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A Study on Design Optimization of Wind Turbine Rotor Shaft

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***Abstract*—Rotor shaft is one of the main parts for wind turbine, and as the wind turbine system is being enlarged, a study for the weight reduction of the rotor shaft is essential. We have conducted our study for the optimal design of hollow shape rotor shaft, using the Finite Element Analysis. The basic design was made using Topology Analysis to create the main form of the hollow shape. By using the Parameter Analysis for the scale and the aspect ratio based on the main shape, we have decided outline dimensions including the flange diameter and the shaft length. Also, by using DOE(Design of Experiments) and Response Surface Method, we have analyzed the influence and sensitivity of the weight and the stress between design factors. Lastly, we have gained the optimal dimensions of each design factor by using the Optimal Design method. As the result, the weight of the hollow rotor shape has decreased about 37% compared to the solid shape.**

***Keywords*—Wind Turbine, Rotor Shaft, Finite Element Analysis, Optimal Design**

I. INTRODUCTION

This document The wind turbine system is consisted of blade, rotor shaft, tower, gearbox, generator, and variety of controllers. Because the generator must operate for at least 20 years, only a few trusted products are available to market. Especially the rotor shaft, which is one of the main parts of the wind turbine, must have two characters, the torsional flexibility and the strength for bending stresses. To dampen the torque oscillation from the blade, the rotor shaft must have certain amount of torsional flexibility, and it also needs to have enough strength for bending stresses to support various weights. Also, as the wind turbine system is being enlarged, a need for the design technology to lighten the rotor shaft in Nacelle for generating efficiency and ensure the safety of the system is being required. [1-2]

The rotor shaft is being made with cast steel in most wind turbine manufactures in Korea. However, the cast steel manufacturing process have disadvantages to make defects like cracks and other problems like deformations and the difficult quality control if it is used in a large structure. To solve this problem, foreign wind turbine manufacturers are trying to develop to forge the rotor shaft.

Forged rotor shaft is stronger than the cast steel product, but the design technology development effort to lighten the weight is also needed since it has the disadvantage of increased weight.

To make a lighter product design, many studies have been conducted using FEA(finite element analysis) and the Optimal Design theory. [3,4,5]

Some researches for the solid shaped rotor shaft using FEA and Optimal Design theory have been conducted. [6] But those for the hollow shape are still short.

Our study also used those two theories to design the lighter forged hollow shape rotor shaft for the wind turbine system.

II. HOLLOW SHAPE DESIGN

By using DOE and the Response Surface Method, we have analyzed the influence and sensitivity of the weight and the stress. We have gained the optimal dimensions using the Optimal Design Technology

A. The Parameter Analysis for the Scale and the Aspect Ratio

We have conducted the Parametric Analysis for the scale and the aspect ratio in order to select the outline dimensions.

The solid shape model of the rotor shaft to conduct the Parametric Analysis is shown in Figure 1.

To reduce the mass of outline form, the analysis was conducted with the scale cases, each 100%, 82%, 64%, and with the aspect ratio cases, each 1.4 and 1.8.

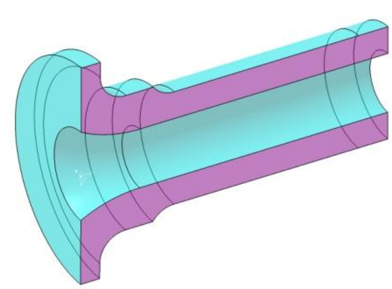

FIGURE 1 MODELING OF A ROTOR SHAFT FOR PARAMETRIC ANALYSIS

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TABLE I
CASES FOR PARAMETRIC ANALYSIS

Case	Flange	Shaft	Aspect Ratio	Scale(%)
1	2,940	4,170	1.4	100
2	2,940	5,358	1.8	100
3	2,420	3,388	1.4	82
4	2,420	4,356	1.8	82
5	1,900	2,693	1.4	64
6	1,900	3,477	1.8	64

B. DOE(Design of Experiments) and Response Surface Method

The entire document should be in Times New Roman or Times font. Type 3 fonts must not be used. Other font types may be used if needed for special purposes.

We have chosen the design factors related to the dimensions by using the hollow shape determined from the Topology Analysis. And we have analyzed the influence and sensitivity between the design factors by conducting DOE and the Response Surface Method.

The design factors for DOE and the Response Surface Method Analysis are shown in Figure 2.

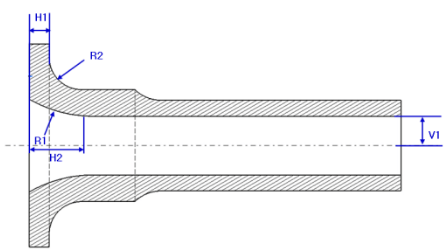

FIGURE 2 DESIGN FACTORS FOR DOE & RSM

We have conducted the DOE method to search the influence and sensitivity of the weight and the stress between the design factors. The number of FEA according to the DOE method is shown in Table 2.

TABLE 2
FE ANALYSIS CASE FOR DOE

	R2	H1	V1	H2	R1
1	350.0	185.0	265.0	700.0	1,700.0
2	315.0	185.0	265.0	700.0	1,700.0
3	385.0	185.0	265.0	700.0	1,700.0
4	350.0	166.5	265.0	700.0	1,700.0
5	350.0	203.5	265.0	700.0	1,700.0
6	350.0	185.0	238.5	700.0	1,700.0
7	350.0	185.0	291.5	700.0	1,700.0
8	350.0	185.0	265.0	630.0	1,700.0
9	350.0	185.0	265.0	770.0	1,700.0
10	350.0	185.0	265.0	700.0	1,530.0
11	350.0	185.0	265.0	700.0	1,870.0
12	340.1	179.8	257.5	680.2	1,748.2
13	359.9	179.8	257.5	680.2	1,651.8
14	340.1	190.2	257.5	680.2	1,651.8
15	359.9	190.2	257.5	680.2	1,748.2
16	340.1	179.8	272.5	680.2	1,651.8
17	359.9	179.8	272.5	680.2	1,748.2
18	340.1	190.2	272.5	680.2	1,748.2
19	359.9	190.2	272.5	680.2	1,651.8
20	340.1	179.8	257.5	719.8	1,651.8
21	359.9	179.8	257.5	719.8	1,748.2
22	340.1	190.2	257.5	719.8	1,748.2
23	359.9	190.2	257.5	719.8	1,651.8
24	340.1	179.8	272.5	719.8	1,748.2
25	359.9	179.8	272.5	719.8	1,651.8
26	340.1	190.2	272.5	719.8	1,651.8
27	359.9	190.2	272.5	719.8	1,748.2

Based on the result from DOE analysis, we have analyzed the sensitivity of the weight and the stress of the design factors with using the Full 2nd Order Polynomial method, one of the Response Surface Methods of ANSYS.

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By using the Optimization module of the ANSYS 13 Workbench, one of the most popular commercial FEA software we have conducted an optimal design analysis. We have set the allowable stress(466MPa, Safety Fator=1.3) as the constraints, and set the minimum weight as the objective function to derive the optimal design factors and dimensions in the optimal design process using FEA method. The constraints on the design factors are shown in Table 3.

TABLE 3
SIDE CONSTRAINTS FOR OPTIMAL DESIGN : UNIT[MM]

Design Parameters	Initial value	Upper limit	Lower limit
R2	350	385	315
H1	185	203.5	166.5
V1	265	291.5	262.3
H2	700	770	693
R1	1,700	1870	1683

We have used the optimal design method to derive the optimal design factors of the design dimensions.

III. ANALYSIS RESULTS

The design of the basic hollow shape in contrast to the solid shape is shown in Table 5. It shows that Case 5 overruns the allowable stress of the material, which is 466MPa. Therefore, Case 6 has been chosen as the final scale and aspect ratio.

TABLE 4
RESULTS FOR PARAMETRIC ANALYSIS

Case	flange	shaft	Aspect Ratio	Scale (%)	Torsional Load		Bending Load	
					Stress	Disp.	Stress	Disp.
1	2,940	4,170	1.4	100	93.2	3.4	132.3	2.0
2	2,940	5,358	1.8	100	91.2	4.3	98.7	1.9
3	2,420	3,388	1.4	82	166.7	5.0	236.4	3.0
4	2,420	4,356	1.8	82	162.8	6.4	177.2	2.8
5	1,900	2,693	1.4	64	339.8	10.4	494.3	4.5
6	1,900	3,477	1.8	64	333.5	8.2	362.6	4.9

The results of DOE analysis is shown in Table 5.

TABLE 5
RESULTS OF FE ANALYSIS BY DOE

	R2	H1	V1	H2	R1	Torsion		Bending	
						Mass (ton)	Stress (MPa)	Mass (ton)	Stress (MPa)
1	350.0	185.0	265.0	700.0	1,700.0	14.4	414.9	14.4	377.7
2	315.0	185.0	265.0	700.0	1,700.0	14.6	414.7	14.6	393.2
3	385.0	185.0	265.0	700.0	1,700.0	14.4	414.6	14.4	369.7
4	350.0	166.5	265.0	700.0	1,700.0	14.3	414.4	14.3	372.4
5	350.0	203.5	265.0	700.0	1,700.0	14.6	414.7	14.6	375.1
6	350.0	185.0	238.5	700.0	1,700.0	14.4	488.6	14.4	357.0
7	350.0	185.0	291.5	700.0	1,700.0	14.5	355.4	14.5	400.2
8	350.0	185.0	265.0	630.0	1,700.0	13.2	548.2	13.2	377.2
9	350.0	185.0	265.0	770.0	1,700.0	16.0	316.0	16.0	382.5
10	350.0	185.0	265.0	700.0	1,530.0	15.3	356.3	15.3	378.5
11	350.0	185.0	265.0	700.0	1,870.0	13.8	473.9	13.8	381.5
12	340.1	179.8	257.5	680.2	1,748.2	13.8	490.3	13.8	376.9
13	359.9	179.8	257.5	680.2	1,651.8	14.2	450.1	14.2	370.3
14	340.1	190.2	257.5	680.2	1,651.8	14.3	450.1	14.3	376.2
15	359.9	190.2	257.5	680.2	1,748.2	13.9	489.1	13.9	375.4
16	340.1	179.8	272.5	680.2	1,651.8	14.2	411.0	14.2	384.6
17	359.9	179.8	272.5	680.2	1,748.2	13.8	447.1	13.8	392.2
18	340.1	190.2	272.5	680.2	1,748.2	13.9	447.4	13.9	385.8
19	359.9	190.2	272.5	680.2	1,651.8	14.3	411.1	14.3	382.0
20	340.1	179.8	257.5	719.8	1,651.8	15.0	385.2	15.0	374.4
21	359.9	179.8	257.5	719.8	1,748.2	14.5	420.1	14.5	371.0
22	340.1	190.2	257.5	719.8	1,748.2	14.7	419.8	14.7	414.3
23	359.9	190.2	257.5	719.8	1,651.8	15.1	387.4	15.1	370.3
24	340.1	179.8	272.5	719.8	1,748.2	14.6	384.5	14.6	384.0
25	359.9	179.8	272.5	719.8	1,651.8	15.0	351.8	15.0	383.3
26	340.1	190.2	272.5	719.8	1,651.8	15.2	352.1	15.2	386.6
27	359.9	190.2	272.5	719.8	1,748.2	14.7	384.2	14.7	380.3

When a torsional load is applied, the factorial effect to each design factor according to the weight is shown in Figure 3.

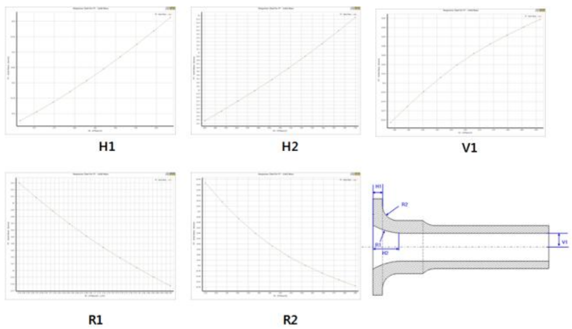


FIGURE 3 FACTORIAL EFFECT GRAPH OF MASS

The result of the DOE analysis is shown in Table 6 and T able 7. We have gained the optimal design figure from the 3 possible points in Table 6, by selecting the point A as the op timal point.

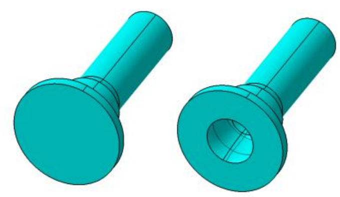
Figure 4 shows the weights of the solid shape and the ho llow shape from the Optimal Design analysis. The hollow shape weight was reduced by 37% compared to the solid shape, by using the Optimal Design method.

TABLE 6
RESULTS OF OPTIMAL DESIGN – TORQUE LOAD

	R2	H1	V1	H2	R1	Mass (ton)	Sress (MPa)
Candidate A	371.03	167.21	288.93	632.58	1643.46	13.21	450.25
Candidate B	360.96	167.86	286.22	664.83	1792.99	13.27	455.79
Candidate C	320.64	167.96	290.87	639.03	1704.63	13.29	457.00

TABLE 7
RESULTS OF OPTIMAL DESIGN – BENDING LOAD

	R2	H1	V1	H2	R1	Mass (ton)	Sress (MPa)
Candidate A	360.53	178.26	274.44	631.23	1834.63	12.71	383.04
Candidate B	380.14	176.60	247.49	638.40	1867.48	12.74	359.40
Candidate C	378.03	171.40	240.95	631.68	1742.58	12.93	355.27



21.2[ton] 13.2[ton]

(A)SOLID SHAPE (B)OPTIMIZED HOLLOW SHAPE

FIGURE 4 MASS COMPARISON BETWEEN THE SOLID SHAPE AND THE OPTIMIZED HOLLOW SHAPE

IV. CONCLUSION

We have designed the hollow shape of the rotor shaft usi ng FEA and the optimal design method in order to develop the forged rotor shaft in wind turbines

i. By analyzing the scale and the parameters, we have selected the proper scale and aspect ratio within the allowable stress.
ii. Using DOE and the Response Surface Method, we have analyzed the influence and sensitivity between the design factors.
iii. By using the Optimal Design method, we have selected the optimal dimension of the hollow shape. As the result, the weight was reduced by 37% compared to the solid shape.

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