Chapter 10
Influence of Electrical Components and Supports on the Modal Characteristics of Timber Distribution Poles

Timothy Kernicky and Matthew Whelan

Abstract Inspection and asset management of timber distribution poles is critical for ensuring the reliability of the electrical distribution network and safety of powerline technicians requiring physical access to supported electrical infrastructure. Techniques for structural health monitoring and nondestructive evaluation of timber poles, including vibration-based methods, have been developed to detect belowground deterioration caused by fungal decay and wood-damaging insects that is not readily detected without costly and time-consuming excavation of soil around the pole. However, published literature on the modal characteristics of timber distribution poles has largely been limited to isolated and free-standing poles. The influence of supported components, such as conductors, crossarms, transformers, and lights, on the modal parameters of distribution poles has not been well established, which complicates the development of physics-based models to support structural health monitoring of the pole. To address this limitation, experimental modal analyses were conducted on a distribution pole under different configurations by sequentially adding and removing supported components. By conducting the test program on a de-energized circuit, an array of accelerometers could be installed along the entire exposed height of the pole in orthogonal directions to enable the experimental estimate of mode shapes from the free decay vibration response. The influences of individual components on the frequency response functions, natural frequencies, damping ratios, and mode shapes of the pole are presented.

Keywords Distribution poles · Energy infrastructure · Experimental modal analysis · Timber poles · Vibration-based structural health monitoring

Introduction

Although vibration-based techniques have been proposed for condition assessment of timber distribution poles by numerous studies [1], referenced within patents [2], and included in comprehensive reviews of nondestructive evaluation techniques [3], the experimental modal analysis of in-situ timber distribution poles has not been published to-date. Although the monopole nature of the primary structure suggests a relatively simple and readily predictable dynamic response, there are several complicating factors that may limit the accuracy of analytical formulas when applied to estimate the modal parameters of timber distribution poles. Timber poles are naturally grown and therefore exhibit a tapered geometry, orthotropic material properties, and local variations due to knots and other growth features. Furthermore, distribution poles are partially embedded in soil and the soil-structure interaction over the depth of embedment affects the dynamic response of the pole. The purpose of distribution poles is to support electrical infrastructure, including distribution lines, transformers, and street lights, which introduce additional mass, stiffness, and damping contributions. The dynamics of some of this infrastructure, such as the conductors, and additional components required to support the infrastructure, like crossarms, may be coupled to the dynamics of the pole. Lastly, additional structural support provided to the pole to resist applied loads, such as guy wires and groundline

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reinforcements, may likely affect the modal parameters of the pole. Analytical models proposed for estimating the natural frequencies and mode shapes of utility poles do not account for many of these complicating factors, aside from the soil-structure interaction [4]. However, the limited experimental data on the effects of electrical components and supports on the dynamic properties of distribution poles provides little basis for justifying the development of more complex models and validating the predictive fidelity of such models.

Research related to the application of vibration-based methods for nondestructive evaluation of in-service timber distribution poles has been largely performed using laboratory scale models or tests on poles in idealized and simplified configurations. Following a laboratory test program conducted on short pole segments, Prestage [5] acquired frequency response functions from a full-length timber distribution pole both prior to and after simulating several stages of decay by drilling holes in the pole near the groundline. The experimental results provided evidence of the sensitivity of the natural frequencies of the pole to the severity of groundline decay. However, the test program was limited to a single freestanding pole without any supported electrical components. Through laboratory testing, Downer [6] provided empirical evidence of a correlation between pole static strength and modal damping ratios as well as the ratio of measured fundamental natural frequency to that predicted by a finite element model. This study involved experimental modal analysis of fourteen full-scale timber utility poles, however the testing was performed with the poles clamped in a rigid fixture to simulate groundline support rather than in-situ. Furthermore, the poles were oriented horizontally and did not support any electrical infrastructure. Using a similar laboratory setup with idealized boundary conditions, González de Paz et al. [7] measured natural frequencies of six full-scale timber distribution poles using impulse hammer testing. Natural frequencies calculated by an analytical model for tapered bars were found to exhibit greater prediction errors for poles with unspecified deterioration than for structurally sound poles. Lastly, Jalali [8] empirically demonstrated the effect of conductors on the dynamic response of timber distribution poles by comparing Frequency Response Functions (FRFs) acquired from two poles with and without the conductors being supported by the pole. The measurements reflected that the presence of the conductors led to decreases in natural frequencies, increases in modal damping, and generally less apparent resonance frequencies in the FRFs.

Full-scale experimental modal analysis has been performed for monopole distribution and transmission structures constructed of materials other than wood. Dai et al. [9] experimentally obtained natural frequency and mode shape estimates for a tapered concrete monopole transmission structure partially embedded in soil as well as suspended in the air. This testing was performed while no electrical infrastructure was supported by the pole, so effects of these components on the dynamic response were not reflected. However, finite element analyses of the pole in two configurations confirmed that strong model correlation for the modal parameters could be obtained when the soil-structure interaction was be modeled with only linear elastic springs. Chen and Dai [10] conducted experimental modal analysis on two in-service monopole transmission poles, one constructed of steel and one constructed of prestressed concrete. Both poles were partially embedded in soil and featured arms, insulators, and multiple supported transmission lines. Several guy wires provided additional structural support to the steel transmission pole. The authors noted significant differences in the FRFs obtained using a roving impulse hammer technique applied to both poles, with clear indications of resonance frequencies in the measurements acquired for the prestressed concrete pole and only one mode identified from the measurements acquired from the steel pole. The authors attributed the challenge in experimental modal analysis of the steel pole to coupling of the dynamic response of the pole with the conductors and guy wires. For the prestressed concrete pole, the authors demonstrated the application of a numerical model to account for coupling of the pole with the transmission line dynamic response.

In this paper, an experimental test program aimed at developing an understanding of the influence of electrical components and supports on the modal parameters and dynamic response of timber distribution poles is introduced. Experimental modal parameter estimates are presented for a subset of the configurations included in the experimental test program. Finite element analyses are also presented to provide insight into how specific supported components affect the modal parameters of the pole.

Description of experimental study

The experimental program was conducted on a full-scale, de-energized, timber distribution pole located within a lineman training facility. In contrast to prior laboratory test programs, the pole was installed in service conditions with direct embedment in soil consistent with field practice. This setting provided a unique opportunity to investigate the modal properties of a timber distribution pole with realistic boundary conditions, attachments, and supports. Figure 1 presents photographs of the pole specimen that serves as the focus of this paper. The pole was Southern Yellow Pine. It had a total length of 12.19 m and, since the portion extending above the groundline was measured at 10.10 m in length, the depth of embedment was 2.09 m. The circumference of the pole at an elevation of 0.30 m from the ground line was measured with a flexible tape measure to be 88.9 cm, while the circumference at an elevation of 1.83 m from the ground line was measured to be 87.6 cm. The test specimen included the full complement of electrical infrastructure typically found on an energized distribution line. These attachments consisted of a mounted transformer, a street light, a crossarm assembly with tie top line post insulators, three phase conductors, a neutral line, and a secondary line. In addition, a service tap line was present to replicate in-field loading conditions. In addition to the supported electrical infrastructure, two guy wires were also installed on the pole to provide restraint in two directions. The presence of these attachments produced complex mass, stiffness, and damping contributions, thereby offering an opportunity to assess the influence of electrical infrastructure, ancillary hardware, and structural supports on the global dynamic response of the pole.

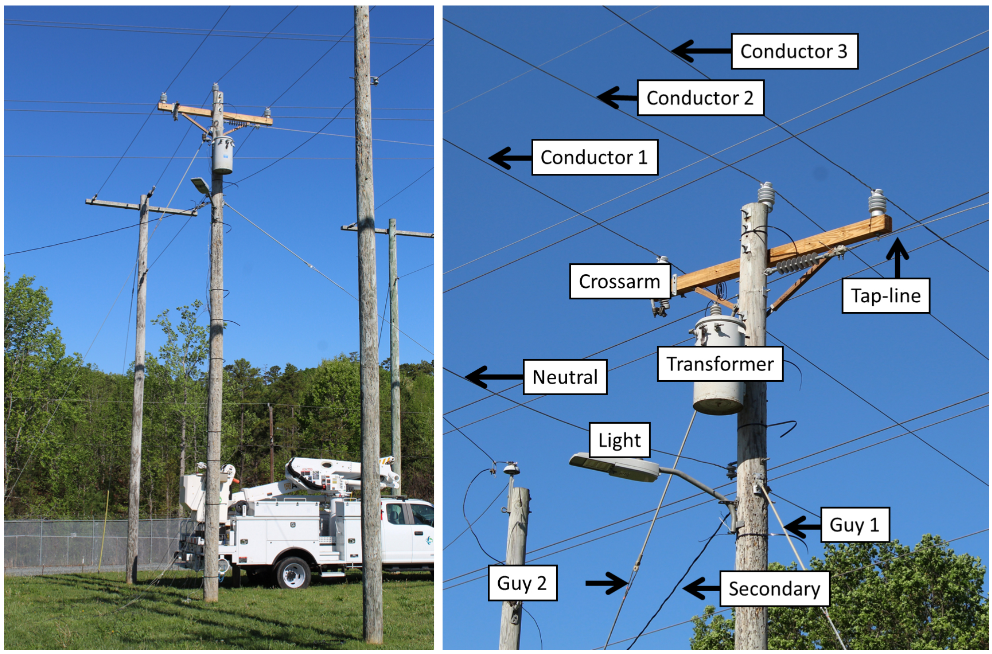

Fig. 1 Photographs of instrumented distribution pole and all of the electrical components and supports included in the test program

Identifying the effect of individual components on the dynamic response of the pole would be plagued by uniqueness challenges if limited to using only measurements acquired from the fully configured state. Consequently, experimental modal analyses were conducted for 15 distinct configurations of the pole that were created by removing and selectively reinstalling different electrical components and structural supports. Table 1 provides a summary of the components present for each of the 15 configurations under which the experimental modal analysis was performed. In this table, a cell filled with gray indicates that the component was present for the corresponding configuration. The first configuration represented the in-service condition with all attachments present, including the crossarm, conductors, neutral line, secondary line, tap line, light, transformer, and guy wires. The final configuration resulted in a free-standing pole embedded in the soil with all attachments removed. Since components were removed or added one at a time, the progression of configurations provided a structured basis for isolating the effects of individual attachments on the global dynamic response. In the exploration of the experimental test data, the final configuration is first investigated, since it corresponds to the simplest case and one that most closely replicates conditions assumed by existing analytical models for predicting the natural frequencies and mode shapes of utility poles.

The experimental modal analyses of the pole were performed using a stationary array of accelerometers and impulse excitation applied at elevations within reach from the ground. This test setup was selected for two reasons. First, a roving hammer approach would be time consuming to perform since it would require repeatedly positioning an individual at different elevated positions to apply the impulse excitations. Second, vibration-based nondestructive evaluation techniques for condition assessment of timber distribution poles typically rely on excitation applied by personnel on the ground, since that is convenient, time efficient, and safer with respect to electrical hazards. A total of 16 PCB Piezotronics J320C33 uniaxial accelerometers were installed along the exposed height of the pole in orthogonally oriented pairs at 1.37 m intervals. The lowest pair was positioned 0.46 m above the ground line, with the remaining sensors continuing upward to the top of the pole. Figure 2 depicts the location of the accelerometers on the pole, as well as the location and orientation of the supported electrical components. The accelerometer layout permitted the acquisition of the lateral dynamic response in both principal bending directions, while providing sufficient spatial resolution to resolve higher-order mode shapes. These accelerometers provide a nominal sensitivity of 100 mV/g, a measurement range of ±50 g, and a frequency response extending from 0.5 Hz to 10 kHz. Sensors were securely mounted using a 3D printed bracket and large cable ties, with cable runs secured to minimize extraneous vibration.

Table 1 Summary of different configurations of the pole under which experimental modal analysis was performed

Component	Configuration														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Crossarm	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Conductor 1	✓	✓	✓	✓	✓							✓	✓	✓	
Conductor 2	✓	✓	✓	✓							✓	✓			
Conductor 3	✓	✓	✓	✓	✓							✓	✓		
Neutral	✓	✓	✓	✓	✓	✓	✓								
Secondary	✓	✓	✓	✓	✓	✓	✓	✓							
Tap-line	✓	✓													
Light	✓	✓	✓		✓	✓	✓	✓	✓						
Transformer	✓	✓	✓	✓	✓	✓									
Guy 1	✓	✓	✓												
Guy 2	✓														

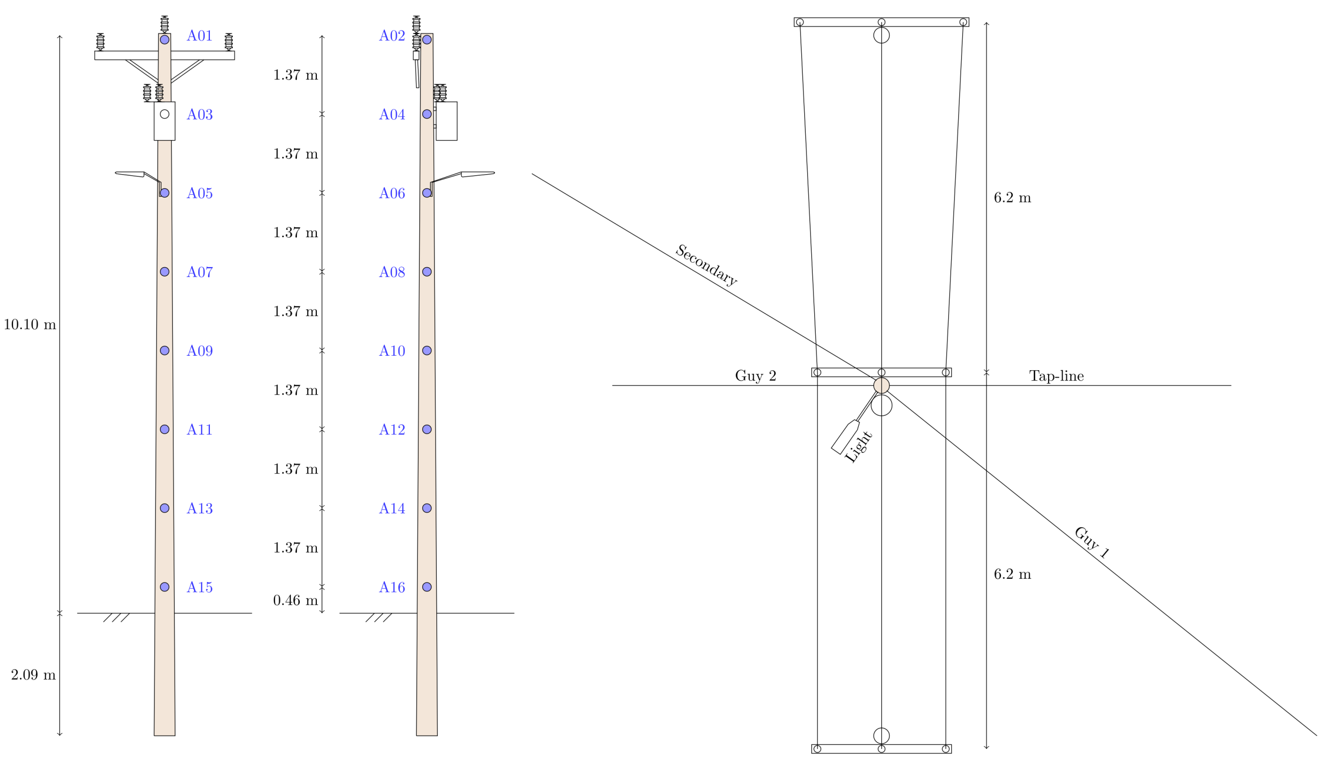

Fig. 2 Elevation and plan views of the pole configuration with locations of accelerometers denoted

The pole was excited using an PCB Piezotronics model 086D20 impulse hammer with a dynamic force transducer integrated in the hammer head. The hammer mass was 1.1 kg and the super soft (gray) tip was used during the testing to concentrate the energy from the excitation into the frequency bandwidth below 100 Hz. Impulse excitations were applied at elevations of 1.22 m (4 ft) and 1.83 m (6 ft) above the groundline in the two orthogonal directions corresponding to the positioning of the accelerometers. At each location and orientation, five impulses were applied to provide a basis for averaging in the development of FRFs. The hammer force and accelerometer response data were acquired using National Instruments PXIe-4497 sound and vibration modules. These modules provide the Integrated Electronic Piezo-Electric (IEPE) signal conditioning for the accelerometers and the load cell integrated into the impulse hammer, as well as anti-alias low-pass filtering and 24-bit simultaneous sampling. An analog reference trigger was established using the signal from the impulse hammer such that the rising edge of the excitation signal was aligned for all recorded data with the same number of pretrigger samples. A sampling rate of 3200 Hz and duration of 4 seconds was used to acquire time histories for each impulse.

Following preprocessing of the measurement data to apply sensitivities provided by manufacturer calibration of the sensors, remove offsets, and window the force measurement to suppress any noise in the signal following the impulse, FRFs were computed using the classical H1 estimator. Impulse responses were then computed by the inverse fast Fourier transform of the FRFs. System identification was performed for each of the configurations using the Eigenvalue Realization Algorithm [11]. Modal parameter estimates obtained for each of the four impulse locations were extracted for multiple model orders after applying stabilization criteria on the undamped natural frequency, damping ratios, and complex mode shape estimates. Final modal parameter estimates for each configuration were then obtained by averaging estimates obtained for each impulse location after matching modes with Modal Assurance Criteria values greater than 0.95 and scaling the consistent modes with the Modal Scale Factor.

Results

The final configuration included in the experimental test program produced data to characterize the simplest case of a free-standing pole with typical soil embedment but no supported electrical components or guy wires. Figure 3 presents the experimental modal parameter estimates obtained for this configuration. The mode shape estimates shown in this figure depict only the exposed region of the pole, since no sensors were placed below the ground line. The modal parameter estimates reflect a lightly damped response characterized by nearly identical flexural modes in each direction. The undamped natural frequencies of the pole were found to be slightly different for the two axes of flexure. This could be the result of differences in material and geometric properties of the cross section, since the cross section of a pole is not perfectly round, wood is not homogeneous material, and holes were drilled in the pole for different attachments. Differences in soil stiffness in each direction of flexure may also contribute to the variation in undamped natural frequencies between the principal axes.

The second simplest configuration included in the test program introduced the crossarm to the pole. This crossarm was dimensional lumber of 2.44 m in length and a 15 cm x 10 cm cross section. Two tie top line post insulators were

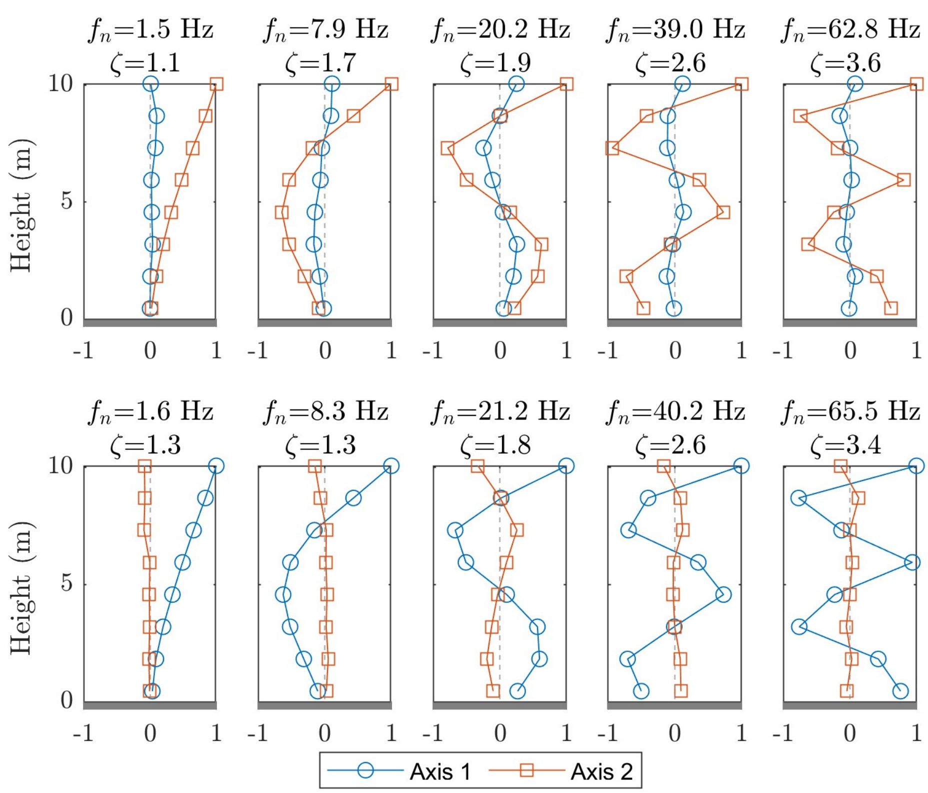

Fig. 3 Experimental modal parameter estimates for free-standing pole with no attachments (Configuration 15)

also installed on the crossarm during the testing, but the conductors were not attached to the crossarm for this particular configuration. Figure 4 presents the average of the mobility FRFs obtained for impulses applied at the 1.83 m elevation for this configuration alongside those obtained for the testing performed on the free-standing pole. While resonance frequencies are observed to decrease as a result of the additional mass introduced by the crossarm, the changes in the FRFs due to the presence of the crossarm reflect greater influence than just the mass. Additional resonance frequencies appear in the FRFs for both directions, indicating a coupling of structural modes of the crossarm with the modes of the pole within the frequency bandwidth of interest. Figure 5 presents the experimentally estimated modal parameter estimates for the pole with the crossarm. The results confirm the presence of additional modes within the bandwidth of interest and show visible differences in the mode shapes that were estimated for the freestanding pole configuration, even for the lower-order flexural modes. Changes in natural frequencies were generally greater for the modes exhibiting flexure about axis 1 than those exhibiting flexure about axis 2. However, modal damping does not appear to be significantly affected by the presence of the crossarm. One exception is the damping ratio estimate for the fundamental mode associated with flexure about axis 1. However, system identification of this mode shape was particularly challenging and, as a result, far fewer stable poles were included in the averaging that led to the final estimate.

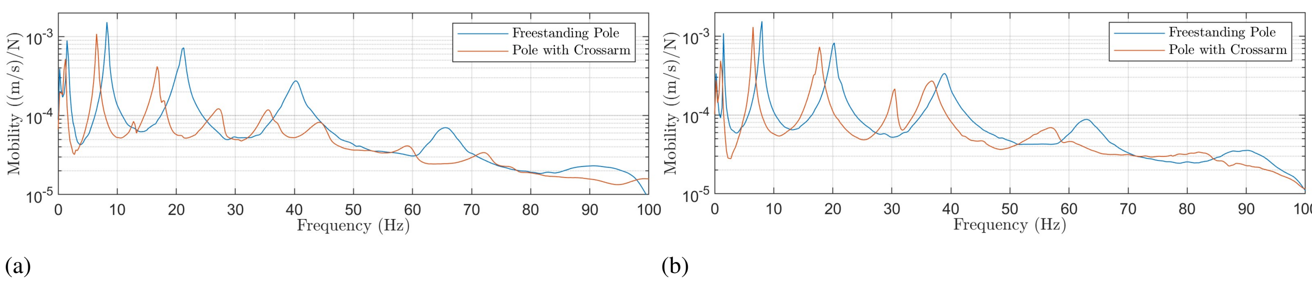

Fig. 4 Comparison of the average mobility FRF for Configurations 10 and 15: a) axis 1 and b) axis 2

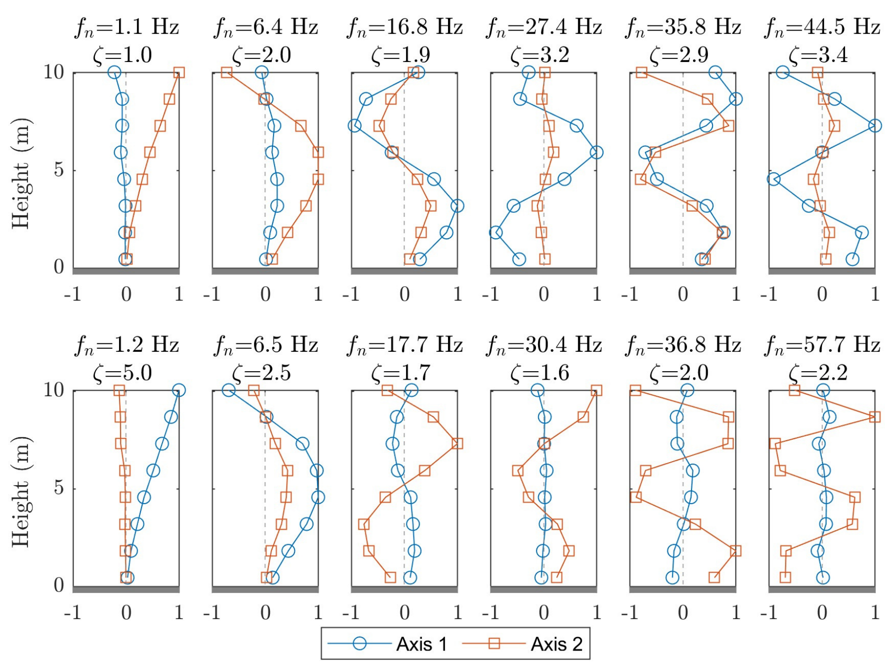

Fig. 5 Experimental modal parameter estimates for pole with crossarm (Configuration 10)

The experimental modal parameter estimates provide clear evidence that the presence of the crossarm has a significant effect on the modal parameters of the pole. To provide greater insight into the nature of the effect, a complementary numerical study was conducted to examine how the introduction of a crossarm affects the natural frequencies and mode shapes of a typical timber distribution pole. First, a finite element model of the free-standing pole configuration was developed. The finite element model used Timoshenko frame elements to model the pole, with axial, shear, flexural, and torsional stiffnesses calculated using assumed orthotropic properties for the timber. The tapered geometry of the pole was approximated by decreasing the diameter used to calculate the section properties in a piecewise constant manner along the length of the pole. Soil-structure interaction was modeled using linear elastic springs along the embedded portion of the length, with the stiffness of the springs increasing linearly with depth. Since the purpose of the model was simply to provide additional insight into the experimentally observed changes in modal parameters, the model was constructed with assumed material properties and no effort was made to calibrate uncertain parameters in the model. A second finite element model was created by extending this model to include a crossarm located at the same height as the crossarm in the experimental test. This crossarm was modeled with Timoshenko frame elements and connected to the elements representing the pole with a shared node. However, to approximate the single through bolt connecting the crossarm to the pole, the rotational degree of freedom associated with rotation of the crossarm about an axis running normal to the surface of the pole was not shared. The braces supporting the crossarm were modeled with truss elements. Furthermore, the post insulators on the crossarm were represented as point masses in the model.

Linear eigenanalysis was conducted for each model to arrive at predictions for the undamped natural frequencies and mode shapes for each configuration. Figure 6 presents the results for the model of the free-standing pole partially embedded in soil with no supported electrical components or supports. The predictions correlate strongly with the experimental estimates obtained for this configuration, which supports the plausibility of the finite element model. Figure 7 presents the natural frequencies and mode shapes predicted using the second finite element model that included the crossarm and crossarm bracing in the model. Consistent with the experimental observations, the results confirm that the crossarm not only reduces the natural frequencies and introduces changes in the mode shapes, but also produces new mode shapes that interrupt the classical progression of modes compared to the free-standing case. The finite element analysis reveals that the dynamics of the crossarm are coupled to the dynamics of the pole. This is particularly apparent in the mode shapes predicted by the finite element analysis at 36.0 Hz and 42.9 Hz. These results indicate that physics-based models for predicting the natural frequencies and mode shapes of timber distribution poles should neither neglect the crossarm nor rely on simplified representation of it, such as treating it as a point mass.

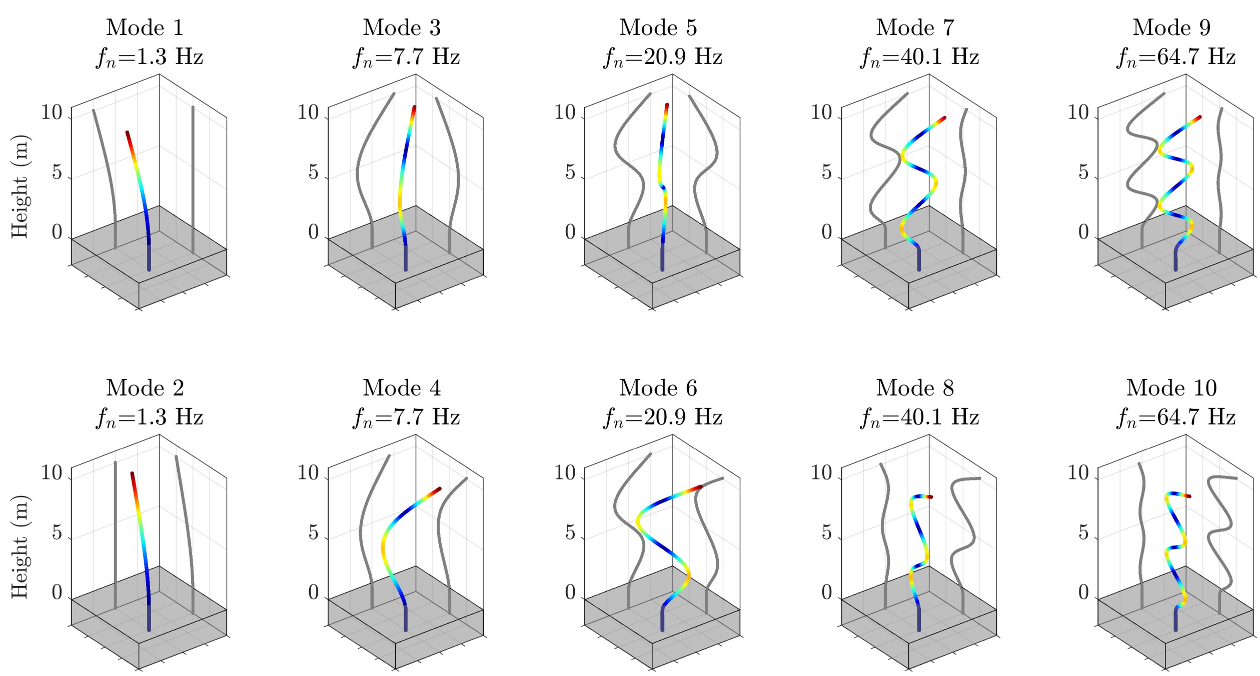

Fig. 6 Modal parameters predicted by finite element model of free-standing pole with no attachments (Configuration 15)

Figure 8 provides some early insight into the effect and relative significance of several additional components on the dynamic response. This figure presents the average mobility FRFs measured for impulse excitation at the 1.83 m elevation in each direction for different configurations involving the crossarm, light, secondary and tap lines, and the transformer. Since these components were added sequentially, their relative influence can be directly inferred through the changes reflected in the average mobility FRF for each configuration. The addition of the light has only a minor influence on the response that is reflected by a small decrease in the resonance frequencies. However, no evidence of coupled modal response of the light with the dynamics of the pole is observed in the measurement. The addition of the service and tap lines has no notable effect on the average mobility FRF for either direction. However, the introduction of the transformer to the pole resulted in significant changes in FRFs. Similar to the addition of the crossarm, it appears that the presence of the transformer results in coupled dynamics that introduce additional modes within the frequency bandwidth of interest. The effect of the transformer appears to be significantly more pronounced in one direction of response than the other. Future papers will provide greater insight into the influence of these and other electrical components and supports on the modal parameters of timber distribution poles.

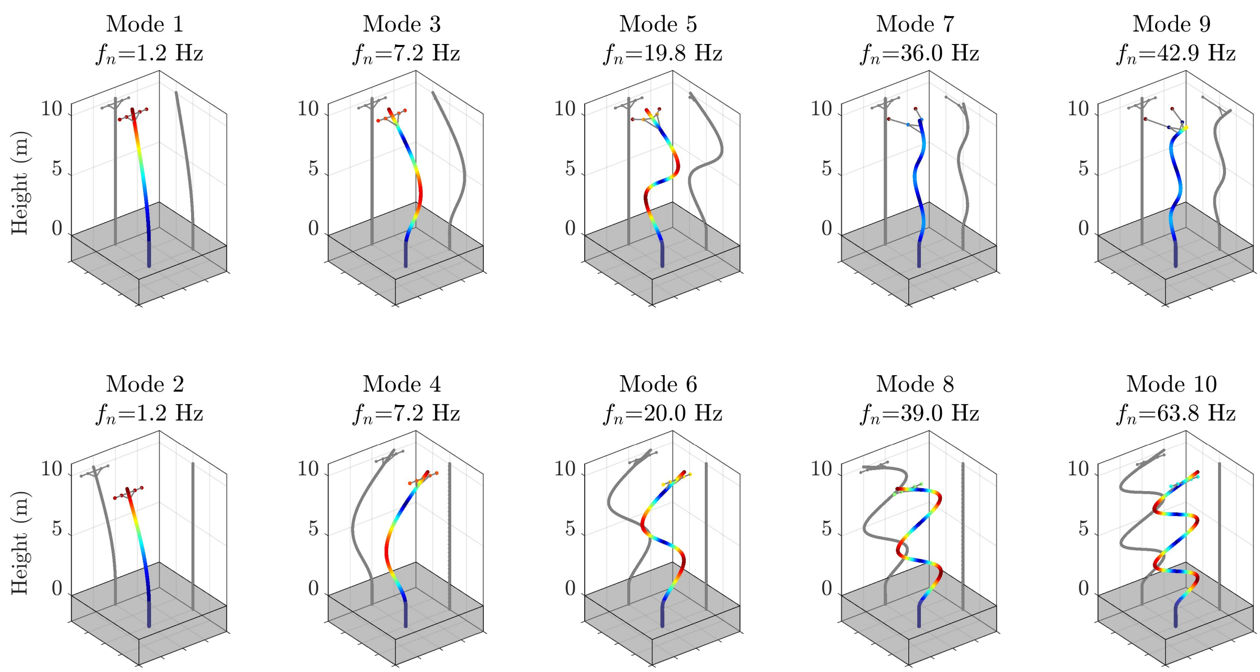

Fig. 7 Modal parameters predicted by finite element model of pole with crossarm (Configuration 10)

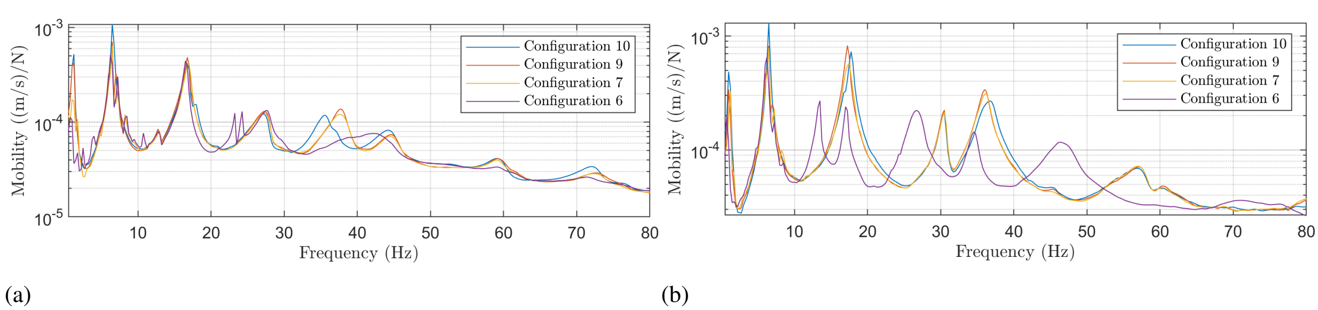

Fig. 8 Comparison of the average mobility FRF for additional configurations: a) axis 1 and b) axis 2

Conclusion

An experimental test program involving a structured basis for investigating how supported electrical components and structural supports influence the dynamic response of timber distribution poles was presented. By progressing from the fully configured in-service condition to a free-standing pole with no attachments, it was possible to isolate the effects of individual components and to observe how their removal or reintroduction altered the modal characteristics of the structure. The results demonstrated that even the introduction of a single attachment, specifically a crossarm, can have a pronounced effect on the modal response. Coupled dynamic response of the crossarm with the pole led to reductions in natural frequencies, distortions in the measured mode shapes, and additional modes within the frequency bandwidth of interest. Complementary finite element analyses confirmed the experimental observations and provided greater insight into the influence of the crossarm on the modal parameters. The findings reinforce the importance of explicitly modeling the crossarm when developing predictive models for vibration-based condition assessment of in-service distribution poles. As additional electrical components and supports are introduced, the effects become more significant with further shifting of natural frequencies, increased damping, and additional coupling of component dynamic responses with the pole leading to additional resonance frequencies. These findings highlight the complex dynamic behavior of timber distribution poles, despite their seemingly simple structural form, and underscore the limitations of existing analytical models formulated with assumptions that neglect or simplify the presence of supported electrical components and supports. Future work will explore in greater depth the additional configurations included in the experimental program and extend the study to other in-service poles with various attachments and boundary conditions to further inform the development of physics-based models for condition assessment.

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