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Life-cycle cost structural design optimization of steel wind towers

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ABSTRACT

The objective of this work is to propose a design procedure, formulated as a structural design optimization problem, for designing steel wind towers subject to constraints imposed by the Eurocode. For this purpose five test examples are considered, in particular steel wind towers varying on their height are optimally designed with minimum initial cost, while the wind load is calculated according to Eurocode 1 Part 2–4 and design constraints imposed by Eurocode 3 on shell buckling and local buckling of flat ring-stiffeners are implemented. Furthermore, two formulations are examined differing on the shape of the wind tower along the height. While, for the solution of the optimization problem the Optimization Computing Platform (OCP) was used.

1. Introduction

Renewable energy sources (RES) are traditionally inefficient providing low rate of return which suggests high implementation cost; however, much work in the areas of technology and proper power source location is tackling these issues. Since early 1980s, many wind parks have been constructed and significant work has been published related to the assessment of wind park efficiency. So far several hundred individual wind turbines, which are connected to the electric power transmission network, form large offshore or onshore wind parks have been in-stalled. Although, offshore wind farms can take advantage of more frequent and powerful winds than are available to land-based installations and they have less visual impact on the landscape, their construction cost is considerably higher. On the other hand, onshore wind facilities harness winds at higher altitudes, which are stronger and more consistent, through the appropriate tower height, while small wind parks are used to provide electricity to isolated locations.

During the last three decades many numerical methods have been developed to meet the demands of structural design optimization. These methods can be classified in two categories, the deterministic and probabilistic ones. Mathematical programming methods are the most popular methods of the first category and in particular the gradient-based optimizers. These methods make use of local curvature information, derived from linearization of the objective and constraint functions by using their derivatives with respect to the design variables at points obtained in the process of optimization, to construct an approximate model of the initial problem. Heuristic and metaheuristic algorithms are nature-inspired or bio-inspired and belong to the probabilistic category of methods. Metaheuristic algorithms for engineering optimization among others include genetic algorithms (GA), simulated annealing (SA), particle swarm optimization (PSO), ant colony algorithm (ACO), artificial bee colony algorithm (ABC), harmony search (HS), firefly algorithm (FA), and many others [1].

A rather limited number of studies concerning design optimization of wind tower systems has been published so far. In particular, Negm and Maalawi [2] presented optimization models for the design of wind tower structures where the main tower body was composed by uniform segments while cross-section area, radius of gyration and height of each segment were the design variables. Harte and Van Zijl [3] presented some aspects of the classical wind energy turbines and discussed topics related to the solar chimney concept (like the wind action, eigen frequencies, stiffening and shape optimization). Uys et al. [4] studied the problem of minimum cost design of steel wind towers where the optimum shell thickness, number of stiffeners and dimensions of the stiffeners were defined. Maalawi [5] presented a design optimization model for engaging wind tower structure frequencies (tower/nacelle/rotor) in free yawing motion. The objective of the work by Silva et al. [6] was to find optimized designs of reinforced concrete

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(RC) towers taking into consideration the cost, computational time, construction techniques and precision of structural models, when subjected to dynamic wind loads while considering the vibration effects of the wind energy generator's components. The objective of the study by Yıldırım and Özkol [7] was to optimize the mass of a 1.5 MW steel wind tower using GA in accordance to ASCE 7-98, AISC-89 and IEC61400-1 design codes. Nicholson [8] used Microsoft Excel in order to design wind towers along with their foundation taking into account the effect of deflections. In the chapter by Maalawi [9] various optimization approaches for wind tower design were presented aiming to develop topology optimization methods for designing smart wind turbine structures. Zwick et al. [10] implemented an iterative optimization approach and have found that structural analyses of the wind tower systems, keeping constant the dimension of the members over the tower height, provide indications about the required dimensions for optimized designs. Katyal et al. [11] performed parametric optimization of wind turbine tubular towers using the wind speed NWP model data for a complex hilly terrain at Idukki District of Kerala.

In this paper, a design procedure formulated as a structural design optimization problem is proposed, for designing steel wind towers subject to constraints imposed by the Eurocodes. For this purpose five test examples are considered, in particular steel wind towers varying on their height are optimally designed with minimum initial cost, while the wind load is calculated according to Eurocode 1 Part 2–4 [12] and design constraints imposed by Eurocode 3 [13] on shell buckling and local buckling of flat ring-stiffeners are implemented. Furthermore, two formulations are examined differing on the shape of the wind tower along the height resulted from the optimization procedure, while three material properties for the structural steel are considered. For the solution of the optimization problem the Optimization Computing Platform (OCP) [14] is used, while in [15] OCP was further developed to be able to handle steel wind towers in terms of optimization and structural design. In the current study, we have added advanced features to the variant of OCP presented in [15], in particular: (1) various problem formulations of the optimization problem are now allowed, varying with reference to the type of constraint functions and the design variables used for the formulation, (2) the cascade optimization concept can now be used for this type of structures while (3) various techno-economic studies have been performed on the optimum designs achieved.

2. Wind tower design optimization – Generic problem formulation

An optimization problem can be formulated in standard mathematical terms as a non-linear programming problem that in general form can be written as follows:

$$\begin{aligned} &\text{opt (min / max)} && \mathsf{F}(\mathbf{s}) \\ &\text{subject to} && g_j(\mathbf{s}) \leqslant 0 \;\; j = 1,\ldots,m \\ & && s_i^L \leqslant s_i \leqslant s_i^U \;\; i = 1,\ldots,n \end{aligned} \tag{1}$$

where $\mathbf{s}$ is the vector of design variables, $\mathsf{F}(\mathbf{s})$ is the objective function to be optimized, $g_j(\mathbf{s})$ are the behavioral constraints imposed by the design codes and/or the design engineer while s_i^L and s_i^U are lower and upper bounds of the ith design variable.

In order to ensure an efficient design of the wind turbine tower structural system, several limit state design checks based on static or dynamic analyses should be satisfied along with limitations on the maximum allowable tower top displacement and natural frequencies. Wind turbine towers are mainly simulated numerically as simple cantilever beams; however, their section forms a thin-walled cylindrical shell and therefore, several issues are identified through structural analysis such as the local buckling of the shell structure or the stress concentrations around the door opening which must be thoroughly examined. Their design is governed by the extreme wind loading, while earthquake loading should also be taken into account when designing the turbine tower on seismic hazardous areas. The evaluation of the shell thicknesses of the tower is performed by means of the plastic limit state design (LS1-plastic), buckling limit state design (LS3-buckling) and fatigue limit state design (LS4-fatigue) as described in Eurocode 3 [13]. More details can be found in the work by Baniotopoulos et al. in [16].

The generic overall cross section design, defined by the outside diameter and wall thickness should take into account the restriction on transportation and therefore may not exceed 4.5 m. Additionally, due to limitations on carbon steel that can be processed in a standardized cylindrical form, the wall thickness shall not exceed 40 mm. Regarding the allowable maximum displacement of the top of the wind turbine tower, this is set conservatively to 1.00% of the total height of the tower in order to avoid excessive movement that would oppose the efficient operation of the wind turbine. Critical for the wind turbine tower design is the avoidance of the resonance phenomenon. Specifically, the natural frequency of the whole structure of the tower should be at a safe distance from the excitation frequencies in the operation phase of the wind turbine rotor. Common values for operating frequencies for small wind turbines are between 0.23 Hz and 0.52 Hz and for large wind turbines in the range of 0.10–0.30 Hz. The natural frequency of the tower structure should remain above the highest operating frequency of the wind turbine, multiplied by a safety factor, typically between 1.1 and 2.0, in order to avoid resonance at any point during the operation.

3. Solving the optimization problem

The solution of the optimization part of the problems presented herein, is dealt with the optimizer component of the optimization computing platform (OCP) presented recently by the authors in [14]. This component is equipped with the eight metaheuristic optimization algorithms (MOA) which have been successfully applied in various challenging problems [17,18]. Furthermore, the cascade optimization concept [19] also implemented into the computing platform was used in the current study.

3.1. Differential evolution

Storn and Price in [20] proposed a floating point evolutionary algorithm for global optimization and named it differential evolution (DE). Several variants of DE have been proposed so far [21], according to the variant implemented in OCP a donor vector $\boldsymbol{v}_{i,g+1}$ is generated first:

$$\boldsymbol{v}_{i,g+1} = \boldsymbol{s}_{r_1,g} + F \cdot (\boldsymbol{s}_{r_2,g} - \boldsymbol{s}_{r_3,g}) \tag{2}$$

Integers r_1, r_2 and r_3 are chosen randomly from the interval $[1, NP]$ while $i \neq r_1$, r_2 and r_3. NP is the population size, F is a real constant value, called the mutation factor. In the next step the crossover operator is applied by generating the trial vector $\boldsymbol{u}_{i,g+1}$ which is defined from the elements of $\boldsymbol{s}_{i,g}$ or $\boldsymbol{v}_{i,g+1}$ with probability CR. The last step of the generation procedure corresponds to the implementation of selection operator where vector $\boldsymbol{s}_{i,g}$, is compared to trial vector $\boldsymbol{u}_{i,g+1}$:

$$\boldsymbol{s}_{i,g+1} = \begin{cases} \boldsymbol{u}_{i,g+1} & \text{if } \mathsf{F}(\boldsymbol{u}_{i,g+1}) \leqslant \mathsf{F}(\boldsymbol{s}_{i,g}) \\ \boldsymbol{s}_{i,g} & \text{otherwise} \end{cases} \tag{3}$$
$$i = 1, 2, \ldots, NP$$

where $\mathsf{F}(\boldsymbol{s})$ is the objective function to be optimized (see Eq. (1)), while without loss of generality the implementation described in

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