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Assessment of the long-term variation of modal properties and aerodynamic damping of a lattice tower

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SUMMARY:
This study investigates the dynamic behavior of a 50 m tall self-supporting lattice tower using long-term full-scale monitoring. Two years of acceleration, strain, temperature, and wind speed data are analyzed to identify natural frequencies, mode shapes, and damping ratios. The effects of environmental conditions on modal properties and aerodynamic damping are evaluated using simultaneous temperature and wind measurements. Results show that natural frequencies decrease with increasing ambient temperature. Damping ratios for the first four modes range from approximately 0.2% at low wind speeds to 0.6% at higher wind speeds. The increase in along-wind damping with wind speed is consistent with predictions from a quasi-steady-based formulation. These findings provide an important addition to the few available studies that investigate the dynamic properties of self-supporting lattice towers using full-scale data, thereby supporting improvements to design standards.

Keywords: Lattice tower, Full-scale monitoring, Aerodynamic damping, Operational modal analysis

1. INTRODUCTION

Lattice towers are critical infrastructure widely used to support electrical transmission lines, communication antennas, lighting systems, and other components. Their design under wind loading typically accounts for dynamic gust-buffeting response, which strongly depends on dynamic properties such as natural frequencies, damping ratios, and mode shapes. Inaccurate assumptions of these properties may lead to underestimation of wind-induced responses or overly conservative and uneconomical designs.

The existing literature on the dynamic properties of lattice towers based on full-scale monitoring is limited. While some studies have reported results from forced or ambient vibration measurements, they primarily focus on the fundamental bending mode and are often based on short-duration datasets. Furthermore, for lightweight and slender structures such as lattice towers, aerodynamic damping can significantly contribute to total damping, sometimes exceeding structural damping. However, its evaluation is largely restricted to wind tunnel studies due to the difficulty of acquiring simultaneous wind and structural response measurements in the field.

This study investigates the long-term variation of dynamic properties and aerodynamic damping of a 50 m high lattice tower using two years of vibration, wind speed, and temperature data. The time variation of the natural frequencies of the first four modes and the wind-speed dependency of the damping ratios of the first bending modes in orthogonal directions are examined. The results provide a valuable addition to the limited research on the dynamic properties of lattice towers through full-scale monitoring.

2. THE LATTICE TOWER AND ITS MONITORING SYSTEM

The monitored structure is a 50 m tall self-supporting lattice tower that supports telecommunication antennas. The tower has three legs and bracing made of steel hollow circular crosssection members connected by high-strength bolts. The distance between the three legs of the tower is 7.5 m at the base, tapering linearly to 2.3 m at a height of 40 m. The legs are vertical from a height of 40 m to the top of the tower.

The monitoring system consisted of triaxial accelerometers on one of the legs at 27 m and 50 m, strain gauges on the three legs and three diagonals at the base, temperature measurement for the outside environment, and an ultrasonic anemometer at the top of the tower. The sampling frequency is 100 Hz for the accelerometers, strain gauges, and temperature sensor, and 4 Hz for the anemometer. Detailed geometrical properties of the monitored structure and further information on the monitoring system can be found in Calotescu et al. (2025)

The monitoring system has registered simultaneous measurements of wind speed, temperature, and structural response data since March 2021. For the current study, about two years of data from July 2021 to June 2023 are used.

3. METHODS

The selected two years of data were divided into consecutive 1-hour segments. The mean wind speed, mean wind direction, and mean outside temperature were calculated for each 1-hour segment.

The system identification to obtain the natural frequencies, mode shapes, and modal damping ratios was done using the MACEC 3.4 Matlab toolbox for experimental and operational modal analysis (Reynders et al., 2014) with an additional script to process several 1-hr data segments at once. Initially, the acceleration data were processed by removing the low-frequency components using a fifth-order Chebyshev Type I highpass filter with a cutoff frequency of 0.5 Hz. For computational efficiency, the signals were resampled with a decimation factor of 5, resulting in a new sampling frequency of 20 Hz. To avoid aliasing while resampling the signal, a digital eighth-order low-pass Chebychev Type I filter with a cutoff frequency of 8 Hz was applied in both the forward and reverse directions to remove all phase distortion before resampling the data. Then, the data were processed using the reference-based covariance-driven stochastic subspace identification algorithm (SSI-cov/ref) to extract the modal properties. The half number of block rows in the correlation matrix is assigned a value $i = 100$. A model order ranging from 2 to 80 in increments of 2 is considered for the construction of the stabilization diagram. The modal properties, such as natural frequencies, modal damping ratios, and modal shapes, were extracted for the stable modes.

After analyzing all the consecutive data segments, outliers, defined as those that are more than 1.5 interquartile ranges above the upper quartile (75 %) or below the lower quartile (25 %), were removed from the obtained natural frequencies and damping ratios for each mode separately. The outliers in natural frequencies for each mode constituted less than 2% of the results for all 1-hour data segments in two years and less than 3.5% for the damping ratios.

4. RESULTS AND DISCUSSION

Fig. 1 shows the time evolution of the natural frequencies after removing outliers. The seasonal variability in the modal vibration frequencies can be observed. The natural frequencies appear to be higher during the winter months and lower during the summer months.

Since design against wind usually considers the first bending modes in the orthogonal direc-

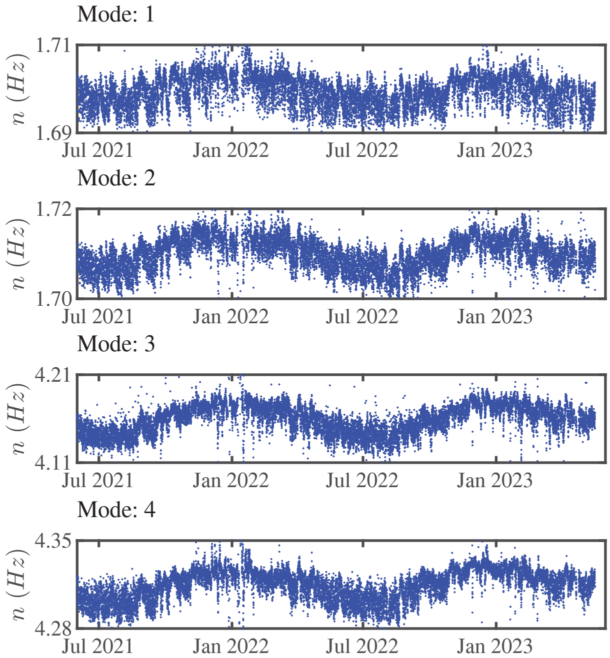

Figure 1. Natural frequencies

tions, the distribution of the total damping ratios of the first bending modes (Mode 1 and 2) has been studied by plotting a histogram, as shown in Fig. 2(a). The total damping ratios for both modes are less than 0.6 %. This value agrees closely with the recommendation for the structural damping ratio given in ASCE 7-05 (2005) (0.15 - 0.5%); however, the recommended structural damping ratio in Eurocode 1-1-4 (2005) (0.5%) appears to be on the higher end of the damping distribution in Fig. 2(a). From the histogram, it can also be observed that the recommended structural damping ratio in ISO 4354, 0.1%, is on the lower end of the distribution (ISO 4354, 2009).

Fig. 2(b) shows the total damping ratio obtained using the full-scale monitoring data in the alongwind and crosswind directions when the mean wind direction is along the principal bending axes of the structure, with a threshold of ±10°. The total damping in the alongwind direction, calculated as the sum of the aerodynamic damping from quasi-steady theory and structural damping, ξ_s, obtained from the full-scale vibration data, is also shown with a solid black line. A clear increase in the damping ratio with the mean wind speed can be observed for both modes. The modal damping ratio increases from approximately 0.2% at low wind speeds to 0.6% at higher wind speeds. In general, the total damping ratio increased with the mean wind speed, both in the alongwind and in the crosswind directions. The increasing trend of the alongwind damping obtained from the full-scale vibration is closely similar to the one obtained using the quasi-steady theory-based formulation.

5. CONCLUSIONS

The dynamic properties and aerodynamic damping of a 50 m tall self-supporting tower are studied using two years of continuous full-scale monitoring data. The dynamic properties were obtained by applying covariance-driven stochastic subspace identification. The results showed that the natural frequencies exhibit clear variation with temperature, increasing in the winter and decreasing in the summer. The damping ratios of the first bending modes in the orthogonal direction varied between 0.1 and 0.6 %. For the considered structure, Eurocode 1-1-4 (2005)

(a) Histogram of damping ratios

(b) Damping ratio as a function of wind speed

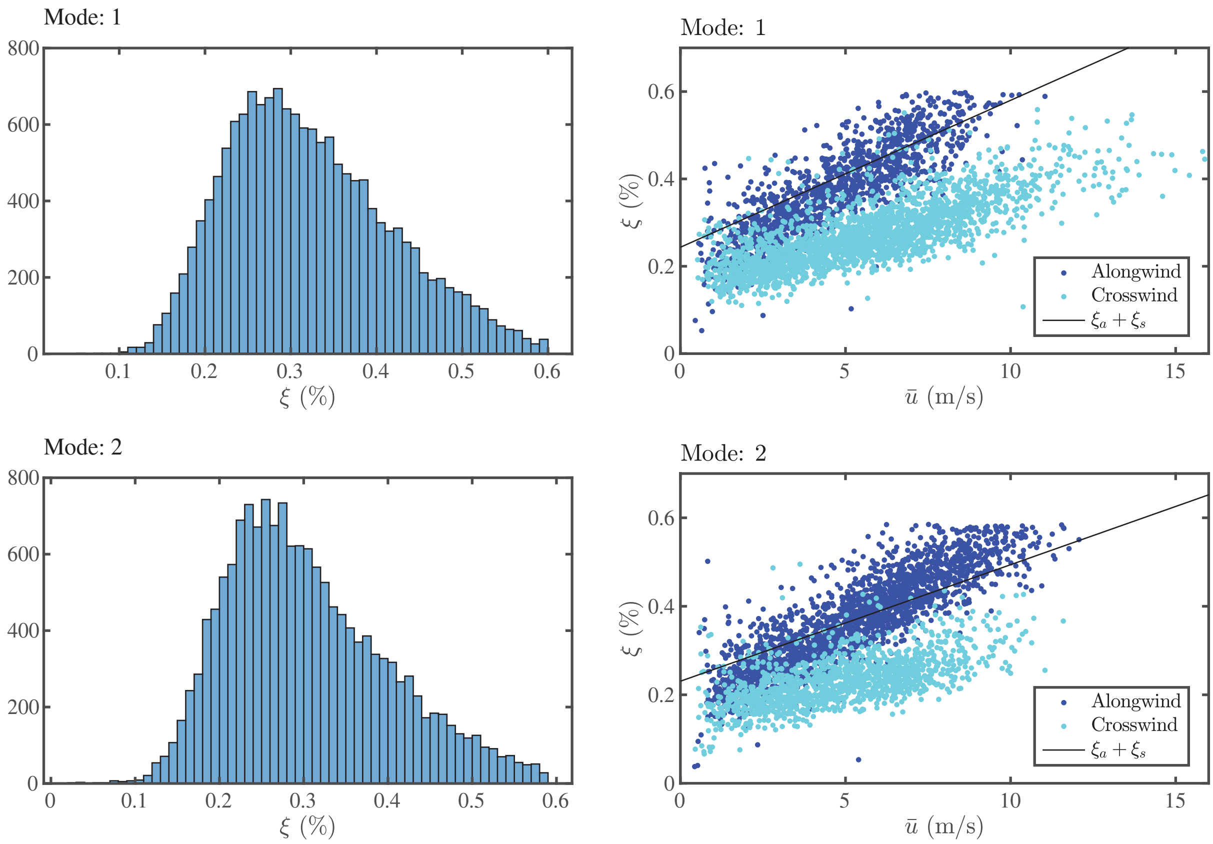

Figure 2. Damping ratios

recommendation of structural damping ratio is on the higher end of the damping ratio distribution obtained in this study. The increasing trend in the total damping ratio in the alongwind direction closely matched the one calculated using a quasi-steady theory-based formulation.

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