Topology optimization of a 500kW wind turbine main load frame

Ahmet Selim Pehlivan
Sabanci University
Istanbul, Turkey
e-mail: spehlivan@sabanciuniv.edu

Mahmut F. Aksit
Sabanci University
Istanbul, Turkey
e-mail: aksit@sabanciuniv.edu

Abstract- **As wind turbines get larger and larger, nacelle weight becomes more important as it affects cost, logistics and even turbine natural frequencies. This work presents a nacelle weight optimization process for a main load frame of a 500 kW wind turbine. While the weight is minimized structural strength has been preserved. In order to achieve an effective weight reduction, topology optimization methodology is used with the aid of finite element solvers like OPTISTRUCT. Combined wind, generator and gravity loading condition have been considered while stress analyses are conducted. The work started with an initial over safe 7000 kg design. Through topology optimization iterations 28.57 % weight reduction has been achieved. Using SIMP method, weight reduction or material removal locations were carefully identified. The redesigned nacelle main frame has maximum stress levels less than 40% of the material yield strength.**

Keywords: Topology optimization, bedplate, volume fraction.

I. Introduction

Wind energy is gaining increasing momentum over the last two decades. Newer and more advanced wind turbine designs are developed every year. Nacelle bedplate is one of the most significant components among the turbine subsystems considering strength, mounting and load transfer. There are different engineering approaches for bedplate design including fully cast, fully welded (Figure 1) and hybrid construction (Figure 2). A hybrid design consists of a cast iron main base and weld formed steel extension. In this work a hybrid configuration has been developed to achieve high stiffness with minimum overall weight.

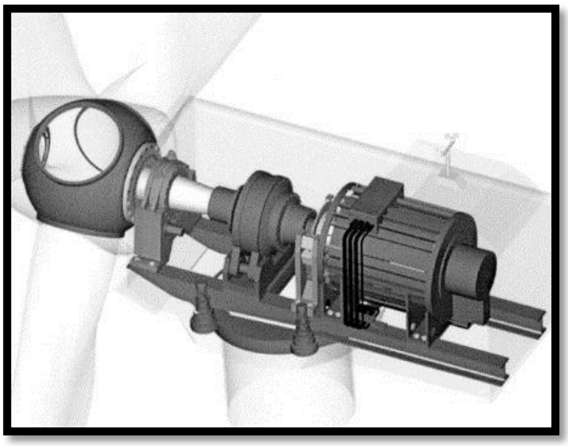

Figure 1: Fully welded bedplate frame design with other components. (2)

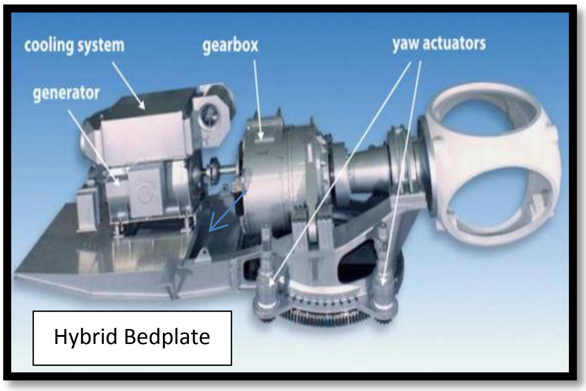

Figure 2: Hybrid bedplate design with other turbine components. [1]

Topology optimization is one of the well-known structural optimization methods that aim to find the best structural shape within given design space and certain boundary conditions. Topology optimization method is nowadays highly used by design engineers. The method is quite effective in determining unnecessary regions of a structure that minimally carries any loads that can be removed from the system without much expense of increased stress levels (see Figure 3). Topology optimization is a finite element based numerical method, which identifies the optimal material distribution that will have the maximum stiffness for a given set of boundary conditions and design criteria. For structural analyses, design parameters can be both stress and deflection values for a body.

Figure 3: 3D topology optimization sample (3).

A. *SIMP Model*

Solid Isotropic Material with Penalization (SIMP) method is used for topology optimization. The method uses material distribution via density to reduce weight of a given structure design with some boundary conditions. SIMP model has five different parameters to be considered. It uses these parameters to solve the problem with a technique called minimum compliance or maximum stiffness for the design set with optimum material distribution [2].

First of all, an objective function should be introduced among these parameters. This function has the form $\int_{\Omega} \emptyset(\rho) * d\Omega$, where Ω represents the design set or a field to be optimized. The function is to be minimized using minimal compliance method for topology that aims to maximize the stiffness of the structure [2] [3].

Ω is the second important parameter used in SIMP model. It is design space or allowable volume for topology optimization. This parameter is significant and widely used in OPTISTRUCT analyses for bedplate designs [2] [3].

Third parameter is the ρ_d value stated at the objective formula. It represents the discrete selection field, and always takes values between 0 and 1 according to the selection or deselecting of the points. This is a discrete optimization. An iterative approach is needed to get further results. The ρ_d value is also called as boundary surface zone which is discretely optimized [2] [3].

Other significant parameters for minimum compliance approach are the design constraints which are widely used in main optimization stage of the bedplate. These parameters can be stress values or deflections or mode frequencies. Iterative topology approach checks for the constraint values given by the designer. At the end of all iterations design constraints should be met.

Finally, the governing equations for the mathematical model are the most important part of the optimization process.

These equations are used in structural analyses. They are the equation sets that solve the physics behind the problem [2] [3].

II. Weight And Stress Optimization

The main reason for the use of topology optimization in this work is the need to reduce the weight of the bedplate. The initial design weighted around 7000 kg. The critical requirement during the optimization process is to achieve satisfactory margins for safety factor and stress carrying capabilities. The cast part was bulky and heavy before the optimization process. This is evident in the analysis results of the bulk model. There were a lot of regions in the structure that rarely carried any load, which made them unnecessary to keep. As illustrated in Figure 5, the analysis predicted minimally loaded regions, which are dark colored in stress plots. The color coding provides guidance towards possible low stress regions which can be subjected to material removal.

As shown in the Figure 4, before the optimization process the structure did not have any weight reduction cavities/holes. Based on the stress results shown in Figure 5, some manual material removal and trimming was possible. After some minor manual trims, the structure was still bulky, and weighted around 6500 kg. When integrated with the profile section, the whole bedplate assembly was around 7000 kg before the topology optimization was applied.

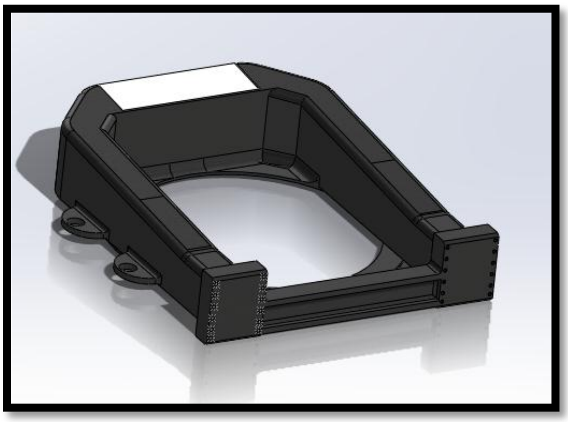

Figure 4: The bulky cast structure before optimization stage.

A. Boundary conditions and stress analysis

Topology optimization process has been applied on the cast frame due to evident opportunities identified by stress analyses. A maximum loading combination is considered while turbine is under full wind loads at maximum power production condition. Structural weights and all external loads are taken into consideration as boundary conditions. The mounting ring below the nacelle is fixed where it is attached to the tower for the stress analyses.

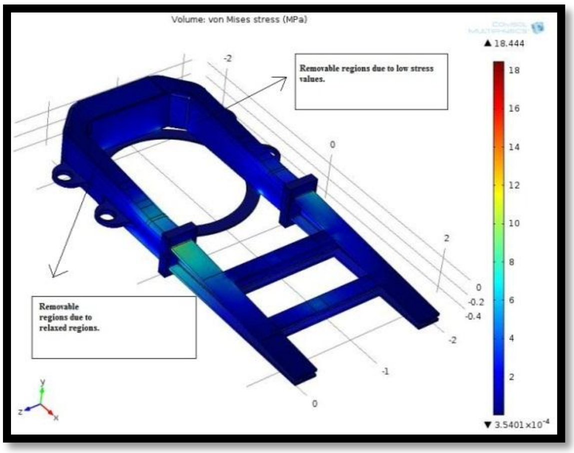

Figure 5: Stress results under certain loadings.

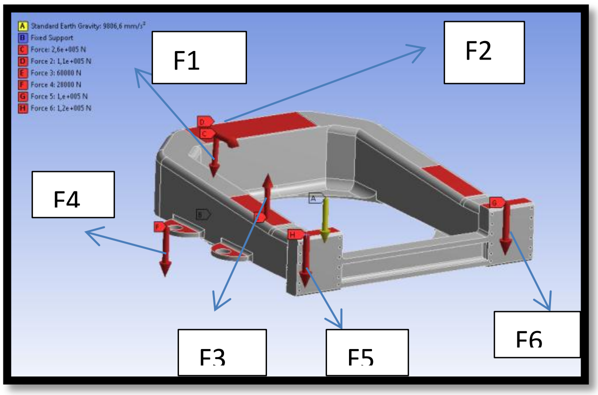

Figure 6: Loads illustrated on the cast part.

The applied load combination is illustrated in Figure 6. The ring below the cast frame constitutes a base for the entire nacelle connecting it to the ground through tower. Therefore, the support ring is fixed with 6 DOF constraints as shown in Figure 7.

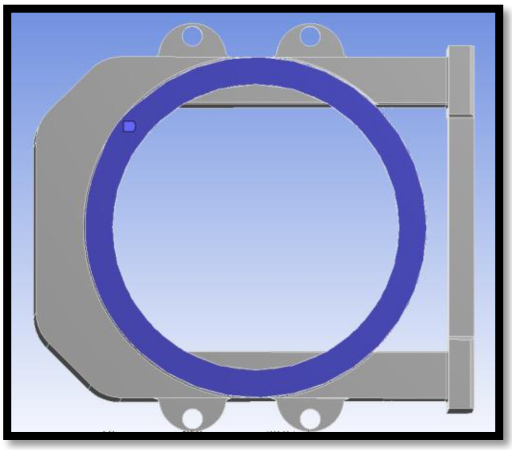

Figure 7: Fixed constraint for the stress analysis.

External forces that act on the system are considered under the maximum wind scenario. Due to large structural weights, universal gravity loads are also applied to achieve accurate stress analysis that will yield better optimization. The applied force values can be found in the table provided below.

Table 1: Applied boundary conditions for the stress analysis.

F1	260000 N
F2	110000N
F3	60000N
F4	7000 N (Each face)
F5	114000 N
F6	106000 N

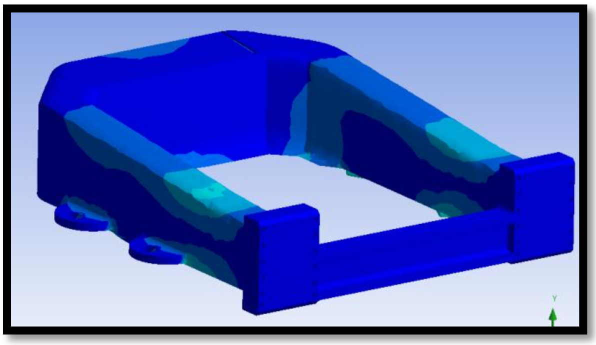

Figure 8: Stress results without optimization.

As shown in the Figure 8, static stress analysis results illustrate the lightly loaded regions, and possible material removal areas. The stresses on the side beams are very low, and some of the material can be safely removed. The stress value around side beams is around 1 MPa as illustrated in Figure 8, which is fairly low for such structure.

A .Design constraint

In order to complete the optimization of the nacelle bedplate, a finite element model has been formed in HYPERMESH environment. OPTISTRUCT toolbox works with SIMP model while creating the optimization results. Only the cast part of the nacelle has been selected for topology optimization. Therefore, the boundary conditions have been applied on the cast part.

Objective function for the problem has been selected as finding the minimal volume of the design space. Cast part is the design space in this optimization analysis. Therefore, the objective function is the minimization of the volume of the design space. For the current topology optimization process design constraints can be both deflection based or stress based. Generally, there can be almost unlimited variety of design constraints. For instance; system mode frequencies, shear stresses, strain energy or thermal parameters can be included as design constraints.

For this problem first design constraint has been selected as stress based. The design constraint was maximum stress to be lower than 30 MPa through the design space under the maximum load combination on the cast part. The second design constraint was the allowable material removal fraction that limits minimum volume. This fraction value should be selected to define the maximum material removal rate for the necessary regions.

III. Optimization Results and Discussion

After the finite element model has been completed and definitions of the optimization constraints for topology have been made, optimization analyses have been conducted. The OPTISTRUCT solver solution has provided some guidance for material removal for the cast part (see Figure 9). The following optimization scheme has been followed. Once the optimization analysis has been performed, the possible material removal regions that are marked as lightly loaded are removed from the structure by the solid modeling code SOLIDWORKS. Then detailed stress analyses have been repeated with weight-optimized model.

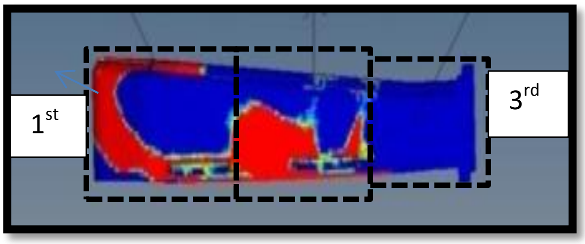

Figure 9: OPTISTRUCT solution providing guidance for optimization and material removal zones.

As shown in the Figure 9, the regions represented in blue are the lightly loaded areas that can be safely removed. Especially, third region towards far right is highly relaxed. However, the second region should be carefully handled due to nearby high bending stresses from the reaction forces.

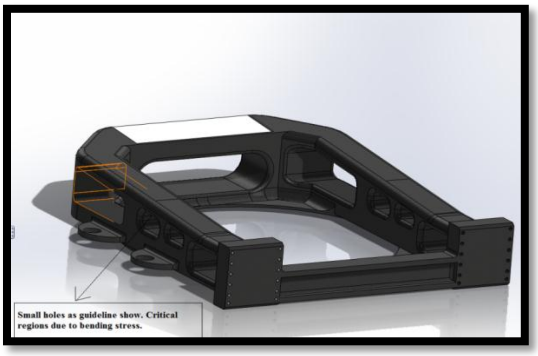

Figure 10: Cast part after weight reduction holes.

The resulting final nacelle structure is presented in Figure 10. After the optimization process has been completed, the design weight has been reduced to 4414 kg which is a reasonable value for main load frame design of middle power range wind turbines. The stress analysis has been repeated after the optimization and material removal process to ensure the strength of the body. Figure 11 shows the stresses under the same boundary conditions after the optimization process.

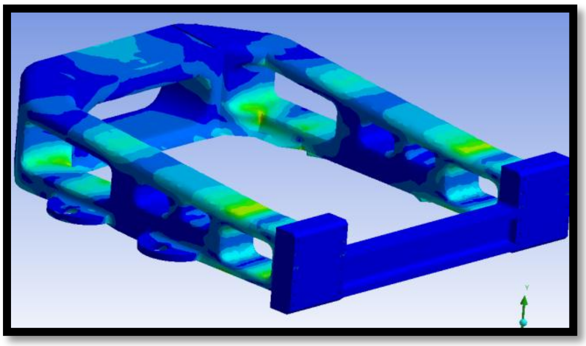

Figure 11: Stress values after the optimization.

The results indicate that the design is safe with no critical stress levels under full loading. Table 2 presents the stress levels and safety factors before and after the optimization process.

As previously stated, second region shown in Figure 9 is critical because this region is near areas that are under high bending stresses. Yet, some small areas in this region have been carefully removed with the guidance provided by the OPTISTRUCT model. Figures 12 and 13 provide comparison for stress details for highly loaded regions.

Table 2: General comparison between the configurations.

	Before Optimization	**After Optimization**
Max Stress	51 MPa	83MPa
Weight	6500 kg	4414 kg
Safety factor	4.9	3.01
Location of maximum stress	Zone 2	Zone 1

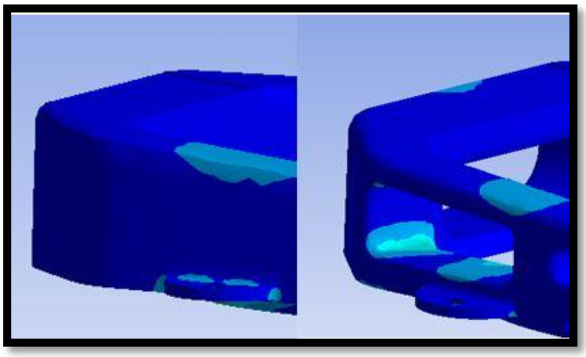

Figure 12: Stress level difference between the optimized and non-optimized versions.

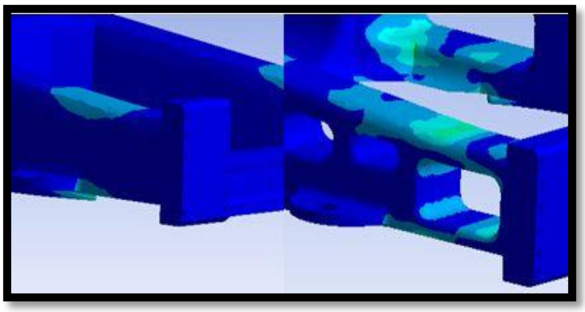

Figure 13: Comparison of the stress levels for the zone3.

It is possible to find nacelle designs in the literature where this area is kept strong due to high stress levels. Figure 14, illustrate one example where the second region is kept solid with no material.

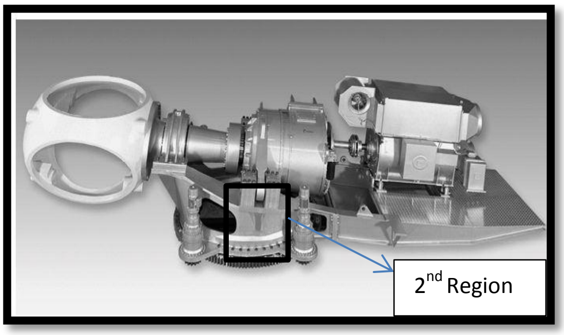

Figure 14: Secondary region without removal [1].

Once the iterations for the topology optimization have been completed, the hybrid design weight including the welded frame has been reduced to around 5000 kg while the structure is kept strong enough to carry the full load combinations. Overall, 28.57 % weight reduction has been achieved through topology optimization.

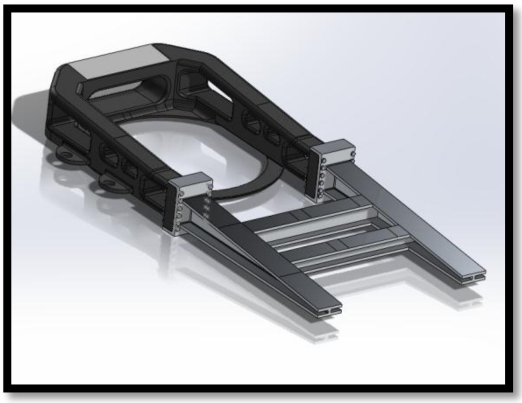

Figure 15: Final shape of the bedplate after the optimization process.

IV. Conclusion

Design of a 500 kW wind turbine nacelle bedplate has been optimized via topology optimization tool known as SIMP model.

- At the end of the optimization process, 0.28 m^3 of material has been removed while % 40 removal fraction constraint has been applied to the structure.
- At the beginning of the optimization, the structure had a volume of 1.1 m3. Therefore, only 28.5 % of the material has been removed with a total weight reduction of around 2000 kg.
- While the weight is reduced, structural strength is not compromised with a final factor of safety of 3 against yield.

The results clearly show that the guidance by OPTISTRUCT solution has been very beneficial and led to weight and cost reduction. Additional work on natural frequency and fatigue life has been performed. However, these are beyond the scope of this work.

V. References

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