International Journal of Precision Engineering and Manufacturing-Green Technology (2020) 7:119–130
https://doi.org/10.1007/s40684-019-00102-8

Online ISSN 2198-0810
Print ISSN 2288-6206

REGULAR PAPER

Design of a telescopic tower for wind energy production with reduced environmental impact

Antonio Pantano[1] · **Tullio Tucciarelli**[1] · **Nicola Montinaro**[1] · **Antonio Mancino**[1]

Received: 5 April 2018 / Revised: 12 March 2019 / Accepted: 19 March 2019 / Published online: 6 April 2019

Abstract

A prototype of a telescopic pole for wind energy production with low environmental impact and its lifting system for a 60–250 kW turbine and a height of 30 m have been designed and manufactured. A telescopic tower, which is raised and lowered by automation or by remote control, allows to differentiate the presence of the generator within the landscape over time. The technology currently available for lifting and lowering wind turbines is made up of telescopic poles of heights of less than 10 meters and with tilting posts of height below 30 m. Without a state of the art to refer to, the telescopic pole and its lifting system have been designed starting from scratch and solving with innovative ideas the various criticalities that have arisen. The design of the telescopic coupling, the design for maintaining the preload and for the rotational decoupling, the optimization the design of the pairs of sleeves by numerical simulations, the design of the pegs and the bushes of the jack-up lifting system have been presented. The prototype was installed in Caltanissetta, Italy, and successfully tested.

Keywords Telescopic tower · Wind turbine tower · Mechanical design · Finite element method

Abbreviations

Reds	Renewable energy devices
a	Blades length
b	Blades width
h	Tower height
FEM	Finite element method

1 Introduction

The main drawback of wind farms is their significant environmental impact, mainly in terms of landscape alteration, as well as possible risks to birds and noise in the closer areas. The discomfort generated by wind farms is aggravated by the persistence of the facilities even during periods of time when the demand for electricity is absent or the benefit from the production is less than the social cost of the environmental factors mentioned above. An example is provided by the renewable energy devices (RED) often requested in smaller islands, such as the Mediterranean ones, with a large seasonal tourist population, in these locations the electricity consumption is higher during the summer months and absent in the winter season or even during the periods of storm. Another example is the production of energy from REDs overnight, when photovoltaic or other solar sources are not available and demand for energy, although lower than the daytime, can be fairly strong due to many social and industrial activities. There are several studies on the optimization of the hybrid renewable energy power system for remote installations such as mountains and islands, one of which is provided by Bhandari et al. [1] whose results indicate that an optimized hybrid system can help remote locations to completely switch from the current fossil fuel system to an energy system based on renewable energy.

An important line of research and industrial development is therefore the creation and production of wind power plants that have a lower environmental impact with the development of a tower which can be lifted and lowered easily and with considerable frequency. A structure of this type has substantial advantages both from a technical point of view and in terms of environmental impact and can be easily used in different ways:

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s40684-019-00102-8) contains supplementary material, which is available to authorized users.

✉ Antonio Pantano
antonio.pantano@unipa.it

[1] Dipartimento di Ingegneria, Università degli Studi di Palermo, Palermo, Italy

- A first use is to install these systems in areas with significant variability of the resident population, as on small islands or in other places with predominantly tourist destination, where the population is mainly present in the summer. The absence of wind generation would not damage significantly the energy producer, as in our climates the summer is also the least windy.
- A second mode would be to maintain the elevation of the tower to the operating height only in the periods with higher wind and to proceed to its lowering in the remaining periods, even in automatic mode or semi-automatic and/or by remote control.
- Another option would be to maintain the elevation of the tower only in the night time, thus making the system completely camouflaged throughout the year.

An important advantage is also to accomplish in the factory much of the work that would otherwise be necessary on site for the tower construction. This would provide an opportunity for the manufacturers of a product industrialization process, resulting in export opportunities also in foreign countries that may not otherwise provide local resources to the construction of the tower.

A further advantage of the proposed system, this being based on the drilling of a pit depth equal to the height of the tower, it is to be able, with small variations, also to draw ground water for domestic or agricultural use.

The currently available technology for the lifting and lowering of the towers for wind turbines is constituted by tipper masts in the mini-turbines sector and by hydro-pneumatic telescopic masts in the micro-turbines sector, but scientific documentations about quantitative performance index such as time, stability, robustness, evaluation after installment are very limited.

The tipper masts, or tilt-up masts, are used for turbine of 5 kW or less, since raising and lowering a heavy wind turbine of high power from the horizontal position would require huge forces and a very rigid and resistant tower capable of withstanding a great bending moment [2–7]. In [2] an 18 m tipper mast for a 1 kW vertical axis wind turbine was designed with the help of an FEM model to analyze its behavior during lifting and lowering of the device. It was found that even for such a small wind turbine and short mast a peak stress of 64 MPa and a 132 mm tip displacement were predicted. These results provide an example of the main limitation related to this technical solution. Another important disadvantage of tipping shafts is the time needed to raise or lower the tower, as this also includes screwing or unscrewing all nuts and bolts securing the two connecting flanges of the mast, as can be seen in [7]. This operation does not only takes a long time but also cannot be automated, and at least one staff unit must reach the site and perform the work. Usually the height of the tipper masts is less than 30 m. Although tilt-up towers are more expensive, they offer the consumer an easy way to perform maintenance on smaller lightweight turbines. Tilt-down towers can also be lowered to the ground during hurricanes and other hazardous weather conditions.

Telescopic towers based on pneumatic or hydro-pneumatic systems [8, 9] are limited by the existing technology that does not allow the realization of large diameter and long stroke actuators due to the impossibility of guaranteeing the tolerances required for the hydraulic seal between the parts. Actually telescopic masts are used in the micro-turbines sector and their height is usually less than 10 m (e.g. [8]). Unless, with a significant cost increase, an electronic or an hydraulic locking system is implemented at the end of each mast unit, the pump must keep the pressure necessary to maintain the payload and the weight of the tower, and this is also source of instability.

There are also several patents of telescopic towers that can be raised by means of cables and pulleys that lift the group of inner masts with respect to the generic mast that already has reached the working position [10–13], however to our knowledge commercial systems widely used were never made for wind turbine but only for antennas and other very low weight devices [14].

On the other hand the category of small wind turbines with horizontal axis, and a power within a range of 60–250 kW, is a rapidly growing market [15], that could get great benefit from the existence of a self-rising telescopic system, which is missing at the present time.

The University of Palermo, together with the partners of the project P.E.R.IM.A (*Produzione Eolica con Ridotto Impatto Ambientale*) of the "4.1.1.1 POR FESR Sicily 2007-2013" program, has developed a special lifting system, based on pre-drilling of a deep foundation pit equal to the height of the pole, but of a much smaller diameter. The system designed in 2015, was produced, assembled and installed in the year 2016 at the headquarters of one of the project partners. The telescopic towers can be raised or lowered in less than 20 min. The device consists of four main parts: a foundation, a telescopic tower, a lifting system, a wind turbine with two blades.

The purpose of the PERIMA project was the development of a RED device powered by the wind that can be easily raised and lowered according to the management requirements, for a power from 60 to 250 kW and a height of 30 m. The telescopic pole and its lifting system have been designed starting from studies on traditional non-telescopic poles [16–46] and solving with innovative ideas the various criticalities that have arisen. The project has enabled the creation of a first prototype at a site near the town of Caltanissetta (Italy). The prototype, which has a tower height of 30 m and a diameter of about one meter, is illustrated by Figs. 1 and 2 and has been lowered and raised several times up to the end of project, at the beginning of 2017.

The originality of the new approach can be summarized in the following points: (1) sleeves joints with inclined coupling surfaces, (2) presence of an internal thrust piston, (3) newly designed lifting jack-up system that is fast and safe, (4) Teflon plates which realize axial sliding, (5) presence of a preloading mechanism of the structure that also realizes the decoupling of the rotation of the tower from that of the piston during the lifting. In Table 1 the novel telescopic must is compared with the available technologies: the tipper masts, or tilt-up masts, and the telescopic towers based on hydro-pneumatic systems.

2 Overview of the project

2.1 The foundation

The foundation needs to (1) secure the stability of the tower at any time, (2) house the tubes of the telescopic tower at rest. The depth is calculated so as to have, at rest, an elevation of the wind turbine of a few meters above the ground. The foundation used is of the type having a tubular shaft constituted by a ring of reinforced concrete piles clamped at the top through an annular edge beam of reinforced concrete and n. 2 steel cylinders where hollow spaces are saturated with cement mortar. The system allows to achieve the lifting by means of tubular elements connected by sleeves and a piston that pushes the plate below the mast of smaller diameter. The lower outer sleeve, which forms the base of the tower, can itself be housed below the ground level. Figures 3, from (a) to (d), illustrate the four lifting stages of the telescopic pole.

Fig. 1 PERIMA prototype with telescoping tower in its lowered position

Fig. 2 PERIMA prototype with telescoping tower in its lifted position

2.2 Telescopic tower

The telescopic structure, Figs. 4a and b, is composed of 3 tubular elements in steel, the mast 1, mast 2 and mast 3, of increasing outside diameter, in order to be able to enter one inside the other during lowering, and equipped with perforated upper and lower flanges for the assembly of 6 sleeves junction (3 internal and 3 external). The axial sliding is guaranteed by the implementation of a system of Teflon plates with a curved profile. Only the outermost inner sleeve slides on the inner wall of the foundation. The Teflon plates, both in the external sleeves in the inner sleeves, are supported by a steel structure bound to the sleeves with screws and nuts to allow possible adjustments.

Table 1 Comparison among the existing technologies and the presented telescopic tower (PERIMA)

	Time for rising or lowering	Stability	Robustness (payload Capacity)
Tipper mast	High	High	Low
Hydro-pneumatic telescopic mast	Low	Low	Very low
Presented telescopic mast (PERIMA)	Low	High	High

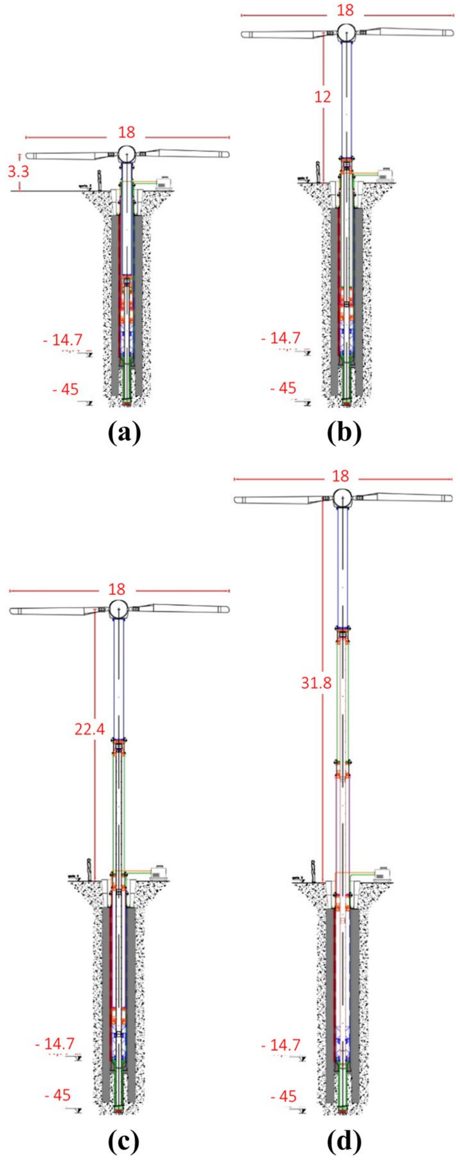


Fig. 3 View in diametrical section of the device during the lifting stages of the telescopic tower: **a** lowered position, **b** mast 1 has been raised, **c** masts 1 and 2 have been raised, **d** final working position. The dimensions shown are in meters

Each sleeve has a truncated conical shape for the lower part and an external shape complementary to it for the upper internal part, Figs. 5 and 6. Starting from the lowered position, the innermost sleeve is raised by the lifting piston by means of the jack-up system, Fig. 7, and slides with respect to the immediately outermost sleeve until the outer surface of the truncated cone does not reach the inside of the shape complementary to it placed on top of the next mast. At that point the inner sleeve drags with it also the next external one. The diameter of the truncated cone is smaller of the internal diameter of the next outer sleeve, so that the sliding between the two elements can take place despite the typical tolerance of commercial tubes (0.5–1 cm), but also sufficiently greater than the top diameter to prevent an unwanted locking of the sleeves at the time of the descent. The mechanism is repeated for all the sleeves until the outermost sleeve, Ext 3, blocks the further raising of the tower. At this point the piston is blocked by means of an appropriate safety mechanism and the presence of an elastic element, a high-load air spring, which ensures conservation of tension and then the lock by friction to the rotation.

The particular advantage of this solution is to foresee only the use of simple and easy to service components, such as sleeves, the conical shape constraints and the thrust piston.

2.3 Lifting system

The lifting system of the prototype is inspired at the lifting system of the jack-up rigs, a type of mobile platform that consists of a buoyant hull fitted with a number of movable legs, capable of raising its hull over the surface of the sea [47, 48]. Jack-up rigs are so named because they are self-elevating with three, four, six and even eight movable legs that can be extended ("jacked") above or below the hull. The jacking systems acting on the legs can be of two different types: a rack and pinion gear arrangement or a combination of holes (on the legs) and pegs actuated by hydraulic pistons. The second type of jacking systems was the one chosen as model for the design of lifting system used to rise the telescopic tower.

In our project a lift jack-up, see Figs. 7a, c and d, actuates the piston of the same length of the telescopic tower in the extended configuration. The piston, see Fig. 7b, is a tube with many holes, where the pegs of the jack-up are placed before lifting or lowering the piston. When the telescopic tower is at rest, the piston is housed in a smaller diameter shaft. In the prototype the well is deep about 30 m. The jack-up lifts the piston with regular runs of 0.85 m and allows to lock the tower after the final level of compression of the air spring is reached.

2.4 Wind turbine

The wind turbine installed on the telescopic tower is a Libellula 55 kW produced by Aria s.r.l [49]. At a wind speed of 3.0 m/s, the wind turbine starts its work. the cut-out wind speed is 25.0 m/s. The rotor diameter of the Aria Libellula 55 kW is 18.0 m. The rotor area amounts to 255.0 m^2. The wind turbine is equipped with 2 rotor blades. The maximum rotor speed is 95.0 U/min. The Aria Libellula 55 kW is fittet with a parallel gearbox. The gearbox has 2.0 stages.

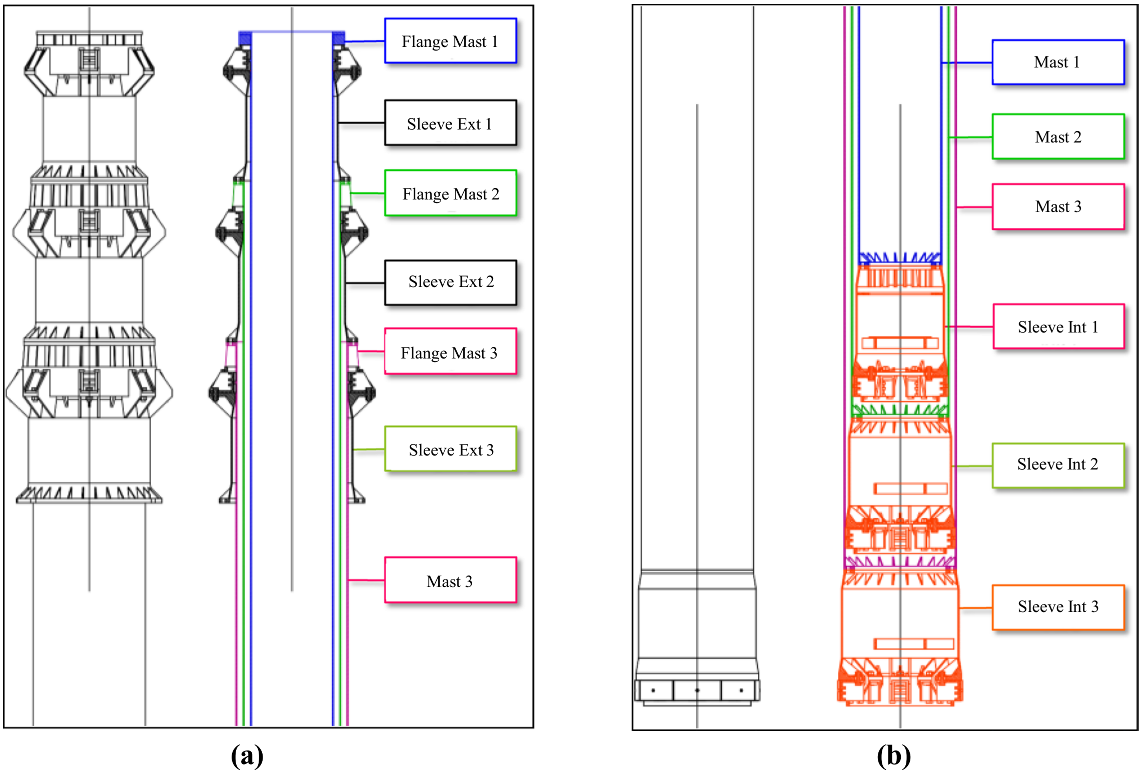


Fig. 4 Schematic draft of the coupling between masts and sleeves: **a** upper part of the masts, **b** lower part of the masts

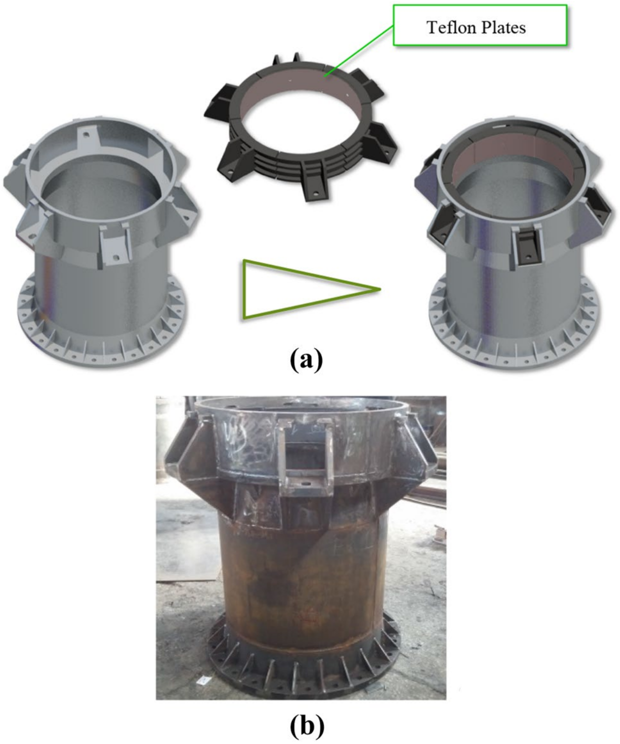


Fig. 5 Outer sleeve: **a** 3D drawing, **b** photo

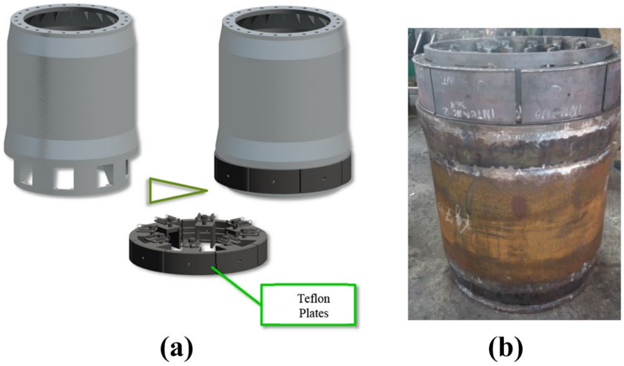


Fig. 6 Inner sleeves: **a** 3D drawing, **b** photo

3 Mechanical design

3.1 Design of the telescopic coupling

Without a state of the art to refer to, the telescopic pole and its lifting system have been designed starting from studies on traditional non-telescopic poles [16–46] and solving with innovative ideas the various criticalities that have arisen.

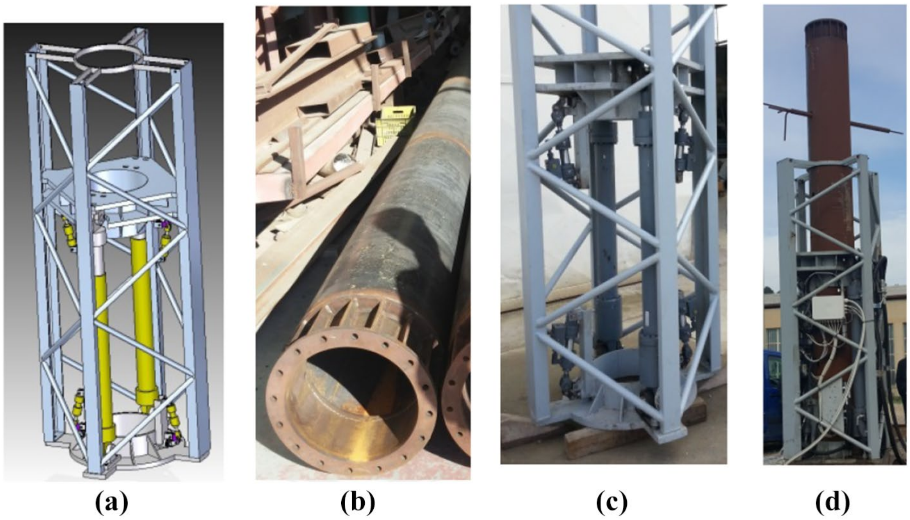

(a) (b) (c) (d)

Fig. 7 Lifting system: **a** 3D drawing of the jack-up and protection cage, **b** picture of the manufactured piston trunk, **c** photo of the manufactured jack-up and protection cage, **d** photo of the jack-up, protection cage and piston

Table 2 Geometry for the calculation of loads on the structure

Blades		Wind turbine body	Tower	
a (m)	b (m)	Radius (m)	Frontal section (m)	h (m)
7.8	0.6	0.75	0.87	32

3.1.1 Forces acting on the structure

A preliminary study was carried out of the external forces acting on all the structures that make up the system: the wind turbine, a 55 kilowatt two blades wind turbine generator, and the telescopic tower. The wind acts on the exposed parts of the complex: the turbine, the blades, the ogive and the generator box and the three main trunks of the telescopic tower. The force of the wind results in mechanical pressure on the various parts of the structure at different heights from the ground. The tower is designed to be lifted and lowered even with wind speeds up to 27 m/s, about 97 km/h. Table 2 lists the geometries of the main components involved in the calculation. The resulting force on the wind tower was applied at 2/3 of the total height. After calculating the forces acting on the structure, the stresses at the most loaded point, i.e. at the pole foot and then on the sleeve 3, were determined, where the resulting bending moment is 333.25 kNm and the cutting force is 14.26 kN. Table 3 shows the mechanical properties of the materials used for the different parts of the structure.

3.1.2 Design using rollers

In the preliminary design phase, to allow the axial sliding of the three poles that make up the telescopic tower, it was thought to use rollers to achieve efficient rolling friction, Fig. 8. However, even though the rollers size was increased several times, rolling contact system has never guaranteed a satisfactory stress distribution on the structure, resulting in locally unsustainable stress levels. As described in 2.2, we have inevitably opted for a coupling system with sliding friction between the poles and sleeve elements. This system allows to use extensive contact surfaces that evenly distribute loads on the structure, particularly on the pole surfaces. For the estimation of loads on each roller, later replaced by Teflon plates

Table 3 Materials properties

Components	Material	σ_R (Mpa)	σ_s (Mpa)	ΔL %
Steel for the components of the tower		Mechanical properties		
Structure and main elements	S320	390	320	17
Pegs and seats for lower and upper jack-up bushes	Steel 39NiCrMo3	740 ÷ 1180	540 ÷ 785	11 ÷ 13
Bushes on jack-up rings	Steel E410	520 ÷ 750	410 ÷ 590	12 ÷ 22
PTFE for telescopic coupling		Mechanical properties		
Teflon plates	PTFE G400	> 24	4 ÷ 5	> 250
Teflon plates on the larger outer	PTFE G403 Loaded (15% glass)	17 ÷ 24	6 ÷ 7	250 ÷ 300

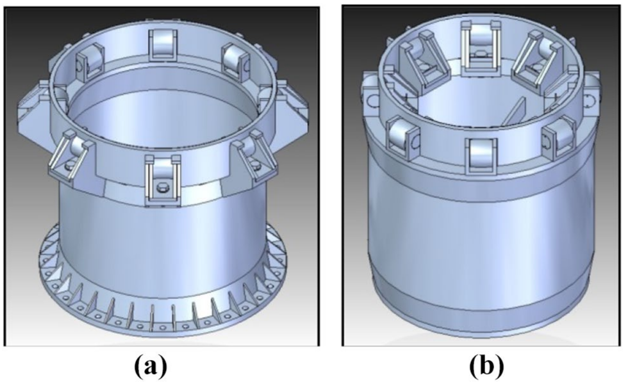


Fig. 8 Design with rollers applied to: **a** outer sleeve 3, **b** inner sleeve 3

and their supports, the maximum moment of 333.25 kNm at the base of the tower was estimated as described in the previous paragraph. This limit value of the moment allows the operation of the tower up to wind speeds of 97 km/h. The maximum moment is transferred from the inner sleeve 3, which is connected to the lower end of the larger diameter pole, to the external sleeve 3, which is bolted to a metal flange in turn connected to the foundation. The torque arm at sleeve 3 is equal to about 1.2 m, the distance between the contact areas between the rollers of the outer sleeve and the larger pole, and the contact areas between the rollers of the inner sleeve and the upper steel cylinder of the foundation.

Prior to abandoning the initial design choice involving the use of the rollers, several possible designs were considered in which it was progressively increased the circumference of the rollers, the diameter of the pins and the size of the supports. Figure 8 shows the last step of optimizing the system applied to the outer sleeve 3 and interior sleeve 3. In this configuration, the roller support is a C-section drawer that acts as a support for the roller and for the pin. A radial adjustment of the position of the rollers, in this case permitted by the sliding capacity of the drawers, is essential due to the large dimensional tolerances of the welded artifacts of such dimensions.

The drawer system guarantees excellent resistance to stress on the supports and, being locked by friction, turns out to be an effective precautionary device for overloading. However, even by adopting this design, too high stress values between the roller and the pole have been reached. Figures 9a and b show the results of a finite element analysis where the distribution of the von Mises's stress, on the rollers and above all the contact area on the pole, is much higher than the yield strength limit of S320 steel (equal to 300 MPa).

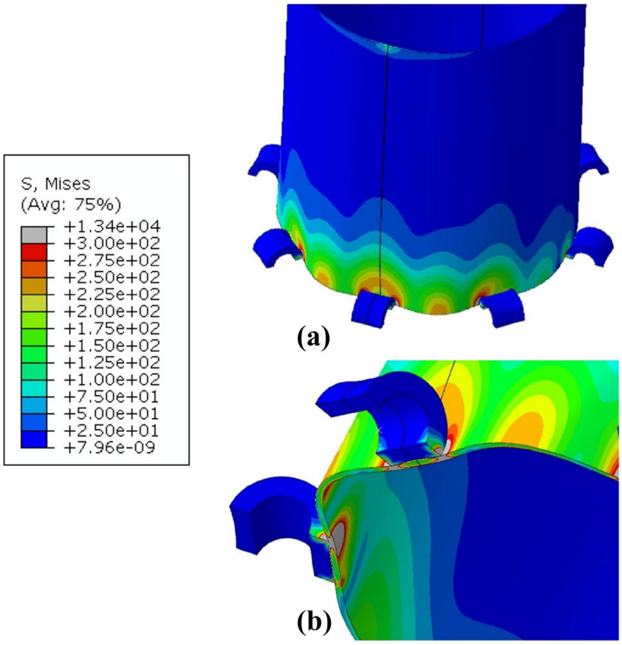


Fig. 9 In **a** distribution of the von Mises's stress on the rollers and on the larger pole when wind speeds is 97 km/h, obtained by FEM. In **b** magnification of the roller—pole contact

3.1.3 Design using Teflon plates

In order to obtain a load distribution compatible with the resistance limits of the materials while realizing the axial sliding, the initial hypothesized rolling friction was substituted with a sliding friction. Teflon plates were used to minimize the coefficient of friction in the PTFE-steel interface, it is known that the PTFE-steel friction coefficient is equal to 0.05. Figure 10a shows a single support drawer and relative Teflon plate. Figure 10b shows the symmetrical half of the system assembly with Teflon

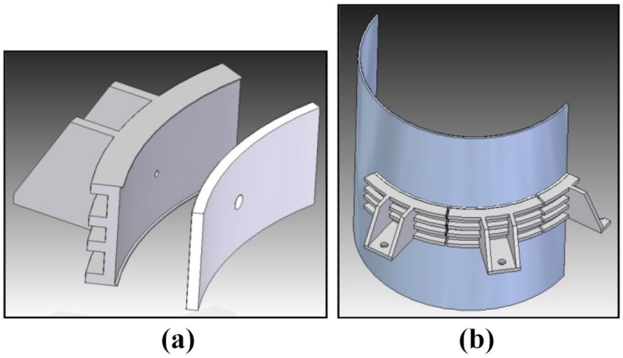
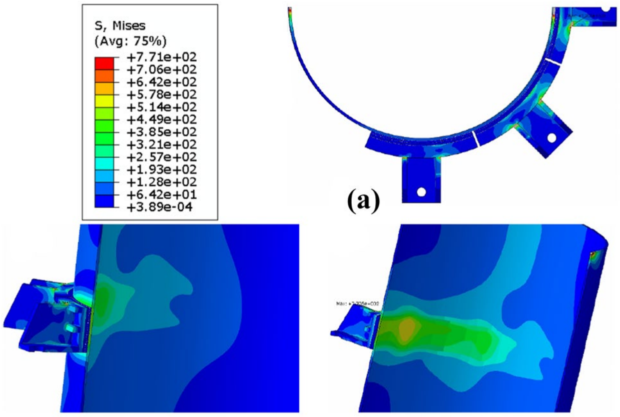


Fig. 10 **a** Supporting drawer and relative Teflon plate used to realize the axial sliding between the three poles that make up the telescopic tower, **b** Symmetrical half of the system assembly with Teflon plates and pole 3

plates and pole 3 to be used in the FEM analysis, thanks to the symmetry of geometry and boundary conditions. Only half of the support drawers and relative Teflon plates are considered since the bending moment apply loads only in one direction normal to the pole axis, while the support drawers and relative Teflon plates on opposite side are not loaded.

The stress analysis FEM analyzes shown in Figs. 11a–d proves that this a coupling system of this type determines a good distribution of loads both on the steel drawers as well as on the PTFE and on the pole. The von Mises's maximum stress on the pole is less than 250 MPa, thus remaining within the resistance limits of the material. The peak stress in the legend of Fig. 11a is due to the presence in the steel support drawers of a sharp edge that results in a concentration of stress that are not actually realized in the manufactured product.



(a)

(b)

(c)

Fig. 11 Distribution of the von Mises's stress on the support drawers, Teflon plates and pole 3 when wind speeds is 97 km/h

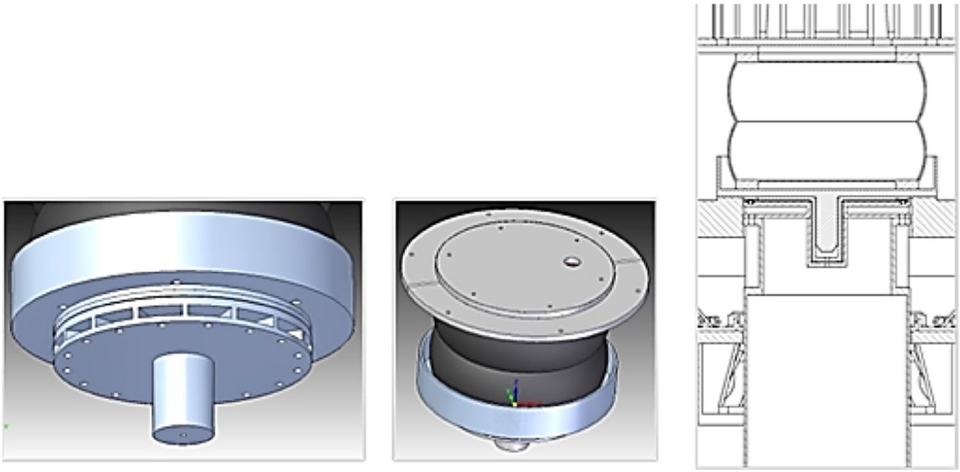
3.2 Design for Maintaining the Preload and for the Rotational Decoupling

The function of the innermost sleeve, Int 1, is not only that of the inner telescopic element, as in the case of the inner sleeve 2 and 3, but also of housing of the preload mechanism of the structure and decoupling its rotation from that of the piston during lifting, see Fig. 12. As illustrated in paragraph 2.2, the telescopic tower is boosted by means of a piston that, actuated by the jack-up system, pushes the innermost sleeve, Int 1, located below the mast of smaller diameter, Mast or Pole 1. During lifting, the rotation of the wind turbine and the three masts is not constrained, thus in presence of strong wind the components of the tower might rotate with respect to the push piston. However the piston cannot rotate since it is always blocked by at least two pegs inserted in the pairs of holes distributed along its length, thus it's important to allow a free rotational motion of the innermost sleeve with respect to the piston. The rotational decoupling is driven by an axial bearing inserted between a component that connects to the end of the piston and another component that supports the pneumatic spring, Figs. 12a and 14c. When the tower reaches its final extended height and all the couples of inner and outer sleeves are in contact along their conical surfaces the piston rise a little further in order to compress a high-load air spring, positioned inside the innermost sleeve, which ensures keeping the entire tower under a constant tension. The tension through the entire structure guaranties presence of normal forces at the conical surfaces, thus bending and rotation of tower is constrained.

3.3 Optimization of the Design of the Pairs of Sleeves by Numerical Simulations

The three pairs of sleeves were subjected to finite element analyses in order to optimize their design by minimizing

Fig. 12 Spring support mechanism inside the inner sleeve 1 which realizes the preload of the structure and decouple the rotation of the tower from the piston during the lifting: **a** Decoupling components, **b** High-load air spring, **c** Sectional view of the mechanism


(a)

(b)

(c)

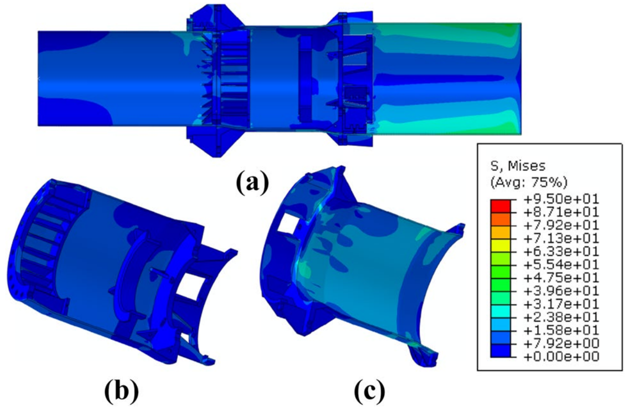


Fig. 13 Distribution of the von Mises's stress on the sleeves Int 1 and Ext 1 and the masts 1 and 2 when wind speeds is 97 km/h

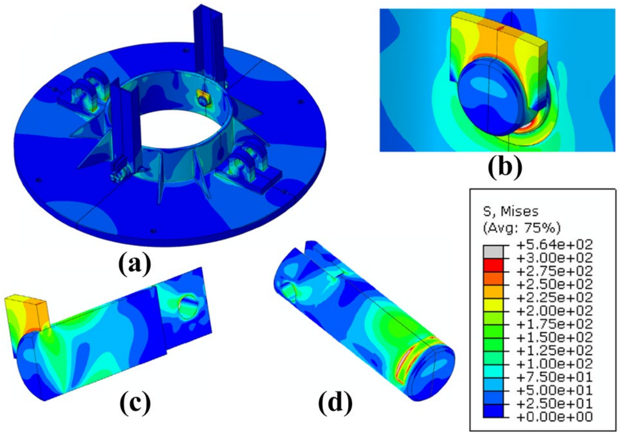


Fig. 14 Distribution of the von Mises's stress on base of the jack-up, the bushes, the pegs and the lifting piston (here only a small portion of the piston is considered, the material near the hole where the peg is inserted)

weight while ensuring resistance to the maximum loading conditions. Here only the results related to the final design of the inner sleeve 1 and the external sleeve 1 are presented. In the FEM analysis the contribution of the conical pairs is supposed to be zero since we are interested in the situation that occurs a few moments before the complete extension of the telescopic pole, shortly before the conical pairs actually come in contact. Figures 13a–d show the distribution of the von Mises's stress, no part of the sleeves or the masts exceeds the yield tension of the material.

3.4 Design of the Pegs and the Bushes of the Jack-up Lifting System

A critical point in designing the jack-up lifting system is the presence of a concentrated load on the pegs used to block the axial movement of the piston and the bushes that allow the pegs to move with respect the base of the jack-up.

Given that the maximum jack-up capacity is 20 Ton and that the blocking pegs are 2, 10 Ton of load is applied on each peg and the associated cemented bush. The cemented bush in turn will be housed inside a further bush, the latter welded to the base of the jack-up. The material properties of the pegs, the associated cemented bushes and the bushes welded to the base of the jack-up are listed in Table 3. In the numerical simulation only a small portion of the piston is considered, the material near the hole where the peg is inserted. The load, 10 Ton, is applied as pressure to the upper surface of the small portion of the piston. Figures 14a–d show the distribution of the von Mises's stress, no part exceeds the yield stress of the material.

3.5 Dynamic Stability Analyses

Wind towers should be designed so that their natural frequencies do not coincide with the excitation frequencies due to the rotor frequency, f_{rotor}, and to the rotation of the blades, blade passing frequency, f_{bp}. f_{rotor} is the rotor's rotation speed, and f_{bp} is the number of blade times f_{rotor}. These are denoted as f_{rotor} $(1p)$ or f_{bp} (np) respectively in the literature and n is number of blades of the rotor, for the present study $n=2$ since it is a two blades turbine. Modal analyzes of the telescopic tower were performed on a finite element model that perfectly reproduces the real tower as it is obtained with an import of its original 3D CAD. The plotted solutions in Figs. 15a and b, specifically the normalized displacement, show the first two mode shapes of the telescopic tower and the corresponding natural frequencies: first mode frequency 0.61 Hz, second mode frequency 3.483 Hz.

The wind turbine installed on the telescopic tower is a "Libellula" 55 kW from the company ARIA and it has a specified working range of 60–95 rpm [43]. Since it is a two blade turbine the excitation frequencies fall in the following two ranges: $1\ \text{Hz} < f_{rotor}\ (1p) < 1.583\ \text{Hz}$ and $2\ \text{Hz} < f_{bp}\ (2p) < 3.166\ \text{Hz}$. Thus the first natural frequency of the telescopic tower is always lower than f_{rotor} $(1p)$ and f_{bp} $(2p)$, while the second natural frequency of the telescopic tower is always higher than f_{rotor} and f_{bp} $(2p)$. The dynamic stability analysis has proved that there is no risk of resonances in the structure.

4 Limitations

The main limit for the technology presented is obviously the cost, which is significantly higher than a conventional tower and can be justified only when one or more of the many advantages listed in the introduction are required. Another drawback is the time it takes to build the tower, which is longer mainly due to the construction of the foundation. The

Fig. 15 Wind tower mode shapes: **a** first mode (frequency 0.61 Hz), **b** second mode (frequency 3.483 Hz)

additional time required is only partially counterbalance by the easier transport and installation of the three masts in which the telescopic tower is divided. The lifting system needs electricity to operate and also requires some maintenance. However, the maintenance of the lifting system is more than rewarded by easier controls and repair on the wind turbine that can be performed at ground level.

5 Conclusions

A prototype of a telescopic pole for wind energy production and its lifting system for a 60–250 kW turbine and a height of 30 m have been designed and manufactured. The pole is raised and lowered by automation or by remote control, allowing to differentiate the presence of the generator within the landscape over time. The technology currently available for lifting and lowering wind turbines is made up of telescopic poles of heights of less than 10 meters and with tilting posts of a height of less than 30 m. Lacking a state of the art to refer to, the telescopic pole and its lifting system have been designed starting from scratch and solving with innovative ideas the various criticalities that have arisen. The system has been described in all its parts: the foundation, the telescopic tower, the self-lifting system.

With regard to the mechanical design, in this paper we have presented: the design of the telescopic coupling, the design for maintaining the preload and for the rotational decoupling, the optimization the design of the pairs of sleeves by numerical simulations, the design of the pegs and the bushes of the jack-up lifting system. Particular attention has been paid to the laborious design process which has led to the final version of the coupling system between poles and sleeves using Teflon plates, that allows their axial sliding while guaranteeing the ability to withstand high loads due to wind action during the lifting and lowering phases of the telescopic tower. The prototype was installed in Caltanissetta, Italy, and successfully tested.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

References

1. Bhandari, B., Ahn, S. H., & Ahn, T. B. (2016). Optimization of hybrid renewable energy power system for remote installations: Case studies for mountain and island. *International Journal of Precision Engineering and Manufacturing, 17*(6), 815–822.
2. Abu-Hamdeh, N. H., & Almitani, K. H. (2017). Construction and numerical analysis of a collapsible vertical axis wind turbine. *Energy Conversion and Management, 151,* 400–413.
3. Staudt, L. (2010). Design and development of small wind turbines. In *Chapter of the book "WIT Transactions on State of the Art in Science and Engineering"* (Vol. 44). Southampton: WIT Press. https://doi.org/10.2495/978-1-84564-205-1/07.
4. Gwon, T. (2011). Structural analyses of wind turbine tower for 3 kW horizontal-axis wind turbine. Thesis. San Luis Obispo: California Polytechnic State University, August 9.
5. Ganser, H., Mamayek, S., Samaroo, M., & Wolkiewicz, D. (2014). Design framework for comparing wind turbine erection methods. Thesis, Worcester Polytechnic Institute, April 10.
6. "Small Wind Guidebook", Web page, WINDExchange. (2018). https://windexchange.energy.gov/small-wind-guidebook#parts. Accessed 29 Dec 2018.
7. "Gaia-Wind Cook up Self Raising Tower", Web page, FarminguK, 14 August. (2013). https://www.farminguk.com/news/Gaia-Wind-Cook-up-Self-Raising-Tower-_26232.html. Accessed 29 Dec 2018.
8. "PMM telescopic masts with pressurized air elevation 9 m/10 m", Online Brochure, Wimo.com. (2018). https://www.wimo.com/mast-pneumatic_e.html. Accessed 29 Dec 2018.
9. "Telescopic mast and tower elevation solutions", Online Brochure, Will-Burt Company. (2018). https://www.willburt.com/download/product_brochures/Telescopic-Mast-And-Tower-Elevation-Solutions-Product-Brochure.pdf. Accessed 29 Dec 2018.
10. Sundin, E. "Telescopic Mast", US Patent 4580377.
11. Brannan, P., & Spraggon, M. "Telescopic Mast", UK Patent 2497921.
12. Creaser Jr., C.W., Hollis N.H., "Telescoping Lightweight Antenna Tower Assembly and the Like". US Patent US5101215A.
13. Gremillion, E.J. "Extendable antenna mast with independent retracting and lifting cables". US Patent 4785309.
14. "ITS Telescopic Tower Systems". (2018). Online Brochure, Integrated Tower Systems Inc. http://www.itstowers.com/files

/FIXED%20FOUNDATION%20TOWERS%20R21716.pdf. Accessed 29 Dec 2018.
15. Van Treuren, K.W. (2016). "Small horizontal axis wind turbines: Current status and future challenges". In Proceedings of the ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition (Vol. 9), Seoul, South Korea, June 13–17.
16. Bang, H. J., Kim, H. I., & Lee, K. S. (2012). Measurement of strain and bending deflection of a wind turbine tower using arrayed FBG sensors. *International Journal of Precision Engineering and Manufacturing, 13*(12), 2121–2126.
17. Bhandari, B., Poudel, S. R., Lee, K. T., & Ahn, S. H. (2014). Mathematical modeling of hybrid renewable energy system: A review on small hydro-solar-wind power generation. *International Journal of Precision Engineering and Manufacturing, 1*(2), 157–173.
18. Lee, K. S., & Bang, H. J. (2012). A study on the prediction of lateral buckling load for wind turbine tower structures. *International Journal of Precision Engineering and Manufacturing, 13*(10), 1829–1836.
19. Oh, Y., Kim, K., Kim, H., & Paek, I. (2015). Control algorithm of a floating wind turbine for reduction of tower loads and power fluctuation. *International Journal of Precision Engineering and Manufacturing, 16*(9), 2041–2048.
20. Baek, J.-H., Kim, C.-W., Kim, Y.-C., Park, H.-C., Shi, W., & Shin, H.-K. (2012). Study on the marine growth effect on the dynamic response of offshore wind turbines. *International Journal of Precision Engineering and Manufacturing, 13*(7), 1167–1176.
21. Shi, W., Park, H. C., Chung, C. W., Shin, H. K., Kim, S. H., Lee, S. S., et al. (2015). Soil-structure interaction on the response of jacket-type offshore wind turbine. *International Journal of Precision Engineering and Manufacturing, 2*(2), 139–148.
22. Wang, Q., Zhou, H., & Wan, D. (2012). Numerical simulation of wind turbine blade-tower interaction. *Journal of Marine Science and Application, 11*(3), 321–327.
23. Wang, X., Chen, T., Zhao, Q., Yuan, G., & Liu, J. (2016). Fatigue evaluation of grouted connections under bending moment in offshore wind turbines based on ABAQUS scripting interface. *The International Journal of Steel Structures, 16*(4), 1149–1159.
24. Ryzhenkov, M. A., Ermolenko, B. V., & Ermolenko, G. V. (2011). Environmental problems of wind power engineering. *Thermal Engineering, 58*(11), 962–969.
25. Axisa, R., Muscat, M., Sant, T., & Farrugia, R. N. (2017). Structural assessment of a lattice tower for a small, multi-bladed wind turbine. *The International Journal of Energy and Environmental Engineering, 8*(4), 343–358.
26. Uys, P. E., Farkas, J., J´armai, K., & van Tonder, F. (2007). Optimisation of a steel tower for a wind turbine structure. *Engineering Structures, 29,* 1337–1342.
27. Lagaros, N. D., & Karlaftis, M. G. (2016). Life-cycle cost structural design optimization of steel wind towers. *Computers and Structures, 174,* 122–132.
28. Dimopoulos, C. A., & Gantes, C. J. (2013). Comparison of stiffening types of the cutout in tubular wind turbine towers. *Journal of Constructional Steel Research, 83,* 62–74.
29. Darrow, J., Johnson, K., & Wright, A. (2011). Design of a tower and drive train damping controller for the three-bladed controls advanced research turbine operating in design-driving load cases. *Wind Energy, 14,* 571–601.
30. Ning, Andrew, & Petch, Derek. (2016). Integrated design of downwind land-based wind turbines using analytic gradients. *Wind Energy, 19,* 2137–2152.
31. Soman, Rohan N., Malinowski, Pawel H., & Ostachowicz, Wieslaw M. (2016). Bi-axial neutral axis tracking for damage detection in wind-turbine towers. *Wind Energy, 19,* 639–650.
32. Kenna, A., & Basu, B. (2015). A finite element model for prestressed or post-tensioned concrete wind turbine towers. *Wind Energy, 18,* 1593–1610.
33. Liu, W. (2016). Design and kinetic analysis of wind turbine blade-hub-tower coupled system. *Renewable Energy, 94,* 547–557.
34. Rebelo, C., Moura, A., Gervásio, H., Veljkovic, M., & Simões da Silva, L. (2014). Comparative life cycle assessment of tubular wind towers and foundations—Part 1: Structural design. *Engineering Structures, 74,* 283–291.
35. Hu, Y., Baniotopoulos, C., & Yang, J. (2014). Effect of internal stiffening rings and wall thickness on the structural response of steel wind turbine towers. *Engineering Structures, 81,* 148–161.
36. Chen, K., Song, M. X., & Zhang, X. (2013). The investigation of tower height matching optimization for wind turbine positioning in the wind farm. *Journal of Wind Engineering and Industrial Aerodynamics, 114,* 83–95.
37. Sarkar, A., & Gudmestad, O. T. (2013). Study on a new method for installing a monopile and a fully integrated offshore wind turbine structure. *Marine Structures, 33,* 160–187.
38. Brodersen, M. L., & Høgsber, J. (2014). Damping of offshore wind turbine tower vibrations by a stroke amplifying brace. *Energy Procedia, 53,* 258–267.
39. Perelmuter, A., & Yurchenko, V. (2013). Parametric optimization of steel shell towers of high-power wind turbines. *Procedia Engineering, 57,* 895–905.
40. Fujiyama, C., Yonetsu, K., Maeshima, T., & Koda, Y. (2014). Identifiable stress state of wind turbine tower-foundation system based on field measurement and FE analysis. *Procedia Engineering, 95,* 279–289.
41. Sintra, H., Mendes, V. M. F., & Melício, R. (2014). Modeling and simulation of wind shear and tower shadow on wind turbines. *Procedia Technology, 17,* 471–477.
42. van der Zee, T., Jan de Ruiter, M., & Wieling, I. (2017). The C-Tower project—A composite tower for offshore wind turbines. *Energy Procedia, 137,* 401–405.
43. Fitzgerald, B., Sarkar, S., & Staino, A. (2018). Improved reliability of wind turbine towers with active tuned mass dampers (ATMDs). *Journal of Sound and Vibration, 419,* 103–122.
44. Zhang, R., Zhao, Z., & Dai, K. (2019). Seismic response mitigation of a wind turbine tower using a tuned parallel inerter mass system. *Engineering Structures, 180,* 29–39.
45. Nezamolmolki, D., & Shooshtari, A. (2016). Investigation of nonlinear dynamic behavior of lattice structure wind turbines. *Renewable Energy, 97,* 33–46.
46. Cheng, Y., Xue, Z., Jiang, T., Wang, W., & Wang, Y. (2018). Numerical simulation on dynamic response of flexible multi-body tower blade coupling in large wind turbine. *Energy, 152,* 601–612.
47. Kang, W., Zhang, C., & Yu, J. (2016). Stochastic extreme motion analysis of jack-up responses during wet towing. *Ocean Engineering, 111,* 56–66.
48. Cao, Y., Nie, W., Hu, X., Zhang, S., Meng, Z., Xin, L., et al. (2016). Parameter sensitivity study of dynamic response for jack-ups by FEM analysis. *Ocean Engineering, 124,* 125–134.
49. Technical Specifications. (2012). Wind turbine Libellula 55 kW, ARIA S.r.l., Viale Vittorio Veneto 60, 59100 Prato, Italy, rev.4 del 23/10/2012.

Antonio Pantano is a professor in Mechanical Engineering at the Dipartimento di Ingegneria (Engineering Department), University of Palermo, Palermo, Italy. He obtained a MS and PhD in Engineering Mechanics from Michigan State University, respectively, in 1999 and 2002. He worked as researcher at Massachusetts Institute of Technology from 2002 to 2004. He joined the University of Palermo in 2004. Research interests: computational mechanics, mechanical design, numerical methods for engineering, mechanical engineering aspects of micro/nanoscale engineering, nondestructive evaluation, wind turbines, biomimetic. He has contributed approximately 100 papers in journals and conference proceedings.

Tullio Tucciarelli is professor of "Hydraulic Engineering" at University of Palermo since November 2004. He has been principal investigator of three two-years national projects involving several Italian Universities, as well as scientific coordinator of three regional projects in the 2001–2007 and 2007–2014 periods, including the PERIMA project. He is author of about 70 papers in highly ranked international journal, with h-index 15. He is member of the proficiency evaluation committee for the Italian professor candidates in the 2018–2020 period in the field of Hydraulic Engineering.

Nicola Montinaro is a mechanical engineer and got its PhD in mechanical design with a thesis on nanostructured material collaborating with the University of Cambridge. He's author of numerous research articles on composite material, nanostructured material and innovative non destructive thermographic and ultrasound inspection. He currently works at the Dipartimento di Ingegneria at Università degli Studi di Palermo.

Antonio Mancino is a mechanical engineer with two MS, one in mechanical design and one in energy efficiency and alternative energy resources. He was involved as fellow in two research projects at the Dipartimento di Ingegneria at Università degli Studi di Palermo: one on the design of a telescopic tower for wind energy production and one on development of innovative eco-compatible composite materials reinforced with natural fibers. He worked in several companies as mechanical designer.