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Abstract

For large wind turbine configurations of 10 MW and higher capacities, direct-drives present a more compact solution over conventional geared drivetrains. Further, if the generator is placed in front of the wind turbine rotor, a compact "king-pin" drive is designed, that allows the generator to be directly coupled to the hub. In presented study, the structural re-design of the innovative 10 MW nacelle was made using extreme loads obtained from a 10 MW reference wind turbine. On the basis of extreme loads the ultimate stresses on critical nacelle components were determined to ensure integrity of the structure. Farther, the tower top mass was reduced on the basis of the topology optimization results with compliance limits applied for the king-pin and mainframe. Presented analysis shows that a structural mass of the nacelle can be reduced without significant influence on the mechanical properties of the load caring elements. The total weight of the nacelle after mass reduction is 24 % lower than for the initial design.

Keywords: nacelle structure, topology optimization, direct-drive generator, 10 MW wind turbine, king-pin, mainframe

1. Introduction

The reference design of a 10 MW offshore wind turbine is presented in [1]. It is a three bladed concept with the rotor diameter of 178 m. This design was modified in [2, 3] where a generator mounted in front of the rotor blades has been proposed, using a king-pin nacelle layout. In figure 1, a detailed view of the analyzed nacelle is presented, wherein the drivetrain is supported by two bearings on the king-pin. The king-pin is fixed to the mainframe, which is connected by the yaw bearing to the tower. On the upwind side the king-pin is connected to the generator stator. The design in figure 1 is conceptual and further refinements are required in terms of joints between the main components and avoidance of stress concentration regions.
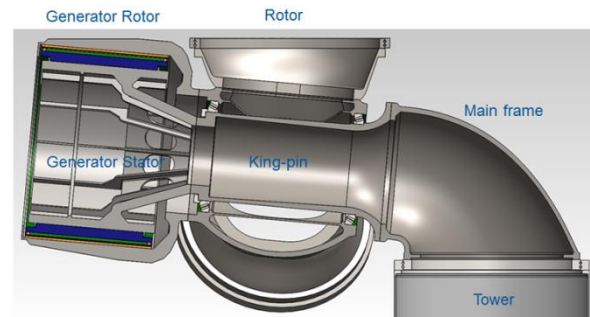
Figure 1: 10 MW wind turbine king-pin nacelle layout.

2. Analysis

2.1 Approach and assumptions

The objective is to reduce the tower top mass for the 10 MW conceptual offshore wind turbine, by application of structural optimization algorithms on a predefined design domain for the chosen nacelle components. Details of the bolted connections and the yaw mechanism were neglected in the topology optimization.

The integrity of the "king-pin" nacelle structure was verified by finite element simulations, and the

means for the mass reduction were provided. The topology optimization analysis for the mainframe under different extreme load sets and constraint parameters were done, on the basis of which two new design concepts were proposed. From proposed concepts only one was chosen for further analysis due to higher possibilities for mass reduction. The chosen geometry was corrected by increasing mass in the critical areas to provide a uniform loads distribution in the flanges. Finally, compliance and safety of the final design were verified on the basis of extreme operational loads for the 10 MW reference wind turbine.

2.2 Finite element model

For a stress analysis and topology optimization purpose, Finite Element (FE) model of the king-pin connected to the mainframe was built. A simplified approach was used whereby the extreme design loads comprising of the thrust, bending and torsional moments on the low speed shaft, as obtained from the HAWC2 aeroelastic software [4], were applied on the model. The extreme loads were obtained in normal operation under extreme turbulence. Figure 2 shows the resulting stresses on the analyzed nacelle components, wherein the high stress concentration areas are caused mostly by sharp edges. Therefore, in further analysis the sharp edges on the profile were modified by adding fillets or increasing existing fillet radius. Presented model was built with 3D elements (tetrahedrons) in Hypermesh [5] and solver Optistruct [6] from Altair for simulations was used.
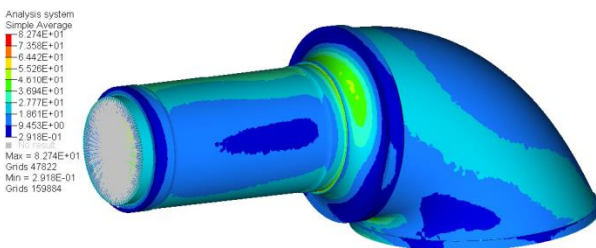

Figure 2: Initial design - von Mises stress distributions in king-pin and mainframe for extreme loads [MPa]

The stress distribution in the model was calculated for the rotor fore-aft moment of 18300 kNm, thrust force 4600 kN and torsional moment 16500 kNm. The torsional moment was applied on the king-pin over the connection with the generator stator using 1D elements. The thrust force was applied on the surface vertical to the rotor axis in the downwind bearing support. The bending moment derived from the rotor was applied as a pressure on the bearings support surface. The model was constrained at the bottom of the mainframe. Applied forces were estimated on the basis of the ultimate loads obtained from HAWC2 simulations for the 10 MW DTU reference wind turbine [1]. The simulations were conducted as per DLC 1.3 from IEC 61400-1, which was the critical extreme load case for the wind turbine. The nacelle design should also be verified in terms of the fatigue damage, but this can be performed in the future study as it is not feasible herein to run DLC 1.2 load cases. In the study it was assumed that the mainframe and king-pin are made from ductile cast iron EN-GJS-400 [7 - 9]. For the chosen material the tensile strength is 370 MPa, what corresponds to the yield strength of 296 MPa. The safety factor for the material strength was assumed 1.2, which gives the design strength of 246 MPa.

Conducted analysis has shown that ultimate stresses on the nacelle components of 82 MPa do not exceed the design limit. Several areas on the mainframe and king-pin have low stress concentration, providing the means for a mass reduction.

2.1 Structural optimization

Topology optimization is a technique to determine the optimal layout of a structure within a specified design domain.. The sensitivity of the optimization method to design parameters has to be analysed to characterize the change of the objective function due to changes in the design variables [10, 11]. In this study the topology optimization was performed for the mainframe where the design domain was assumed between the mainframe upwind flange and yaw bearing. In presented analysis the design variable was density of finite elements, the objective was to minimize volume of the design area, and the displacement of nodes located on the surface connecting the king-pin with generator was the

constraint. The Optistruct solver [6, 11] with the finite element model described in the previous section was used to arrive at an optimal topology of the nacelle.

Three different optimization cases in the study were run, in which values of constraints and load sets were varied to provide wider perspective on the optimal topology setups. The structure was chosen to be about three times more flexible then the primary design, for which maximum deformation magnitude is 6 mm (nodes connecting the king-pin with generator). In the first case the constraint limit 15 mm was assumed and load set consisting of the fore-aft and torsional moment as well as thrust force, as described in section 2.2 were applied.
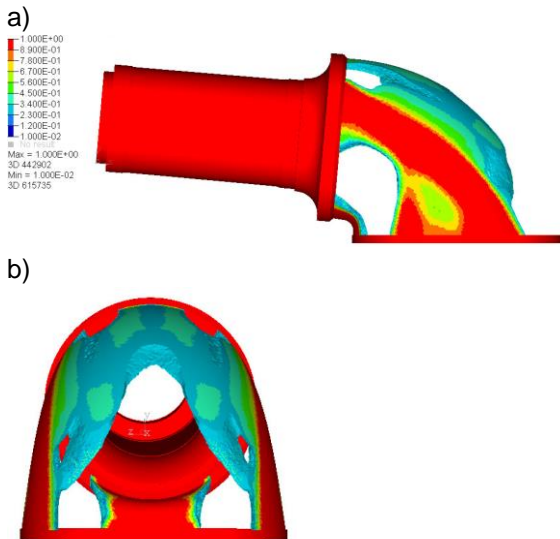
a)

b)

Figure 3: Topology optimization case with fore-aft, torsional moment and thrust force (disp. const. 15 mm, elem. dens. > 0.3), a) side view, b) back view.

In figure 3, the obtained optimum topology is presented which fulfills the specified constraints. The solver converged in a few iterations to the feasible design shown in figure 3 which can serve as an input for a new design of the mainframe, in which the mass can be reduced from the sides and bottom of the component back. In the next case the displacement constraint on the upwind side of the king-pin was assumed 20 mm and the same loads arrangement as described above was applied.
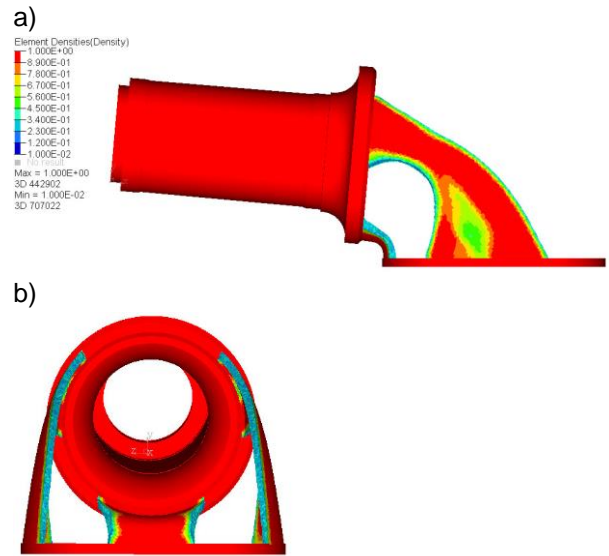
a)

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Figure 4: Topology optimization case with fore-aft, torsional moment and thrust force (disp. const. 20 mm, elem. dens. > 0.3), a) side view, b) back view.

In this case the optimization converged after 24 iterations and a feasible design was obtained within the prescribed constraints. Analysing front and back views of the model one can see that a significant amount of weight was reduced in the mainframe by removing material from back and side parts. In the third case the effect of the side-side bending moment was also included and the displacement constraint as specified before (20 mm).
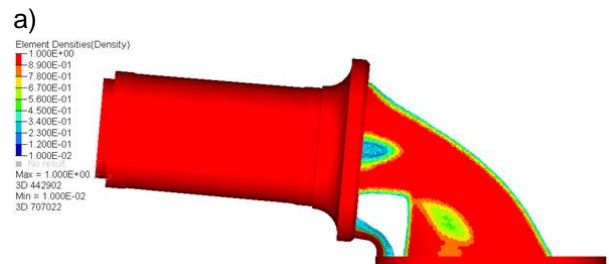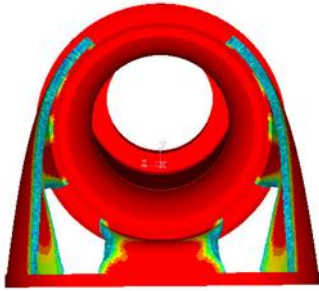
a)

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Figure 5: Topology optimization case with fore-aft, side-side, torsional moment and thrust force (disp. const. 20 mm, elem. dens. > 0.3), a) side view, b) back view.

The results presented in figure 5 show the impact of the additional side moment acting on the king-pin on the topology. The mainframe topology in this case has stronger side walls than for the case without the side-side moment as is shown in figure 4. The rotor side-side moment was assumed as 10000 kNm which is the coincident moment corresponding to the extreme thrust, and was applied on the bearings supports.

The loads introduced in the topology optimization study did not cover all spectrum of the hub loads for a wind turbine, but only a subset of the thrust, fore-aft, side-side moments and torsion. These loads did not include the weight of the generator and blades since it is more conservative, as the moment from the vertical force is in the opposite direction of the fore-aft bending moment and thereby reduces the net moment.

It is also noted that the manufacturing constraints were specified as the symmetry of the design with respect to the rotor axis and the minimum membrane size higher than 360 mm. These constraints enable the resulting solution to be reasonable for casting.

3. Topology study

3.1 Concepts of mainframe geometry

The optimization algorithm used in the study alters the material distribution to minimize mass under given constraints and loads sets. In this section two mass reduced designs of the mainframe and king-pin are proposed. The "design 1" was based on the results presented in figure 3, and provides maximum stiffness of the structure. On the basis of results presented in figure 4 and 5 which shows optimal topology for higher compliance, the "design 2" was proposed. Besides the mainframe modifications, additional mass from the king-pin was reduced by decreasing thickness of the cylinder wall about 7 % for the "design 1" and 20 % for the "design 2", that connects the upwind and downwind bearings.

New concepts of the nacelle components were verified on the basis of strength and compliance under extreme loads, described in section 2.2.
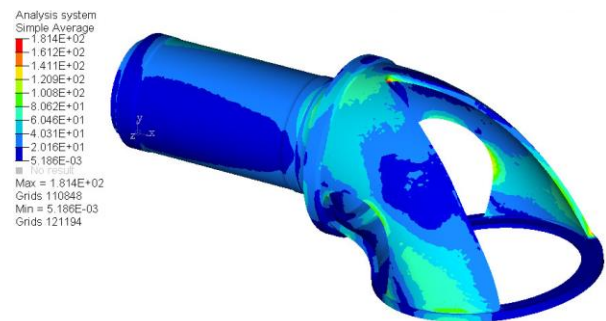
Figure 6: "Design 1" - von Mises stress distributions in king-pin and mainframe for extreme loads [MPa]

The von Misses stresses have a peak value of 181 MPa for "design 1" presented in figure 6. The maximum stress concentration point is in the fillet around the removed material in the back of the mainframe. The maximum stress increases by about 100 MPa in comparison to the initial design, but it is still under ultimate design level of 246 MPa. The maximum deformation of the structure under applied loads is about 12 mm.
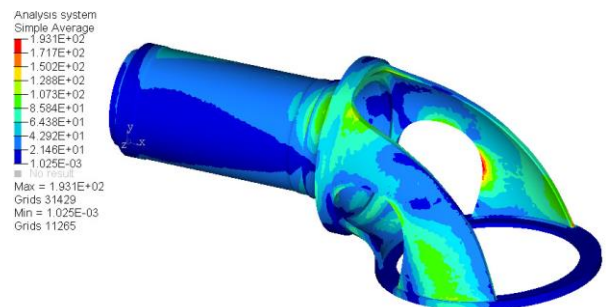

Figure 7: "Design 2" - von Mises stress distributions in king-pin and mainframe for extreme loads [MPa]

In figure 7 the extreme stress levels for "design 2" are presented. The maximum value in this case is 200 MPa and displacement magnitude up to 17 mm.

The modifications of the mainframe by removing material will influence bending and torsional stiffness of the structure, which will result in changes to the natural frequencies. The influence of geometry modifications on dynamical properties of the structure should be investigated in a future study.

3.2 Comparison

Comparison of proposed designs was done in terms of the structural integrity, mechanical properties and mass reduction possibilities. The stresses and deformations for new designs under extreme loads were analysed in order to verify safety of the new structures. In table 1 the results of the finite element analysis for the new concepts are compared with the initial design.

Table 1: Stress and displacement results comparison

Design	Max. von Misses stress	Max. displacement	Design stress limit	Weight of structure
Initial Design	87 MPa	6 mm	246 MPa	122,219 kg
Design 1	181 MPa	12 mm	246 MPa	99,281 kg
Design 2	193 MPa	17 mm	246 MPa	82,621 kg

The stresses for the analysed structures do not exceed the design value, as well and the deformation is lower than assumed value of 20 mm.

As it was mentioned in the previous section, modification of the components geometry will influence the torsional stiffness of the king-pin and mainframe, which is important from the point of view of a generator controller. In the study the torsional stiffness of proposed structures was estimated by applying a torque on the king-pin connected with the mainframe, which was constrained on the yaw bearing. In table 2 the torsional stiffness for analysed designs is presented.

Table 2: Torsional stiffness of analysed concepts

Design	Torsional stiffness
Initial Design	21.7e9 Nm/rad
Design 1	9.2e9 Nm/rad
Design 2	5.5e9 Nm/rad

The stiffness for the "design 1" is about 57 % lower with comparison to the primary structure, but between both new designs the difference is about 3.7 GNm/rad which is only 17 % of the primary design stiffness. The effect of the lowered torsional stiffness on the nacelle natural frequencies is not considered herein.

Finally, the comparison of the mass reduction for the resulting designs is presented hereunder.

Table 3: Mass reduction

	Initial design	Design 1	Design 2
King-pin mass	57,043 kg	55,225 kg	49,927 kg
Mainframe mass	65,176 kg	44,056 kg	32,694 kg
King-pin mass reduction	-	3.2 %	12.5 %
Mainframe mass reduction	-	32.4 %	49.8 %

By reduction of the king-pin wall thickness in "design 1", it was possible to reduce its mass by 3.2 %, and by reducing it by 30 mm in the "design 2" mass has decreased about 12.5 %. By changing geometry of the mainframe on the basis of topology optimization results, its mass decreased by 32 % in the first concept, and almost 50 % for the second one. Overall mass reduction for analysed structure that was the king-pin connected with the mainframe was 19 % for the "design 1" and 32 % for the "design 2".

Comparing both proposed concepts, the "design 2" is characterized by higher maximum stress level under design loads and lower torsional stiffness than the "design 1", but these differences are relatively small with possibilities of further mass reduction given in "design 2". The second design allows for 14 % higher mass reduction of the structure than the first one, and it fulfils ultimate design integrity requirements, so it was chosen as the concept for further analysis. In the next section, corrections to the chosen design is done in term of mass distribution around the

flanges, to avoid low local stiffness which can lead to the failures of bolted connections and yaw bearing.

4. Final design

In presented analysis the influence of bolts and the yaw mechanism parameters on the optimal design was neglected. To increase a local stiffness in the mainframe flanges and to provide a uniform load distribution on the yaw bearing, the geometry of the mainframe was corrected. An additional mass was added to the optimal design presented in figure 7. The mass was increased by adding fillets in the flanges area. The new geometry of the mainframe is presented in figure 8.
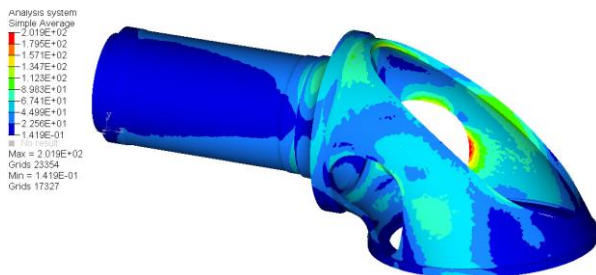

Figure 8: Final design - von Mises stress distributions in king-pin and mainframe for extreme loads [MPa]

To verify the safety of proposed design and rigidity of the structure finite element analysis was conducted. In the analysis torsional moment (16,500 kNm), tower top fore-aft moment (16,500 kNm), thrust force (4,600 kN) and tower top side-side moment (10,000 kNm) were applied, as described in section 2.2. For this concept the maximum von Misses stress is 201 MPa (figure 10), and is lower than the limit of 246 MPa, the deformation of the structure do not exceeds 15 mm. The comparison of the weight between the initial design and final one are presented in table 4.

Table 4: Mass reduction summary

	Initial design	Final design
King-pin mass	57,043 kg	49,927 kg
Mainframe mass	65,176 kg	43,084 kg
Total mass	122,219 kg	93,011 kg
King-pin mass reduction	-	12.5 %
Mainframe mass reduction	-	33.9 %
Total mass reduction	-	23.9 %

The modifications increased a weight of the mainframe about 15 % with comparison to the "design 2".

To sum up, the total mass reduction of 24% for the nacelle components for the conceptual offshore 10 MW wind turbine was obtained..

5. Conclusions

In the paper, reduction of a tower top mass for the 10 MW offshore innovative wind turbine was presented. On the basis of a structural optimization study two lightweight designs of the mainframe were proposed, from which one was chosen as the concept for the final topology. In the optimization analysis the yaw bearing and bolted connection between the king-pin and mainframe were not taken into account explicitly. but the optimal design was modified by adding mass, thus stiffening the structure which partially accounts for non uniform loads transfer. Finally, the total mass reduction of the nacelle for the direct-drive 10 MW wind turbine was obtained as 24 % with respect to the initial design. Material and manufacturing cost estimated by CAPEX shows 17 % reduction for the new "king-pin" design in comparison to the 10 MW baseline turbine.

Proposed design of the mainframe can be improved in terms of its stiffness e.g. by including stiffeners and ribs. In the future, influence of the geometry modifications on the wind turbine dynamics should be analysed either.

Acknowledgments

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