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Technical Report

Lightweight structure design for wind energy by integrating nanostructured materials

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A B S T R A C T

Wind power develops very fast nowadays with high expectation. Although at the mean time, the use of taller towers, however, smacks head-on into the issue of transportability. The engineering base and computational tools have to be developed to match machine size and volume. Consequently the research on the light weight structures of tower is carrying out in the main countries which are actively developing wind energy. This paper reports a new design scheme of light weight structure for wind turbine tower. This design scheme is based on the integration of the nanostructured materials produced by the Surface Mechanical Attrition Treatment (SMAT) process. The objective of this study is to accomplish the weight reduction by optimizing the wall thickness of the tapered tubular structure. The basic methods include the identification of the critical zones and the distribution of the high strength materials according to different necessities. The equivalent strength or stiffness design method and the high strength material properties after SMAT process are combined together. Bending and buckling are two main kinds of static loads concerned in consideration. The study results reveal that there is still enough margin for weight reduction in the traditional wind turbine tower design.

1. Introduction

After the 1973 oil crisis, several countries initiated the renewable energy programs, including biomass, geothermal, hydropower, solar, wind, tidal and wave, offers tremendous benefits for meeting global energy needs [1]. Wind power plays an important and growing role in helping to affordably satisfy electricity needs, and can do without producing damaging greenhouse gas emissions [2]. Globally it seems reasonable to expect wind power's contribution to our electricity needs to continue to grow strongly [3,4]. Worldwide growth in wind generation since 1994 has been 30% or more annually [5]. The global cumulative installed wind power capacity increased to more than 282 GW by the end of 2012.

Modern wind technology is able to operate effectively in a wide range of sites [6,7]. In order to increase efficiency, larger-scale dimensions are the trend in the current wind energy industry. As the equipment is reaching higher levels, this industry has reached an obstacle: As the height of the towers increases, the transportation, assembly, installation, and servicing of the components also become increasingly more difficult and costly. The weight and cost of conventional tubular towers increases exponentially with height. The cost proportion of a tower and transportation cost proportion are even larger for some countries such as China where the high wind-energy density zones are located in the areas without dense road network. Based on this reason, research has been done on tower designs [8,9]. One central problem with respect to the future economics is to find out the cost reduction potential.

As the largest component of wind turbine equipment, the tower attracts a wide variety of concerns. In the past two decades, a great deal of analyses and optimization schemes have been carried out on wind turbine towers to try to make them work more effectively. At the beginning of the 21st century, Negm and Maalawi had already proposed an optimized structure for wind turbine towers; the model they used was a cylindrical thin-walled structure [10].

Although the main field of wind power is fluid dynamics, researchers have extended their interest to several different fields of mechanics. Fatigue loads on wind turbine towers were investigated by Mikitarenko and Perelmuter [11]. Bazeos et al. performed a stability analysis on a steel tower [12]. Lavassas et al. analyzed a prototype of 1 MW steel tower [13]. Murtagh et al. studied the response of a tower to the wind along tower [14]. Binh et al. discussed the non-Gaussian response of towers [15]. Chou and Tu synthesized failure analysis and risk management in a collapsed tower case [16]. Uys et al. [17] and Bahadori et al. [18] suggested an optimization design method for towers through calculation

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and experiments. AlHamaydeh and Hussain discussed an optimized wind tower design based on frequency while the design focused on the foundation of the tower [19]. These research results have formed the basis for structural improvement.

Material selection is based on production design requirements, sometimes starting from the concept design stage [20]. A lighter structural design is getting more involved with material selections [21,22]. Tower configurations include lattice type, concrete type, free-standing steel tubular towers, guyed steel tubular towers and other special designs. Among them, the most popular configuration for a tower is a free-standing steel tubular tower. The section shape (e.g., solid, tubular, and I-section) of a component can be a variable in the process of the material selection. This is important for some certain modes of loading. This fact provides an opportunity to combine different materials with related section dimensions. If high-strength materials are used, a better section shape will be implemented in tower design to achieve the lightweight structural design.

Nanocrystalline and ultrafine-grained metals and alloys, with average and range of grain sizes typically smaller than 100 nm, have been the subject of considerable research in recent years [23]. These materials are believed to possess some appealing physical and mechanical properties as compared with their coarse-grained counterparts. Several laboratory-scale processing techniques are available to produce nanocrystalline metals and alloys [24,25].

In 1999, the process of surface mechanical attrition treatment (SMAT) was first proposed by Lu and Lu [26]; this process has attracted increasing interest in recent years. SMAT is an efficient way to create nanostructured surface or subsurface layers on a metal's surface [27,28]. Consequently, it has been extensively developed and exploited in the past decade [29,30]. SMAT are especially good at processing plate, tube and wire structures.

SMAT is an effective advanced technology for the improvement of metallic materials' mechanical and physical properties. Its combination with modern industry in the future will be valuable. To implement this more effectively, a great amount of research work has been conducted on the effect when SMAT is introduced to different original materials, including Cu [31], Ti [32], Fe [33,34], Al [35], and Ag–Cu [36]; and their physical properties in varied environmental conditions including thermal capability change, wear and corrosion [37–41]. SMAT also has excellent performance on fatigue life of materials. Since most of fatigue fractures of materials occur on their surfaces, the improvement of the surface microstructure and properties may enhance the global fatigue behavior of materials. Roland et al. reported a 21% improvement on the fatigue limit of AISI 316L with nanostructures [42].

The properties of SMAT materials compared with mild steel, conventional HSS and AHSS are shown in Fig. 1.

The advantages of SMAT are considered to be its efficiency in obtaining nano-scale crystalline layers, its universality for many types of metallic materials, its flexibility with regard to the target strength or other mechanical properties, and its potential applications on certain products with critical strength requirements.

This study analyzes a current wind turbine tower structure. The locations of weakness in the tower under different loadings are pointed out. Based on an equivalent strength design, various types of materials related to different section parameters can be provided. The enhancement proposal using SMAT materials and appropriate wall thickness of tower is also listed and compared with other options. The advanced material in demonstration is 304 grade stainless steel after SMAT processing. It is a type of typical and representative materials in industries and has remarkable properties after SMAT processing. It also has excellent corrosion resistance which is expected in offshore wind power applications because natural sea water is the most corrosive of all natural environments.

2. Loading analysis

Wind turbine tower is a complex structure. It usually has a tapered shape instead of simple cylindrical shape with a varying wall thickness. In the previous discussions, mostly only cylindrical shape was involved. In this paper, all loading analyses are carried out on tapered structures.

2.1. Bending

According to the flexure formula of the Bernoulli–Euler beam theory, there is:

$$\sigma_x = \frac{My}{I} \tag{1}$$

Furthermore, for a tapered cantilever beam with linearly-varying thickness which is supporting an external load as shown in Fig. 2, it has:

$$\sigma_A = \frac{Fx}{\pi\left[r_1 + \left(\frac{r_2-r_1}{L}\right)x\right]^2\left[t_1 + \left(\frac{t_2-t_1}{L}\right)x\right]}, \quad (r_1 \neq r_2, t_1 \neq t_2, t \ll r) \tag{2}$$

where σ_A is the bending stress where the distance from the smaller end of the tapered tubular structure is x. r_1 is the mean radius of the smaller end of the tapered tubular structure. r_2 is the mean radius of the bigger end of the tapered tubular structure. t_1 is the wall thickness of the smaller end of the tapered tubular structure. t_2 is the wall thickness of the bigger end of the tapered tubular structure. L is the total length of the tapered tubular structure. And let:

$$\begin{aligned}\frac{\partial\sigma_A}{\partial x} = &\frac{F}{\pi[r_1 + (\frac{r_2-r_1}{L})x]^2[t_1 + (\frac{t_2-t_1}{L})x]} \\ &- \frac{2Fx}{\pi[r_1 + (\frac{r_2-r_1}{L})x]^3[t_1 + (\frac{t_2-t_1}{L})x]}\cdot\frac{r_2-r_1}{L} \\ &- \frac{Fx}{\pi[r_1 + (\frac{r_2-r_1}{L})x]^2[t_1 + (\frac{t_2-t_1}{L})x]^2}\cdot\frac{t_2-t_1}{L} = 0\end{aligned} \tag{3}$$

The solution of Eq. (3) is:

$$x = \frac{\left(t_1^2 + 8t_1r_1\cdot\frac{t_1-t_2}{r_1-r_2}\right)^{1/2} - t_1}{4(t_2-t_1)}\cdot L \tag{4}$$

This solution indicates the location on the wall of this taper where the optimal σ_A can be achieved. And the fact $\frac{\partial^2\sigma_A}{\partial x^2} < 0$ shows that the stress is the maximum stress.

It can also be approved that, when the wall thickness is a constant, the maximum stress should occur at somewhere in the middle of the taper if the structure satisfies $r_1 < \frac{1}{2}r_2$. Otherwise it occurs at the fixed end of the taper. When the wall thickness varies over a very small range and the biggest wall thickness is far smaller compared with the mean radius of the taper, this rule can be followed to identify the location of the maximum bending stress.

Therefore, for a tapered thin-walled structure with a linearly-varying thickness, the dangerous cross-section location can be easily determined. And after that, this kind of structure can be handled as a cylindrical structure in the next tubular structural selection system stage.

2.2. Eccentric compression

As is known, when a column is eccentrically loaded, there are two components of maximum stress:

$$\sigma_{\max} = \frac{F}{A} + \frac{M_{\max}c}{I} \tag{5}$$

where A is the cross-sectional area of column. c is distance from the neutral axis to the extreme edge of the cross-section of column.