# Optimization of a tall wind turbine tower

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## Résumé :

*Cet article présente un cas de conception optimale pour une tour éolienne de grande hauteur. Ce problème d'optimisation structurelle est résolu en utilisant un algorithme d'optimisation par essaim de particules en formulation Lagrangienne augmentée. Cette optimisation doit vérifier des propriétés matérielles et des contraintes imposées par les normes du génie civil. La vérification des contraintes est réalisée à l'aide d'un outil d'analyse mécanique. Les résultats illustrent la capacité de la boucle proposée à fournir une conception à moindre coût d'une tour éolienne.*

## Abstract

*This paper presents an application of optimal design for tall wind turbine tower. This structural optimization problem is solved by using an augmented Lagrangian particule swarm based optimizer. It is constrained by both material properties and civil engineering standards. The verification of constraints is carried out by a mechanical modeling tool. Results show the ability of the proposed loop to find lowest cost design for wind tower.*

**Mots clefs : optimization, wind turbine, high tower.**

## 1 Introduction

The significant increase in wind turbine dimensions is necessary for the H2020 program's energy production targets. The current technological innovations aims at increasing the height of wind towers in order to enhance their profitability. Because it can gain access to better wind resources at higher altitudes. In the case of land-based wind tower, hub height is currently usually fixed at an altitude of 100 meters. However, this height is increasing up to 140 meters in some new installations [1].

Meanwhile, the structure of tower must be oversized in order to ensure their lifetime and mechanical performance. This reduces the interest of wind power comparing to other energy resources. This growing demand for wind energy's profitability fosters new research fields. The structural optimization of the wind tower is asked to improve the economic profitability of this kind of resource.

This paper gives a demonstration for solving such optimization problem. This work follows the EOLIFT Project (collaborating work between Freyssinet, INSA Rouen Normandie and Université du Havre) which targets $100m$ to $140m$-high onshore wind towers supporting turbines of 3 to $6MW$. For such dimensions, concrete represents an alternative solution to steel conventional masts because of its economic (cheaper) and technical advantage (more sturdy). Moreover, the flexibility of shaping the concrete allows to envisage more precise optimized designs. However, the increase in the number of optimization variables requires the use of robust analysis tools.

## 2 Optimization of a wind turbine tower

The purpose of optimization is to reduce the construction cost of a tall wind turbine tower. This cost is determined by both materials prices and construction costs. Hence, the objective function to be minimized depends on volume of materials with weighted coefficients representing construction costs. The design of the tower is driven by a set of parameters $\mathbf{P}$ that has to be chosen in order to minimize the cost (eq. 1).

$$\mathbf{P}^* = \underset{\mathbf{P}}{\mathrm{ArgMin}} \left( Cost \left( \mathbf{P} \right) \right) \tag{1}$$

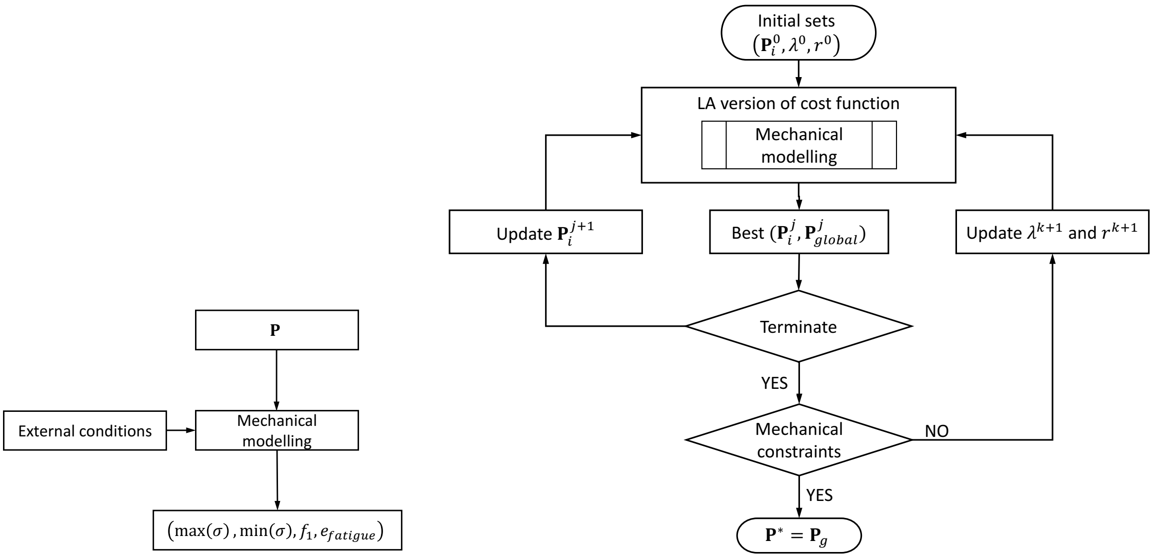
The studied wind turbine is calibrated to ensure a given level of power production. So the height of the tower and the external conditions are imposed. The proposed design must then verify several mechanical conditions. Firstly, the stress state $\sigma$ analysis in the whole tower is performed by static analysis and validated by using Eurocode. Secondly, the dynamic behavior of tower has to be so that its first natural frequency $f_1$ is in an allowable domain in order to avoid resonance with the coupled wind turbine. In this case, the allowable boundaries of frequencies are given by the manufacturers of wind turbines. The last restraint concerns the cumulative damage in the structure. The fatigue analysis is evaluated by applying civil engineering design code [5]. The material performance is characterized by a Wöhler curve associating the magnitude of a cyclic stress (S) against the logarithmic scale of cycles number to failure (N). The rainflow count strategy is used for non constant cycle stresses. Then, the cumulative fatigue damage $e_{fatigue}$ is evaluated using Palmgren-Miner linear damage hypothesis. A mechanical modeling is realised to validate these optimization constraints. The structure is analyzed by Timoshenko beam elements through the FEA Code_Aster software to acces all static stress states and natural frequencies. The fatigue analysis is carried out by python programming. A parametric procedure (fig. 1-a) allows to evaluate mechanical characteristics $\left( max \left( \sigma \right), f_1, e_{fatigue} \right)$ for a given set of design paramters $\mathbf{P}$. The Augmented Lagrangian Particle Swarm Optimizer (ALPSO) is an efficient algorithm for dealing with constrained design optimization problems [7]. It is a population-based global optimization method, which allows to solve large scale problems and has already been successfully applied to structural optimization [8, 9, 10]. It uses an augmented Lagrange multiplier approach to handle constraints so that it can guarantee constraint feasibility in the optimization solution. The process starts with an initial population of sets of design parameters ${\mathbf{P_i}}^0$, Lagrange multipliers $\lambda^0$ and penalisation coefficients $\mathbf{r}^0$. These sets are updated (fig. 1-b) so that minimizing the cost and verifying the mechanical constraints for each $\left( {\mathbf{P_i}}^{k+1}, \lambda^{k+1}, \mathbf{r}^{k+1} \right)$. At the end of the iterative process, the set giving the lower cost is chosen as the result of the optimization.

Table 1: Mechanical constraints

| Characteristic | Condition to verify |
|---|---|
| $max \left( \sigma \right)$ | $< \sigma_{design} = 0.6 \cdot f_{ck}$ |
| $min \left( \sigma \right)$ | $> 0$ |
| $f_1$ | $\in \left[ f_{lower}, f_{upper} \right]$ |
| $e_{fatigue}$ | $< 1$ |

## 3 Application to a $140m$ HH wind turbine

The tower studied in this paper is a $140m$ hub height concrete tower designed for a $3MW$ turbine. The shape combines conic and cylindric cross sections as following:



a - Mechanical modeling b - ALPSO optimization

Figure 1: Optimization strategy

- A conical concrete part with variant thickness of tower at bottom;
- A cylindrical concrete part with variant thickness in middle;
- A cylindrical metallic adapter with constant thickness on top.

The concrete part of tower is constructed by annular segments of fixed-height. The external dimensions, i.e. diameters of the cone and of the cylinder, are fixed. Each segment has a constant thickness. The whole concrete structure is prestressed by several post-tensioning tendons. Tendons are all located outside of the concrete volume and anchored on foundation at the ground level. The figure 2 illustrates the shape states during the calculation. Two soil conditions are considered: rigid restraints blocking displacements and rotations in all directions, or joint rotational springs with stiffness values of $150.10^9 Nm$. The applied loads on the tower are:

- Concrete structure's and top metallic adapter's self-weight;
- Wind turbine mass given by manufactory;
- Prestressing force at the end of tendons;
- The ultimate loads coming from IEC load cases [4] and given by contractor, which are applied at the top of the tower (moment and forces);
- Wind loads from bottom to top, based on a aerodynamic pressure and an exponential wind distribution [2, 3];
- The fatigue loads given at various levels (Markov matrices), coming from IEC computations as well;

The set of parameters $\mathbf{P}$ of the optimization is composed by the thickness $t_h$ of each concrete segment, where Markov matrices are available for fatigue analysis, and the prestress load of tendons $P_s$. Some

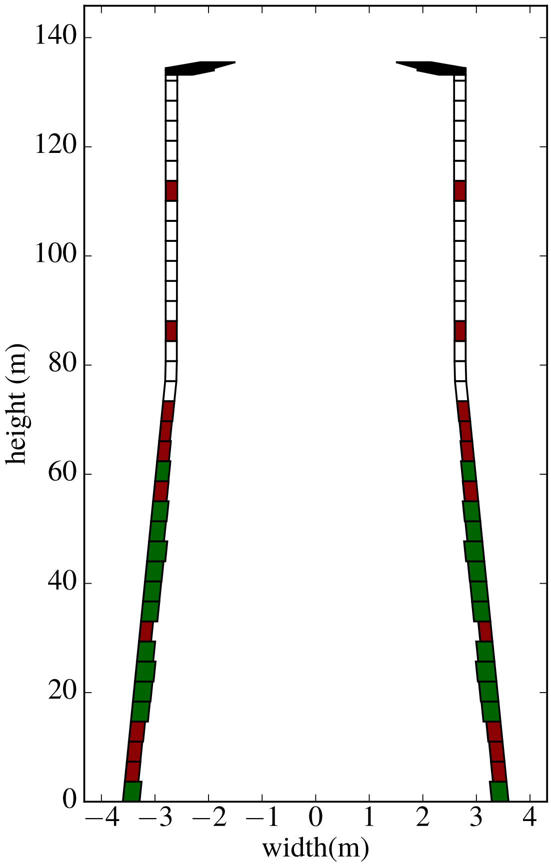


Figure 2: Cross-section view of tower (tendons are not shown)

sections can't be verified for fatigue since no data has been provided at this altitude by the nacelle manufacturor. For these sections (in white on figure 2), the thickness is computed by linear interpolation of surrounding optimized sections. Each configuration is studied trought the mechanical modeling tool so that the design constraints may be evaluated. In the figure 2, the red segment means the optimization constraints are not satisfied; the green means all constraints are satisfied in this segment.

The ALPSO is running with a population of 48 sets. An optimal solution is found after 48 iterations and 11560 calls of the objective function and thus, the mechanical modeling tool. About 18 hours were necessary to reach convergence, running in parallel on a 12 cores CPU. Comparing to the initial design (fig. 3 and fig. 4), 170 tons of concrete is saved that is 10% of initial weight.

# 4 Conclusions

In this paper, we presented the possibility of integrating mechanical modeling (FEA and fatigue analysis) into structural optimization problem for high-raise wind tower design. On the one hand, several types of analysis are performed in order to respect civil engineering standards. On the other hand, the structural optimization problem is solved by using an Augmented Lagrangian based optimizer to efficiently and reliably enforce constraints. concrete and ultra-high performance fiber reinforced concrete. It is also planned to couple the optimization loop with an aeroelastic computation software like FAST (NREL) in

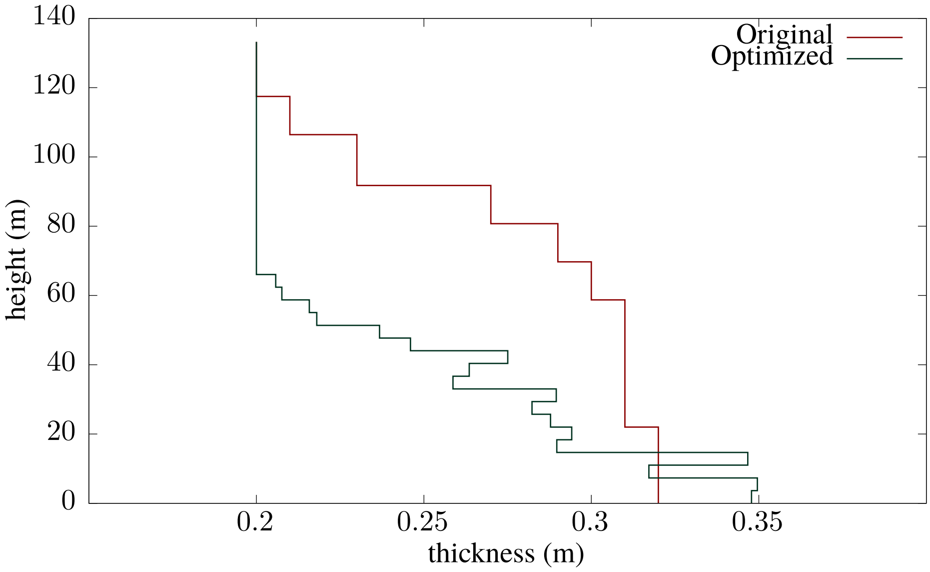


Figure 3: Thickness distribution along the tower.

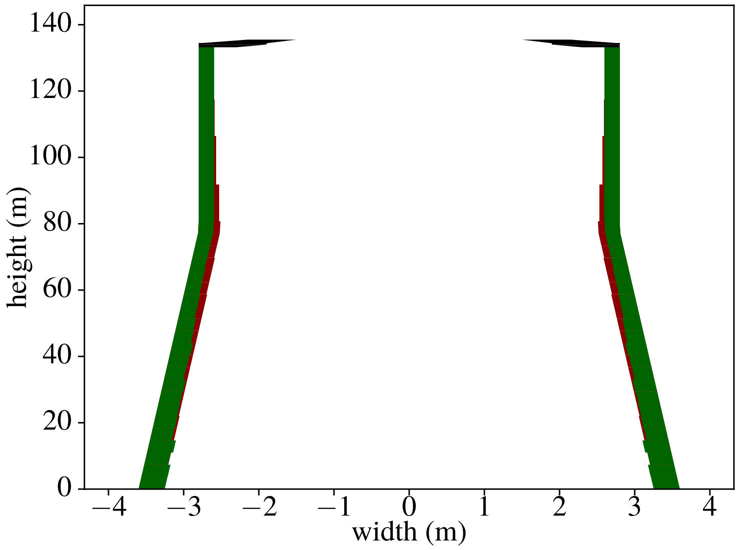


Figure 4: View of the optimized design compared to the original one.

order to improve the accuracy of ultimate and fatigue loads. The mechanical model may be improved too in order to handle more optimization constraints, with respect to the construction process or to the connections between each concrete part.

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