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Use of Terrestrial Laser Scanning for Measurements of Wind Power Stations***

Abstract: The continuous development of the technologies used in the construction of wind turbines makes them a promising and widely used source of energy. Wind turbines keep getting bigger, resulting in increases in their production capacity. However, both the wind turbines and their support structures are exposed to huge loads that cause the deformation of the rotor blades, vertical deflection, or vibration of the support structure and rotor blades. In this context, the issue of monitoring the technical condition of the structures of such facilities becomes important, particularly in terms of reliability and the service life of the whole system. This document shows a method of measuring a wind power station using the Leica P40 terrestrial laser scanner.

The object of the research was a few-years-old wind turbine located in the village of Kluczewsko (near Włoszczowa). The examined wind turbine is 35 m high measured to the turbine base and has rotor blades that are almost 13 m long. The measurements were performed at two stages: during turbine operation and with the wind turbine at rest. This enabled us to determine the changes in the geometry of the object at dynamic loads during the operation of the plant. Each series of measurements was made from three stations evenly arranged around the entire facility, which allowed for a full recording of the wind turbine geometry as well as of its supporting structure. The measurements taken at rest and during operation of the turbine were recorded on the basis of the same points of reference, which allowed us to obtain data on the same coordinate system. The measurements were used to determine the deflection of the turbine support from the vertical axis at rest and the change of deflection under wind pressure during the turbine's operation. The vibration amplitude of the turbine's support during operation was also determined. In addition, an attempt was made to determine any changes in the geometry of the rotor blades under wind pressure. The obtained results are presented in a tabular and graphical manner.

Keywords: laser scanning, determination of deformation, wind turbines

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1. Preface

The continuous development of the technologies used in the construction of wind turbines makes them a promising and widely used source of energy. This fact is best proven by publications of the Central Statistical Office of Poland (GUS) [1, 2]. Whereas the output of wind power plants was 124 GWh in 2003, it was as much as 1664 GWh in 2010, and in 2015 – a staggering 10,858 GWh (which amounted to 47.87% of the energy generated from renewable sources [RES]). According to the reports from the National Power System and Balancing Market [3], the share of wind power increased from 0.1% in September 2006 to about 8–10% during the winter of 2016–2017.

Wind turbines keep getting bigger to increase their production capacity. However, both the wind turbines and their support structures are exposed to huge loads, causing the deformation of the rotor blades, vertical deflection, or vibration of the support structure and rotor blades. This leads to failures, starting from malfunctions of the electrical wiring through the tearing off of the rotor blades to the destruction of the whole wind turbine structure. The number of accidents with bodily injury and property damage is growing along with the growth of the number of commissioned turbines. According to the authors of a publication in "The Telegraph," [4] over 5 years, there were 1500 accidents and incidents on UK wind farms alone. The report (updated on a current basis) is available on the "Caithness Windfarm Information Forum" website [5] and clearly shows an increase in the number of documented accidents and incidents related to wind turbines. The report also indicates that the majority of accidents are related to the failure of the rotor blades. Entire torn-off blades or their fragments have actually been found about 1.5 km from a wind turbine's location.

This raises the question of monitoring the technical condition of such facilities, particularly in the aspect of reliability and the service life of the entire system. The publications involve the examination of both the changes in the material structure of the wind turbine blades [6, 7] and the changes in their geometry. The majority of the available publications deal with the application of modal analysis in the diagnostics of turbine structures and supports [8, 9]. The latest publications deal with the application of remote measurement techniques in this area, such as laser interferometry [10], photogrammetry [11, 12], or a combination of the image recording and measurements made with terrestrial laser scanners [13].

The purpose of the research presented in this paper was to determine the scope of the geometrical information of a wind turbine that can be obtained using a single terrestrial laser scanner.

2. Examined Facility

The examined wind turbine (Fig. 1) is located in the village of Kluczewsko (Świętokrzyskie Province). It was built in 2010 and consists of a steel tubular tower, a nacelle with a generator, a set of rotor blades (3 pcs.), and electrical and hydraulic equipment for power generation and turbine control.

Fig. 1. Examined facility – wind turbine
(November 2016 – Kluczewsko, phot. P. Klapa)

Technical data of wind turbine:
- power: 225–250 kW,
- generator: asynchronous,
- number of generators: 2,
- generator power rating: 225 kW and 50 kW to 250 kW and 50 kW,
- tower height: 35.25 m,
- height to hub: 36.50 m,
- rotor diameter: 27.0 m,
- blade length: 12.75 m.

3. Experiment

The wind turbine measurements were performed using a Leica P40 laser scanner from three stations evenly distributed around the facility. The accuracy of the 3-D measurement of a single point for this scanner is ±3 mm by 50 m. The distance between the stations and the turbine was 35 m, which (at a hub height of 36.5 m) allowed us to avoid excessively sharp laser beam incidence angles on the measured surface. The measurements were performed at wind speeds of 3–4 m/s. The wind turbine scanning was performed at rest with immobile rotor blades and blocked nacelle rotation as well as also during the turbine operation.

In order to eliminate the external errors that may occur in the compilation while georeferencing the cloud, a local reference system was used. These errors are related to the minor control and accuracy of the measured value of their global coordinates by the GNSS-RTK method, identification of the control points on the point cloud, and adjustment of the cloud to the control points. The position of the first scanning station was adopted as the local system (Fig. 2).

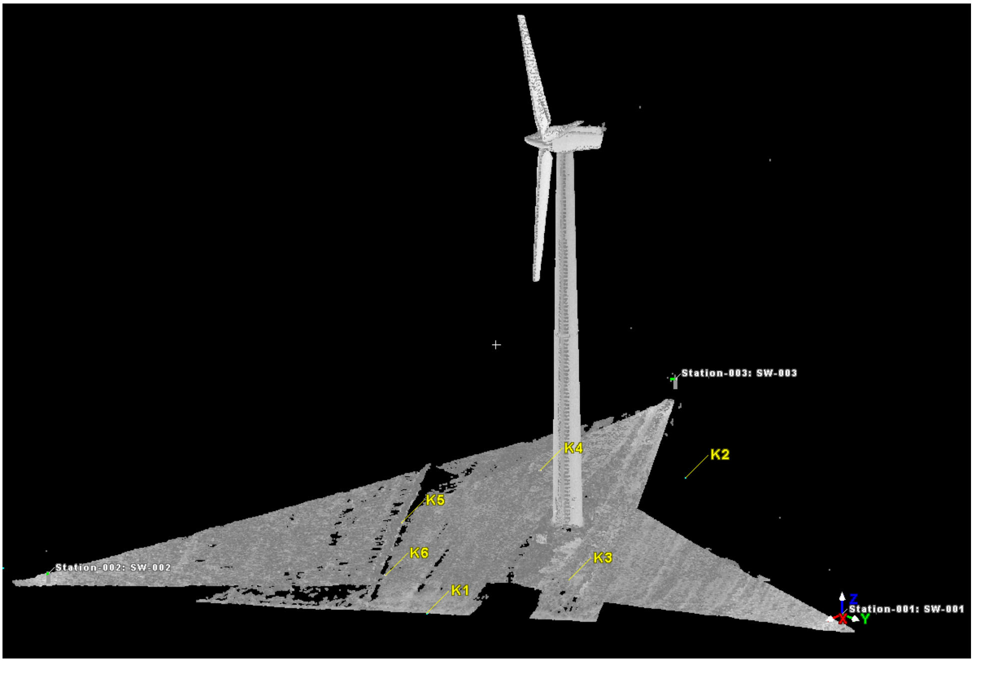


Fig. 2. Local coordinate system and deployment geometry of stations relative to object

Steel balls with a diameter of 150 mm were evenly placed around the facility and with fixed locations throughout the experiment and used to connect the individual scans and obtain a common coordinate system. The scanning angular resolution was chosen in such a manner as to obtain a point cloud from a single scan with 3 mm density at the nacelle level. This condition was satisfied by measuring the distance from the scanner to the chosen point on the facility and setting the horizontal and vertical intervals between the obtained points on this distance. The reference balls were scanned in two telescope positions with the 0.8 mm/10 m density, obtaining a mean absolute error (MAE) equal to 1 mm on the reference points after the orientation of the point clouds. The data was processed using Leica Cyclone 9.3.1 software in the areas of the orientation and filtration of the point clouds and Bentley MicroStation V8i software for the graphical representation and geometrical measurements.

4. Results

4.1. Examination of Tower Verticality

The point cloud allowed us to obtain the vertical axis of the wind turbine tower at rest (Fig. 3). The study indicated a maximum structure deflection of 0.195 m on the XZ plane and 0.155 m on the YZ plane, which corresponds to a 0.25 m deflection from the vertical line in the XY position at the highest point of the tower (greatest deflection).

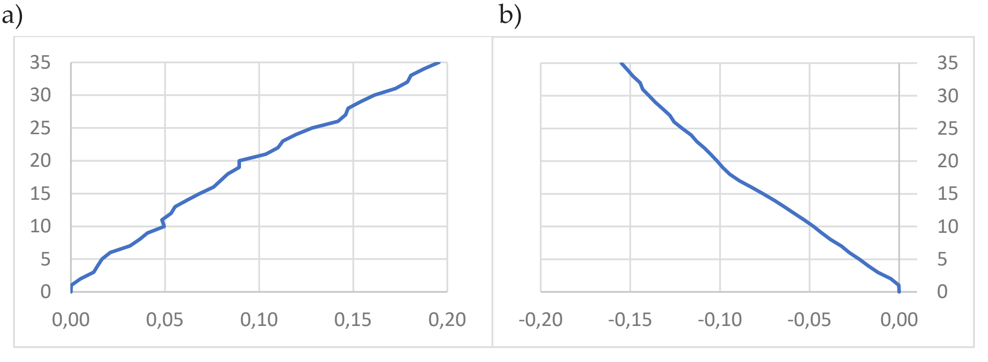


Fig. 3. Tower vertical axis deflection at rest: a) on XZ plane; b) on YZ plane

A comparison of the data obtained at rest and during the operation of the wind turbine allowed us to determine the tower deformation caused by wind pressure during operation. Figure 4 shows the deformation at selected cross sections towards the direction of the wind.

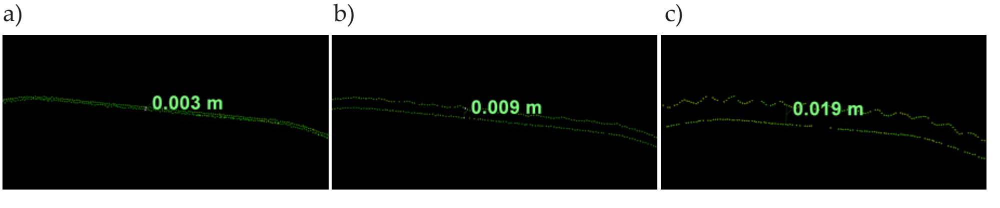


Fig. 4. Tower deformation under wind pressure at heights of 10 m (a), 20 m (b), and 30 m (c) during operation

In addition, the recording of the tower in the point cloud form allowed us to determine the type of structure vibration as well as the vibration amplitude and peak-to-peak values during the turbine operation (Fig. 5). At a wind speed of 3–4 m/s, the vibration amplitude recorded at the top of the tower was 3 mm. However, due to the absence of timestamps for the individual terrestrial scanner pulses, it was not possible to precisely determine the vibration frequency.

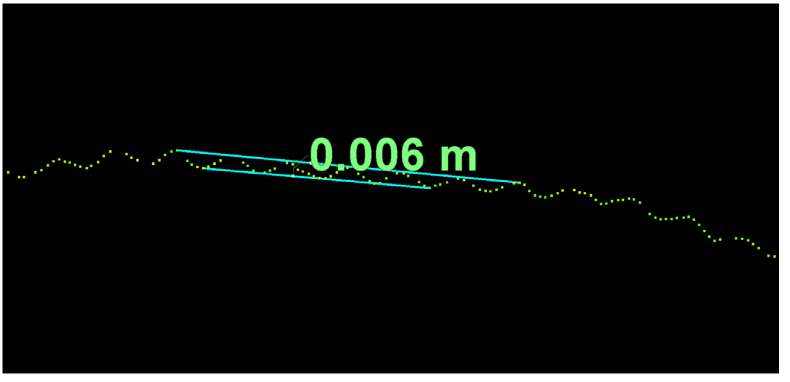


Fig. 5. Tower vibration during operation. Vibration peak-to-peak value

4.2. Measurement of Wind Turbine Blades

The measurements made from three stations evenly spaced around the wind turbine allowed us to principally record the full geometry of the rotor blades (Fig. 6), which in turn allowed us to make our analyses in terms of the permanent deformations of the individual blades.

a) b) c)

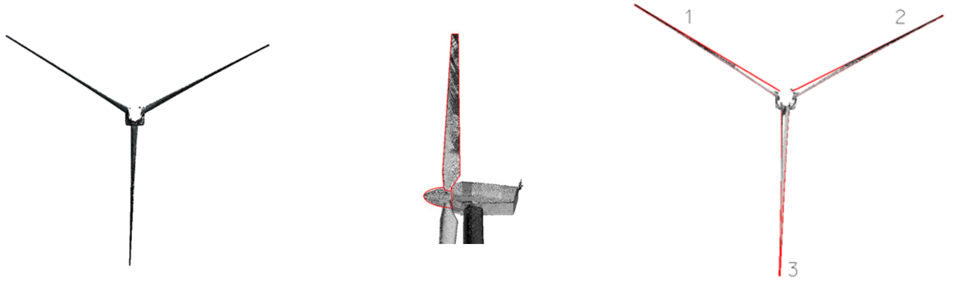
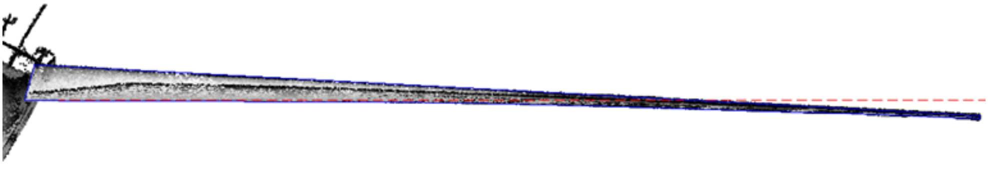


Fig. 6. Point cloud with vector elements recorded for wind turbine blades: a) front view; b) lateral view; c) vector contour and numbering

Figure 7 presents the variability of the blade front profile relative to a straight line. If the turbine design documentation is available, it will be possible to verify the as-is state vs the design state and check whether the recorded geometry variations are within the acceptable limits determined by the manufacturer.

a)



b)

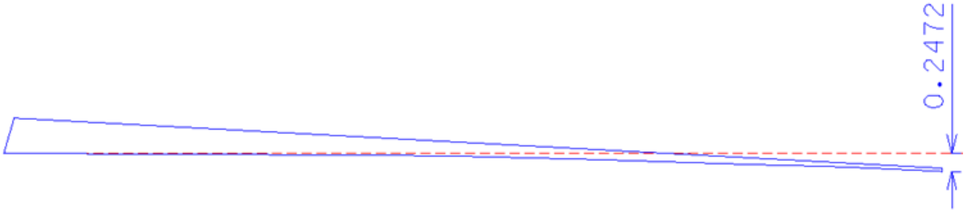


Fig. 7. Variability of blade front profile relative to straight line: a) fragment of point cloud – Blade 2; b) blade section and comparison with straight line

The measurements of all three blades indicated a significant difference between the rectilinearity deviations for Blade 3 and the deviation of Blades 1 and 2 (Tab. 1).

Table 1. Blade rectilinearity deviation

Blade no.	Blade 1	Blade 2	Blade 3
Deviation [m]	0.293	0.247	0.156

The obtained data also allowed for a comparison of the actual angle between the blades with the theoretical value of 120°. Figure 8 presents the obtained angular discrepancies between the theoretical distribution and the measured values. The reference axis in this case was the axis of Blade 3, which is approximately vertical.

The point clouds obtained during the wind turbine operation also show vibrations in the blades; however, at a wind speed of 4 m/s, the vibration peak-to peak value approached 3 mm (an amplitude of 1.5 mm), which corresponds to the accuracy of determining a 3D point at a scanning distance of 50 m. This means that, although vibrations are observable, their values are within the measurement noise.

In addition, the analysis of the point clouds obtained during the wind turbine operation allowed us to determine the inclination angle of the blade rotation planes relative to a vertical line.

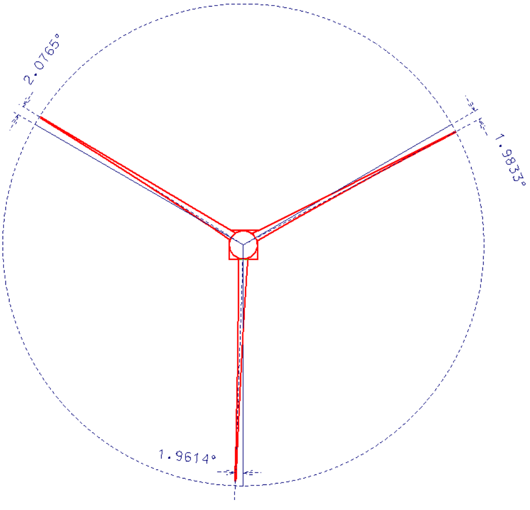


Fig. 8. Distribution of rotor blades relative to theoretical values – angular deflection

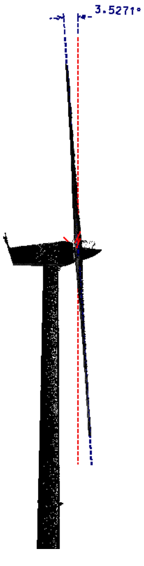


Fig. 9. Inclination angle of blade rotation planes relative to vertical line during operation

5. Conclusions

The measurements and data indicate that, by using a single laser scanner, it is possible to obtain a lot of significant information on both the geometry of a wind turbine at rest and its behavior during operation.

The measurements were used to determine the basic dimensions of the examined facility, deflection of the vertical axis of support at rest, and blade geometry. The measurements taken during the wind turbine operation allowed us to determine the tower's deformation under wind pressure as well as the tower vibration amplitude. It was also possible to determine the inclination angle of the blade rotation planes relative to a vertical line during operation; however, due to the small amplitude of this vibration, it was not possible to determine its value in a reliable manner. In addition, the locations of individual scan lines on the blades in motion were not identified; as a result, it was not possible to compare the blades' geometry at rest and under load during wind turbine operation.

The authors claim that, if it is possible to obtain information on the time of acquisition of each pulse (a so-called "timestamp") in a manner analogous to the measurements made with aerial laser scanning, the potential for analyzing the dynamic behavior of the wind turbine structures will be significantly broadened.

One should also emphasize the advantage over traditional land surveying measurements; i.e., tachymetry or angular measurements using a theodolite in the stock taking of moving objects. Tools such as laser scanners allow us to record the movement of objects in some way and present them as a point cloud. This enables us to determine the parameters that define the displacement vectors of the individual structural elements and also allows us to record the variable position of a moving object during our measurements.

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Zastosowanie naziemnego skaningu laserowego w pomiarach elektrowni wiatrowych

Streszczenie: Ciągły rozwój technologii stosowanych w budowie turbin wiatrowych sprawia, że jest to coraz bardziej obiecujące i powszechniej występujące źródło energii. Budowane są coraz większe elektrownie wiatrowe umożliwiające zwiększenie zdolności produkcyjnych. Jednakże zarówno turbiny wiatrowe, jak i ich konstrukcje nośne narażone są na wysokie obciążenia powodujące odkształcenia łopatek wirnika, wychylenia od pionu czy też drgania konstrukcji nośnej. Pojawia się więc zagadnienie monitoringu stanu technicznego konstrukcji tego typu obiektów, szczególnie istotne w aspekcie niezawodności i czasu żywotności całego systemu. W niniejszym artykule przedstawiono sposób pomiaru elektrowni wiatrowej przy użyciu naziemnego skanera laserowego Leica P40.
Obiektem badawczym była kilkuletnia elektrownia wiatrowa, znajdująca się w miejscowości Kluczewsko niedaleko Włoszczowy. Badana elektrownia wiatrowa jest obiektem o wysokości 35 m mierzonej od podstawy turbiny i długości łopat wirnika wynoszącej prawie 13 m. Pomiary wykonano przy dwóch stanach elektrowni: w trakcie pracy turbiny i w stanie spoczynku, co umożliwiło określenie zmian geometrii obiektu przy obciążeniu dynamicznym w trakcie pracy elektrowni. Każda z serii pomiarowych została wykonana z trzech stanowisk rozmieszczonych równomiernie wokół całego obiektu, co pozwoliło na pełną rejestrację geometrii turbiny wiatrowej, jak również konstrukcji jej podpory. Pomiary turbiny w stanie spoczynku i w trakcie jej pracy zostały przeprowadzone z wykorzystaniem tych samych punktów nawiązania, co pozwoliło uzyskać dane w jednolitym układzie współrzędnych.
Na podstawie wykonanych pomiarów określono wychylenie od pionu podpory turbiny w stanie spoczynku oraz zmianę tego wychylenia pod naporem wiatru podczas pracujący turbiny. Wyznaczono również amplitudę drgań podpory w czasie pracy turbiny oraz przeprowadzono próbę określenia zmian geometrii łopat turbiny pod naporem wiatru.
Uzyskane wyniki zostały przedstawione w sposób tabelaryczny i graficzny.

Słowa kluczowe: skaning laserowy, odkształcenia, elektrownie wiatrowe