cameras in the literature, and the specific requirements on dynamic behaviors of CCTV poles are not documented (Jung et al. [5]). A commonly used tapered pole's height may vary from 20 ft (6.1 m) to 65 ft (19.8 m) depending on the applications, which in turn causes the variation of other parameters such as base diameter, top diameter, pole thickness, base plate thickness, and bolt diameter. Also, wind loads vary in different regions and seasons, and the vibrations caused by vehicle traffic effect a pole's deflection and ultimately the images transmitted by the cameras. Thus, prior to the study by Jung et al. [5], the lack of generalized equations for stiffness and strength of the CCTV poles as the functions of their geometric variables was under scrutiny (Abolmaali et al. [6]). Cameras currently in use are supported by wood, concrete, and steel, while recently fiber-reinforced plastic FRP

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Nomenclature

e	2.718281828
l	pole length
t_p	plate thickness
$t_{\text{pole-top}}$	thickness at the top of pole
$t_{\text{pole-btm}}$	thickness at the bottom of pole
d_b	diameter of bolt
d_{btm}	diameter of pole at the bottom
d_{top}	diameter of pole at the top
c_d	clearance distant
b_c	diameter of the bolt circle
p_d	plate dimension

Table 1
Material properties used in the parametric study

For all poles:	$E = 29{,}000$ ksi (200 GPa); $\nu = 0.29$;
	Pole yield stress = 50,000 ksi (580 GPa)
	Bolt yield stress = 84,000 ksi (580 GPa)

poles have gained wide popularity (Lacoursiere [7]). State departments of transportation, including the Texas Department of Transportation, generally use tapered steel poles most often on or at the vicinity of bridge structures (Abolmaali et al. [6]). The California Department of Transportation has recently installed several FRP poles on bridges at different locations (www.dot.ca.gov).

For dealing with the dynamic Finite Element Analysis (FEA) of the pole, it is important to consider the role of the bolted connection assembly which supports the pole to the concrete base. Even though using the dynamic (or cyclic) FEA of bolted connection is less noticed in the existing literatures concerning the dynamic behaviors of pole, there are many literatures reported on static FEA analysis of steel connections. Researchers such as Krishnamurthy [8] and Kukreti et al. [9] have developed detailed finite element models for large capacity extended end-plate connections, and compared their analysis results with those of experiments. Yorgun et al. [10] used FEA to develop a three-dimensional model of the connection that included material nonlinearity and strain hardening for end-plate and bolt components. The adequacy of their analytical model was verified through comparisons with reference tests. Bahaari and Sherbourne [11] investigated nonlinear behavior of bolted connections considering the plasticity of the material and the changes in the contact area. A325 slip critical bolts were used to assemble the connections. Wanzek, Gebbeken [12] and Citipitioglu et al. [13] emphasized the importance of thorough thickness deformation in the analysis of steel end-plate connections by using three layers of elements through the thickness of the end-plate. The effects of friction and slip due to the response of the connections were also considered. Chutima and Blackie [14] investigated the effect of pitch distance, row spacing, and bolt diameter on composite joints. Stallings and Hwang [15] presented a simple pretensioning model in the FEA of bolted connections by using temperature changes for the bolts modeled with rod elements. Kulak and Birkemoe [16] conducted field studies on bolt pretension. This study showed that actual pretensions were 35% greater than specified minimum pretensions. Therefore, bolt pretension would be at least 70% of the ultimate tensile strength of the bolt, known as proof load. In addition to the bolt modeling, geometric nonlinearity should be also addressed for a long tapered pole. Geometric nonlinearities are incorporated as large strain analyses that account for the stiffness changes resulting from the shape and orientation changes in elements. The large strain procedure places no theoretical limit on the total deformation or strain experienced by an element, but requires incremental loading to restrict strains for maintaining accuracy in the computations. Several other works related to geometric nonlinearity is found in the dissertation of Jung [17] and in the work done by Lees and Wollaston [18].

In this study the first three natural frequencies of long tapered hollow steel poles are obtained by performing three-dimensional FEA using ABAQUS [19] software while taking into account the couplings between material, contact and geometric nonlinearities. Elastoplastic solid elements with eight nodes are employed for the effective three-dimensional analysis. A surface-to-surface contact algorithm is used to simulate the interaction between contact surfaces. An energy-based convergence criterion is adopted to obtain the converged coupled nonlinear solutions. By performing sensitivity analyses on different geometric parameters, more effective parameters are found, and empirical equations using regression analyses are proposed. These equations can be further employed for the optimization of the pole geometry to make the natural frequencies of the pole invulnerable to wind-induced vibrations.

2. Modeling

2.1. Basic considerations

A popular circular CCTV pole shape is created and studied in the models for dynamic analysis as shown in Fig. 1. The effective geometric parameters considered for the development of prediction equations are the pole's: length, top and bottom diameters; bolt diameter; thickness; and end-plate thickness as shown in Fig. 2. The material properties used in the FEA analysis are displayed in Table 1. The definition of each geometric parameter can be found in the nomenclatures listed in the very beginning of this article. Several different shell and solid element types were tested to obtain the optimum finite element mesh. The 8-noded solid element is selected for meshing the structure of the pole because of accuracy of the results and simplicity of the analyses. Taking advantage of the symmetry, one-half of a typical pole is modeled as shown in Fig. 3. The bolts are modeled using tetrahedron elements. A typical view of the bolt model is shown in Fig. 4.

2.2. Pretension load

Pretension load (Jung [17]) is used to simulate the effect of fastener in the behavior of the bolts. This load is applied across a defined pretension section. This pretensioning force is applied