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Remote monitoring system for an onshore steel wind turbine

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Abstract

The paper presents a monitoring system applied to an existing steel tubular wind tower located in Italy, having almost 45 meters of total height. The monitoring system was comprised by strain-gauges and thermal couples, mounted on the tower shell at 21 meters of height, and few accelerometers, located along the tower's height. The monitor system was used for two main reasons: i) to understand the nature of the resonance problem experienced by the tower and ii) to evaluate the effective stresses distribution on the shell with different rotor velocities. Finally, a debate about the extension of the life of the wind tower is proposed.

Keywords

Steel wind Turbine, Fatigue, Resonance, Structural health monitoring

1 Introduction

The extensive use of fuel of the last century led the new generation into a deep energetic crisis. Climate change and environmental degradation are a huge threat to Europe and worldwide. To overcome these challenges, the European Green Deal was developed with the main aim to promote the efficient use of resources by moving towards a clean and circular economy [1-3]. Moreover, the events happened along the last years (lockdown due to COVID19, Russia-Ukraine war, etc.…) highlighted the need of each European country to become as much as possible energetic independent. An important step can be done in the direction of producing electricity from renewable sources: this is the topic on which a good portion of modern scientific research is focusing [4]. In this direction, obtaining electricity by exploiting the natural wind force, represents an excellent eco-sustainable and very profitable solution. The well-known wind farms have been widely installed along the last thirty years, becoming more and more necessary over the time. Wind farms are formed by wind towers which are vertical structures, generally made of steel or concrete, used to elevate turbines (and blades) to a designed height (Fig. 1). Onshore steel wind turbines are characterized by the presence of circular cross-sections which diameter can reach also 4m. Moreover, depending on the zone in which they are installed, the height of a single column can range from 30 to 100 meters making these structures the biggest rotating machine in the world. It may seem obvious that the taller the tower is and the more is the produced energy, however nowadays it is common to increase the performance of the wind towers by using more efficient blade shapes, involving also new materials. Steel turbines are generally realized using a tubular steel column with different diameters along with the height.

Figure 1 Tubular steel tower and its main components (courtesy of SEVA srl)

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For the design of these structures, a high-level engineering knowledge is required, nevertheless collapses due to not correct design or poor maintenance are quite common. Recent papers showed that main collapses are due to electrical problems on rotors that caused huge fire, insufficient strength of bolts, poor bolt quality control during construction or collapse of the connections due to fatigue [5]. Moreover, also the rotor - steel turbine resonance [6] generates huge and dangerous displacements that can yield to a global collapse. The problem of fatigue is even more complicated than in the classic steel industrial buildings because wind towers are not stationary structures. From a structural point of view, the wind tower can be simplified as a cantilever beam, with a variable cross section along its length and an eccentric mass concentrated at the free end. Also, the interaction with the soil should be always considered by using ad-hoc calibrated springs or by modelling the soil itself with finite (FEM) *brick/shell* elements. The design of these structures is performed by adequately mixing the use of the various packages of finite element software with the equations deriving from design practice and prescribed in the standards. Finite element analyses can be used in different degrees of detail: the *beam* elements are used for the global behavior, while the connections, the foundations and the presence of openings require more advanced FEM elements, like *shell* and *brick*. For the structural design reference must be made, as for classical structures, to Eurocodes and to national laws. Additional specific and precise rules for wind towers are contained in the IEC61400 [7] standard. It is important to always check the problem of the resonance of the structures with the wind or with the rotor itself. In fact, when the frequencies of the rotor coincide (or are very close) with the natural ones of the structure, unacceptable deformations could be reached. To prevent massive structural damage the integrated control system of the wind turbine monitors continuously the displacements and the accelerations on the top of the tower and automatically perform a shutdown if a predefined threshold is exceeded. It should be remarked that frequencies of the wind turbines depend always also on the foundation-soil and their interaction with the structure having extremely huge concrete structures as foundations. In general, steel turbines are designed with 20 years of operational life and then they are dismantled, generating an environmental issue. To overcome the pollution problem, the best way seems to be the increasing of the operational life of the tower itself and to this aim structural designers and standards should focus more attention on the increase of performance of parts and components, such as connections. On the other hand, constructors must improve quality control and maintenance. In this view, it is interesting to install a permanent monitoring system based on the use of strain-gauges, thermal couples, anemometer and accelerometers. Such a monitoring system is able to check daily the status of the tower and make a prevision on the residual life of the monitored component, preventing damage and/or a global failure. Similar studies were carried out in the past [8,9] in which sensors were used to monitor crack propagation on connections of different types of wind towers.

In the present research, an almost 45 m steel tower, located in Italy, has been continuously monitored for 1 year: 16 strain gauges were placed along the tower in a pattern of four Wheatstone bridges at 45 degrees, together with thermal couples, at a specific elevation level (21m from the ground). Moreover, 6+1 accelerometers were located along the turbine lengths. The monitor system worked with remote acquisition boards and different operational conditions were tested. Moreover, also the wind direction and velocity were always registered by using the internal instrumentation contained in the rotor. It should be noted that, the analyzed turbine showed big top displacements every time the rotor reaches 32rpm (due to the resonance between the rotor and the first fundamental period of the tower) and in this situation the emergency system stops the rotor and hence the energy production. The scope of the paper is to show the stresses experimentally measured in normal operating condition and at the maximum permitted rotor velocity before the resonance (32 rpm).

2 The monitoring system

The wind turbine under consideration was designed with an original total height of 65 m. However, due to Italian law prescriptions for the preservation of the landscape, it has been mounted with a total hub height of almost 45 m (Fig. 2). The turbine is equipped with a main shaft which directly connects the generator to the rotor hub (2.5m diameter) which hosts three blades. The foundation is a single huge reinforced concrete cylinder (13 m of diameter by 3 m of height) plus 16 concrete piles (0.8 m of diameter for a length of 10 m). All the connections have been realized using welded ring flanges with preloaded high-strength bolts.

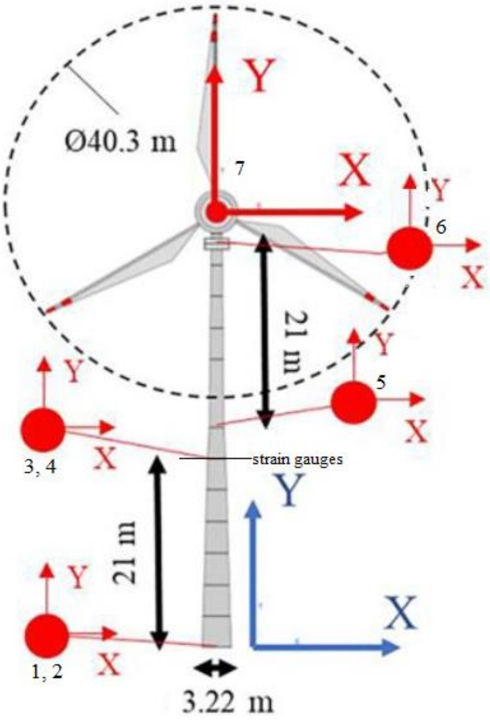

Figure 2 Main dimensions of the monitored tower and monitored sections (red dots accelerometer axes) [6]

A total of 16 strain gauges (350 Ohm, gauge factor 1.5) have been placed in a pattern of four Wheatstone bridges at 45 degrees spacing. Each one has been obtained by connecting four strain gauges in full-bridge configuration (Fig. 3). The bridge unbalance, which is caused by the varying bending loads in the tower, can be directly related to the bending deformation once the gauge factor and the input voltage are known. The tower section selected for monitoring is located in proximity of the intermediate flanged connection, at about 21 m height from the ground. The presence of a resting platform made this a suitable spot. In addition, four thermal couples were mounted to monitor the structural steel temperature. The installation of the strain gauges was performed by specialized technicians. The sensors were cabled and a protective coating was applied in order to protect both the sensors from dust and humidity and the tower steel from corrosion (Fig. 3).

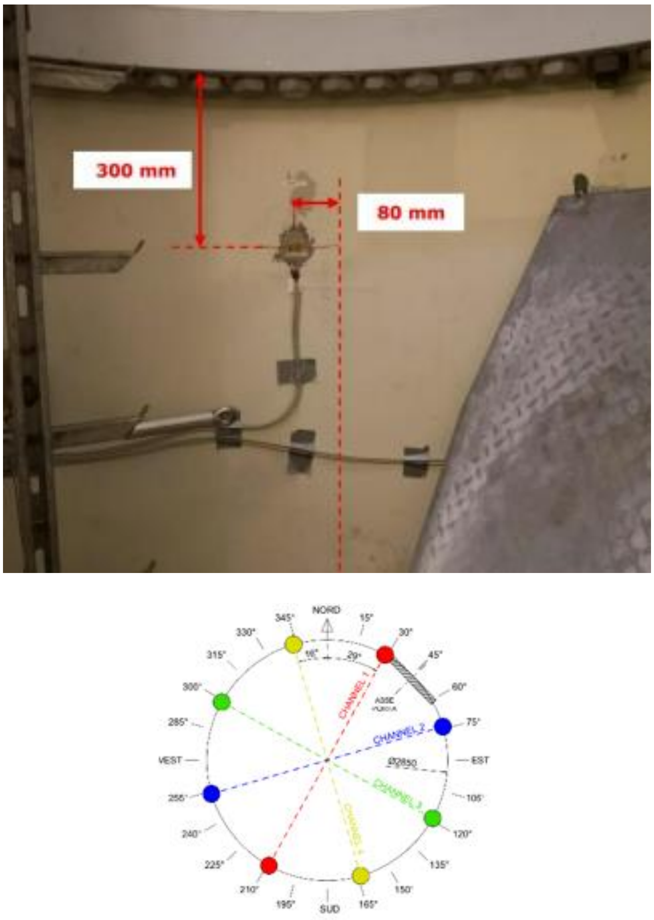

Figure 3 Detail of the strain gauges and their orientation

The data acquisition system is composed of a precision instrument for static and dynamic acquisition which includes a scanner with 8 channels. Each channel can be configured independently to accept strain gauge with multiple configurations or thermal couples. Acquired data is processed and filtered using Finite Impulse Response (FIR) to achieve an optimal noise reduction. The software also allows for a wide range of sampling frequencies (from 10 Hz to 1000 Hz) and provides a simple way to arm or disarm the sensors. In the current configuration, the bolts were not monitored. Finally, uniaxial piezoelectric seismic accelerometers PCB 393A03 type (Fig.4, sensitivity 1000 mV/g, range +−5 g) were installed. Considering a preliminary theoretical modal analysis, 6 measurement points have been identified along with the steel tower height (Fig. 2). An additional accelerometer (n 7) was installed on the turbine inside of the hollow shaft, at the rear bearing, which supports the generator. To cover all the measurement points, several measurement sessions were conducted with different arrangements of the available sensors.

Figure 4 Detail of the installed Accelerometers

3 Main results

Firstly, the Operational modal analysis (OMA) technique has been used to understand the nature of the resonance problem [6]. In this kind of technique, the main part of the dynamic load is composed of several components, typically from artificial and/or natural sources of vibration (traffic, industrial plants, wind, seismic microtremor, etc.) present around the structure. Having an unknown input, it is possible to analyze only the response of the structure (modal output-only analysis). The analysis of the acquired data was based on the study of the Power Spectrum function, Cross power-spectrum of two signals, one of which is taken as a reference between all the collected data sets. In the specific case under consideration, two different working conditions have been considered: turbine under environmental conditions (nil speed rotor) and turbine at maximum rotation allowed (32 rpm of velocity, which means 0.55 Hz of frequency). The eigenmodes shapes are reported in Fig. 5 together with the Cross-spectra density. The first vibration mode shape represents both the 2 orthogonal fundamental modes having almost identical frequencies. The deformed shape is the classic one for an inverse pendulum with a rotational mode of the tower head that follows an elliptical trajectory on the horizontal plane. The Cross-spectra density is proposed underlines the prevalence of the first mode with respect to the others. In fact, the greatest content of energy can be observed around the 0.6 Hz frequency (highlighted in dark red color). The other non-negligible content of energy is close to about 4.0 Hz (third mode). These results confirmed that, when the turbine is at its maximum working range, a resonance problem occurs: the first fundamental period of the structure is very close to the one of the rotor.

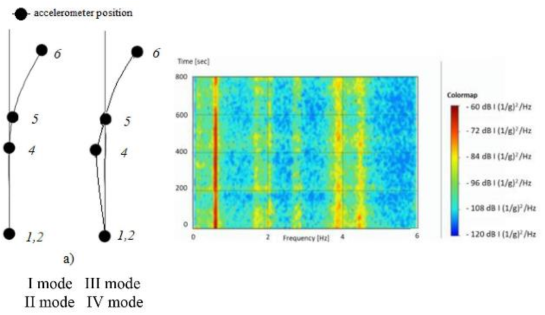

Figure 5 Modal shapes and cross-spectra density

To understand the importance of the resonance phenomena on the internal stresses, one-year experimental campaign was carried out by continuously monitoring the tower with the use of the strain-gauges. The direct results derived from the campaign were the curve which relate strains in one main direction, ε, over the time. From the complete measuring system, it was possible to correlate strains measurement with i) wind velocity; ii) hub position; iii) rpm of the rotor. It is important to notice that, since the strain gauges were mounted on an already working tower, the self-weight and the weight of the rotor cannot be measured with the proposed system, therefore only the strain generated at the operating condition are considered in the following. If the data are used for a damage evaluation, it is convenient to refer the results to a variation of stresses, $\Delta\sigma z$, by using the Hooke expression, assuming or measuring the young modulus of the steel material (for this tower equal to 210 GPa). Moreover, it should be noted that the thermic variation, ΔT, during the measuring activities it was always registered, thanks to the presence of the thermal couples.

As an example of the output derived from the monitoring system, Fig. 6 can be considered, related to 30 h of continuous monitoring. In the figure the variation of the normal stresses in time (for 2 selected channels) is reported together with the rpm of the rotor versus time. The time-series are related to 26th April 2022.

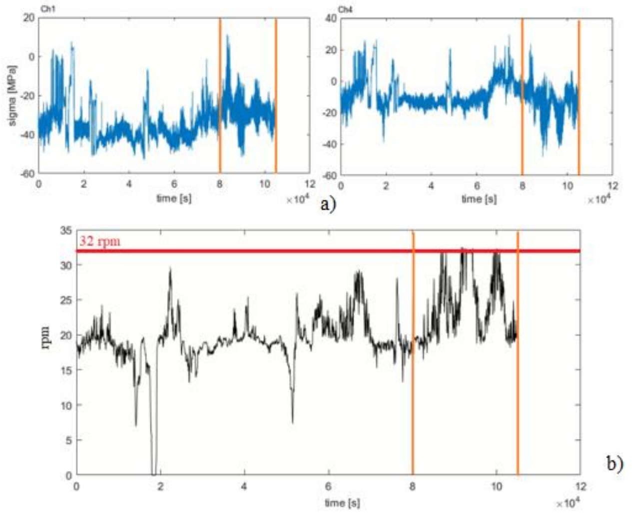

Figure 6 Typical output for 30 h monitoring (26th April 2022): a) stresses vs time and b) rpm vs time

The limit of 32 rpm is highlighted with a red horizontal line. This limit cannot be overpassed by the rotor. With orange vertical lines is highlighted the range in which rotor operate into the best range of energy production (28÷32 rpm). It can be noted that, independently on the season, once the rotor enters into the optimal range, the measured $\Delta\sigma z$ increase immediately. Hence it is expected that when the turbine works into this range of velocities also the damage index increases noticeably. It should be noted that sometimes curve b) shows rotor velocity equal to zero: this can be related to a drop of the wind velocity (which is not sufficient to ensure power production) or to a stop of the rotor for maintenance or safety reason.

To study in detail the problem of the resonance, during a windy day (the 30th of April 2022), the tower was left to work at its limit for 20 h. In Fig. 7 the output in terms of maximum stresses and rpm is reported. It can be noted the great increase of the monitored stresses with respect to the initial part of the registration for which the stress level is comparable to the ones reported on the previous Fig. 6. The phenomenon is directly correlated to the initiation of the structural resonance which results in a dangerous state of stress for the tower. The limit of 32 rpm is hence necessary to guarantee the safety of the tower and cannot be overpassed, not only with respect to the fatigue life but also regarding the maximum admissible stresses itself.

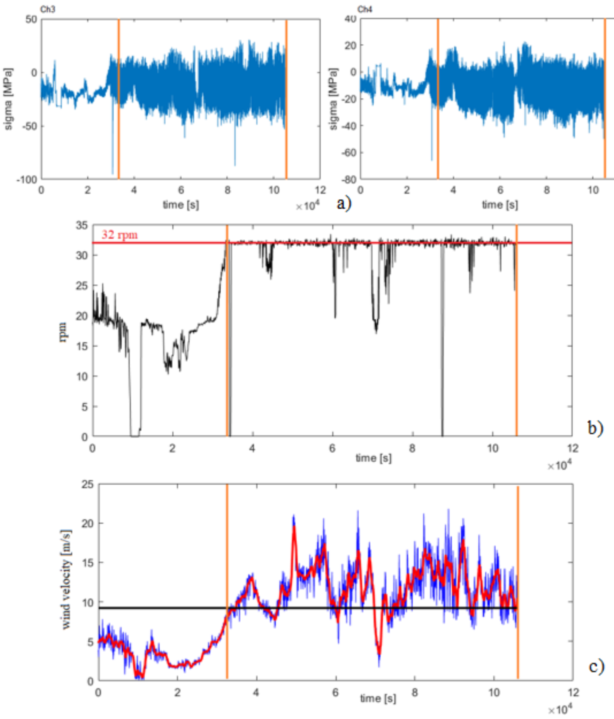

Figure 7 Output in resonance for 20h: a) stresses vs time, b) rpm vs time and c) wind velocity

4 Concluding remarks and future developments

The monitored tower suffers resonance problems which have been detected by the using a suitable monitoring system made by a few accelerometers, located along the tower height. Moreover, to study the effects of this phenomena on the internal stresses strain-gauges were placed in a specific cross-section. It has been shown that the resonance causes a non-negligible increment of internal stress which can lead to dangerous structural damage. The next step of the research will be the evaluation of the damaged index by using the well-known Miner rule [10]. In fact starting from the stress distribution, it is possible to evaluate the number of occurrence of a specific stress variation and create the S-N spectrum, like the one proposed in Fig. 8, which can be directly compared and related to the one proposed by the EC3 and hence evaluate the damage index.

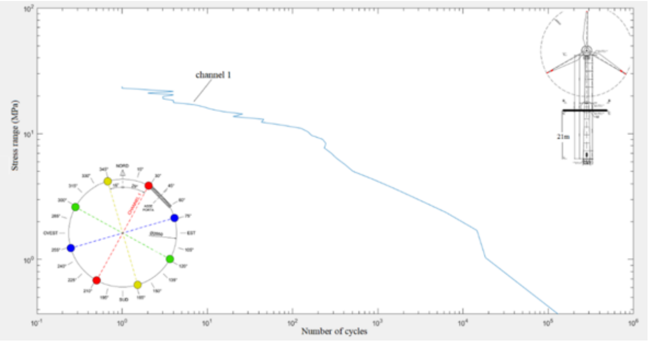

Figure 8 Typical S-N spectrum from experimental measuring.

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