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High accuracy measurement of deflections of an electricity transmission line tower

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ABSTRACT

The displacements of the top of an H-type, 30 m-high lattice tower of a 150 kV electricity transmission line have been measured using a Robotic Total Station (RTS). Horizontal displacements approximately up to 30 mm and vertical up to 8 mm have been measured on a passive reflector set on the tower top during days with moderate wind. Measurements are reliable and above the noise level which is determined from measurements in a second reflector near the stable base of the tower. Displacements in the cross-wind direction were found larger than along the wind. Such measurements, probably the first to be made in a pylon, may be used to constrain models of their dynamics controlled by a very large number of unknown parameters.

1. Introduction

Measurement of deflections of various engineering structures subject to various loads, especially dynamic loads, has been a dream of structural engineers for centuries, at least since the first measurements of the deflections of Eiffel Tower in Paris in the 1880s [1]. Such measurements, however, became possible only during the last few decades with the advent of new geodetic instruments, GPS [2,3] and Robotic Total Stations (RTS, sometimes referred to as Robotic Theodolites) [4–6], as well as instruments such as tiltmeters [7], radar or microwave interferometers [8–10]. The main advantage of these instruments is that they allow the extraction of time series of deflections of measuring points relative to a stable (global) coordinate system above the threshold of a few millimeters to a few centimeters for relatively rapid oscillations (i.e. with a frequency lower than 5 Hz [11,12,6,13,14]. A second advantage of these instruments is that they can record quasi-static movements, including very long-period motions (<0.5 Hz; see [15]) which may be generated by wind loading [16], and which cannot be recorded by accelerometers.

The present paper is probably the first case of accurate measurements of dynamic deflections of the top of a lattice tower of a 150 kV electric transmission line using an RTS set on the ground at a distance of up to a few tens of meters from the tower (Fig. 1). These measurements are very unusual, and only rare reports of measurements of the response of existing towers in terms of accelerations exist (for example see [17,18]).This is mainly due to the fact that transmission lines are always on duty, and it is not easy to fix various types of electronic devices on them, while high electric and magnetic fields make measurements by various electronic sensors rather impossible. For this reason the dynamic characteristics of electricity transmission towers and of transmission lines are either predicted or estimated from models in wind-tunnel experiments [19–21].

The present study became possible because there was given the opportunity of a very rare service interval of the specific transmission line (once per ten years) which made possible to fix on the upper part of the tower a small optical reflector. This was a type of a prismatic (optical, passive) reflector which permits a very narrow angle coded signal emitted by the RTS falling onto the reflector to be passively reflected back to the RTS practically without loss of energy. The reflected signal is not sensitive to the electric and magnetic field around the cables, while the RTS is equipped with a target identification device and a servomechanism which permits to analyze the received signal, track the movements of the reflector and record its instantaneous coordinates in a pre-defined coordinate system (global system, independent of the study structure).

RTS has been successfully used in the past for monitoring various engineering structures with different measurement rates, low rates for slow deforming structures such as buildings above tunnels [22], and high rates for industrial chimneys [23] and even long- and short-span bridges excited by passing cars or

Abbreviations: RTS, Robotic Total Station; GPS, Global Positioning System.

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Fig. 1. An RTS roughly below the transmission line sighting to a reflector fixed on the upper part of the tower, marked by an arrow. A second arrow points to a second reflector (lower reflector, near the base of the tower), used to control the measurement noise.

pedestrians using RTS with sampling rates of the order of 5–7 Hz [6,14,24].

The aims of the present study are:

(a) to report for the first time directly measured displacements of the top of a lattice tower under wind loading by moderate wind for the studied area,
(b) to study the measured displacements in combination with the measured wind characteristics in the area and to compare the results with existing analytical studies,
(c) to extract possible periodic characteristics (oscillation frequencies) of the tower response,
(d) to evaluate the performance of the Robotic Total Station for the measurement of the 3-D deflections of a transmission line tower.

2. Characteristics of the tower, of the transmission line and of the terrain

The measured lattice tower is part of a 150 kV transmission-line crossing the Campus of the University of Patras, Greece, in a north-eastern direction (azimuth approximately 50°). The tower is approximately 27 m high, and is founded on a 10 m high hill. The tower top is located at an absolute elevation of 134 m above sea level. The studied tower is a truss structure made of L-shaped rod elements connected together with bolted joints. Five transmission-line cables are connected on it. Three transmission cables are connected via ~2 m long insulators hanging from the tower, while two lighting protection cables are connected on the top of the tower (Fig. 1). This type of tower is usually referred to as H-type.

The location of the tower is characterized by smooth relief and moderate wind. Since the tower is located in the University of Patras Campus it is characterized by a terrain category III (Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights, such as villages, suburban terrain, permanent forest, see paragraph 4.2 in [25]) corresponding to a roughness length factor z_0 equal to 0.3 m according to [25] (Eurocode 1 Part 1–4; Wind actions on structures).

3. Methodology

The intention of the study was to measure the instantaneous changes of the position of a reflector (and hence the oscillations of a selected point of the upper part of the tower) during periods of strong wind in three axes, along cable, across cable and vertical using an RTS set on stable ground and the passive reflector installed at the top of the tower. The RTS was setup on a tripod, on a point rather protected from the wind and from oscillations introducing noise to the pylon measurements. In addition, the instrument used in the present study is equipped with an automatic built-in control system aiming to interrupt the measurements if the instrument is subject to oscillations or tilting above a certain limit. During the field measurements the same instrument was used, installed on the same position, while during each session of measurements the wind direction remained practically constant (Table 1).

Field and experimental evidence [26,6,14] indicates that RTS can record oscillations with amplitude above a few mm and with frequency below 4 Hz, but its level of performance deteriorates in the case of atmospheric turbulence [6,14]. In order to confirm that results are reliable, a second reflector was fixed at a lower point of the tower not expected to oscillate during measurements (for details see paragraph 4). Since no significant oscillations of the second prism at the bottom the tower were expected, these measurements provide an estimate of the measurement noise (see Section 4 for details). Because the RTS can track only one point at the time, the overall strategy was to measure alternatively sessions of about 30 min long on the upper and lower reflectors, permitting to control the noise in measurements, as well as possible drifts of the instrument. This procedure permits to identify statistically significant (i.e. above the noise level) displacements at the top of the tower. Spectral analysis of the measured deflections in each axis is expected to permit to extract the dominant frequencies of deflections and constrain certain dynamic characteristics of the pylon in the framework of the transmission line. A last problem is that the high sampling rate of RTS is not stable, and this forces to adopt a special spectral analysis methodology. Details on the spectral analysis procedure are given in Section 5.3.

4. Field measurements

A few hours interval of interruption of the operation of the transmission line due to maintenance and development works, gave the opportunity to install close to the top of the study tower a high quality AGA super-type reflector (see Fig. 1 and paragraph 1). Measurements were made using a Leica 1201 Robotic Total Station (RTS), each time temporarily installed approximately 60 m from the tower. The RTS permits to obtain 3-D instantaneous coordinates of the reflector system with a nominal sampling rate of 10 Hz. Since the instrument experiences sampling rate instabilities, the real mean sampling rate was around 6–7 Hz and measured coordinates are not equally spaced in time (for details see [6,26]). The measured coordinates reflect oscillations of the specific part of the tower because of wind excitation, plus some measurement noise. The reflector coordinates are obtained in a Cartesian System with two horizontal axes, one parallel and one perpendicular to the line of sight of the RTS, and one vertical axis. During the measurements analyzed in the present study, the RTS was installed right