

OPTIMIZATION OF LIGHTENING HOLE ON A SPUR GEAR OF AN AIRCRAFT MOTOR

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ABSTRACT

Gears are fundamental machine elements that are generally used in various areas of industries and transmission of movement. The structural weight is the one of the significant factors effecting the performance of aircraft engines, it should be minimized through optimization. For this reason, lightweight holes are commonly used in gears to reduce the weight. In this study, the optimization of the geometric position and the radius of lightweight holes along with the radius of the gear shaft used in a spur gear in aircraft engines are performed. In optimization, these values are used as the design variables, the weight of the gear is used as the objective function, and the maximum von Mises stress on the gear is used in the design constraint. The optimization problem is solved by using ISIGHT software.

KEYWORDS

Optimization, DOE, ISIGHT, Spur gear, Stress

NOMENCLATURE

m =module of gear(mm)

N = number of teeth

Φ = pressure angle(°)

R = radius(mm)

σ_y = yield strength(MPa)

σ_{ut} = ultimate tensile strength(MPa)

T =torque(Nm)

F = force(N)

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ϵ = poisson's ratio

E = modulus of elasticity(MPa)

FEM= finite element method

DOE: Design of Experiment

INTRODUCTION

In recent years, weight reduction of gear systems has become an important topic and numerous studies have been conducted on this subject. While some studies focused on lightening the gears at the design stage before production, remaining studies are related to lightening of the available gears. Gears are also crucial parts for aerospace industry, and low weight parts are preferred in this branch. Since weight is one of the significant parameter which affects flight performance, the weight of a gear system needs to be optimized.

[Yokota et al. 1998] worked on the problem of optimal weight design of a gear and solved that problem by using improved genetic algorithm method with nonlinear design constraints [1]. [Ozek et al. 2007] investigated the effect of various geometric types of holes on stress of spur gears to decrease their weight. They found out that the best appropriate model in aspect of stress value was the model with circle hole and stepped gear [2]. [Savsani et al. 2009] focused on determining the most suitable combination of design parameters for the minimum weight of spur gear system by using Particle Swarm Optimization (PSO) and Simulated Annealing (SA) methods. They found that both PSO and SA resulted in competing results [3]. [Reddy et al. 2016] used Genetic Algorithm (GA) to find the minimum weight design of a gear train problem, and they found that GA gave better solutions for gear train design [4]. [Belsak et al. 2018] minimized the vibration and noise of solid body of a spur gear by changing its lattice structure topology [5].

DEFINITION OF THE OPTIMIZATION PROBLEM

As noted earlier, the optimization of the geometric position and the radius of lightweight holes along with the radius of the gear shaft used in a spur gear in aircraft engines are performed in this study. Aim of this study is to reduce the weight of a spur gear as much as it could be done without loss or with negligible decrease on its strength.

Five lightening holes are drilled onto the spur gear which is made from normalized 4140 steel. Holes are drilled with $\varnothing h$ diameter at $\varnothing p$ position according to the center of the gear. Also there is a shaft hole on the gear with $\varnothing s$ diameter and there is a key groove on this hole.

Find $x = \{\varnothing s, \varnothing h, \varnothing p\}$

Minimize Mass(x) (1)

Such that $\sigma_y(x) < 850$

FINITE ELEMENT MODELING

General Properties

Stress analysis of the gear is made via Abaqus software which is an advanced FEM software. FEM models are solved by using static analysis on Abaqus2017.

CAD Geometry

CAD geometry of the gear is generated via CATIA V5R20 software. Geometrical properties of the gear is given at Table 1.

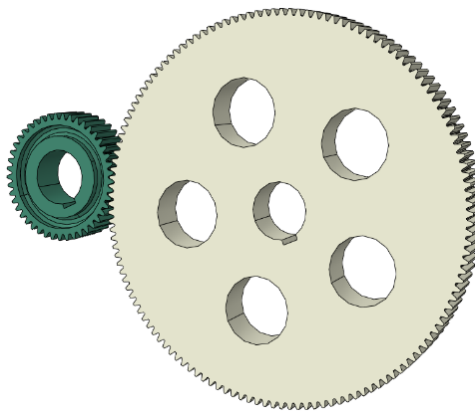


Figure 1: Geometry of the gear

Property	Value
Module of the gear (m)	2.5 mm
Number of teeth (N)	135
Pressure angle	20°
Pitch diameter	337.5 mm
Diameter of the addendum circle	342.5 mm
Diameter of the dedendum circle	331.25 mm
Width of the gear	40 mm
Mass of the gear	23 kg

Table 1: Geometrical properties of the spur gear

Material Properties

Alloy steels are used at industry for the gears which are subjected to huge loads. The gear in this study is subjected to huge loads, because of this reason 4140 steel which has increased outer surface strength is used. Properties of the material is given at Table 2.

Material	Modulus of elasticity (MPa)	Poisson's ratio	Yield strength (σ_y) (MPa)	Tensile strength (MPa)
4140 Steel	200000	0.3	1150	1200

Table 2: Properties of Material

Assumptions

Only the gear of the gear train is taken into account on FEM model, the pinion of the gear train is not taken into account so contact case is not counted in FEM model. Because of only one gear used at FEM model, force value is defined instead of torque.

Two dimensional model is used by thinking of geometrical properties of the gear, suitability of load and boundary conditions, FEM and optimization times of solution. The part is in the case of plane stress when the width of the gear is taken into account.

Mesh

Precisely calculation of the stress values from FEM solution is crucial since these stress values which are calculated on the gear are input values of the optimization solution. As it is mentioned at stage earlier, gear is modeled as 2D. Mesh convergence studies are done with 'second order full integration hexagonal element' in Abaqus in order to obtain precise stress values. Different mesh sizes are tried on at tooth root and force application point because of high stresses calculation. Results are obtained at the mesh size which the convergence is obtained. Solutions are calculated with general mesh size as 8mm.

Forces and Boundary Conditions

When gears work, the contact point is changed instantaneously for this reason angle of the contact force is changed consistently. Since contact between gears acts along a straight line. The case which is coincidence of the line and pressure angle is taken as force's transfer angle. As it is mentioned before, pressure angle is 20° . Contact point of mated gears is on the pitch circle. In this case the radial and tangential components of the force are defined as respectively[8];

$$F_t = F_n \cos 20^\circ$$

$$F_r = F_n \sin 20^\circ$$

Because of both radial component of the force and the force arm is too small with respect to tangential force, only tangential force is subjected to gear. Torque value is calculated as tangential force without taking radial force into account and is subjected. Torque value which is applied to gear is 5600Nm.

Because of both shaft of gear and contact are not used on the model, the surface which gear contacts to shaft is fixed to the point which is on the center of gear.

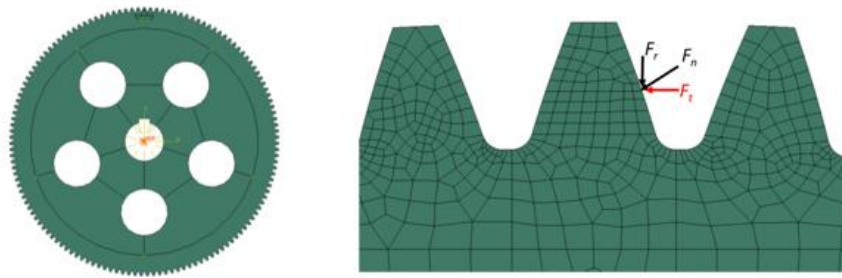


Figure 2: Boundary conditions of gear and location of force application point

Results of Stress Analysis

While calculating stresses on the gear, mesh convergence are performed. Mesh convergence working are performed on the gear where maximum stresses are calculated with three different element size. Mesh convergence and calculated stresses on these meshes are shown in Figure 3. The highest stresses are observed at the root of the teeth and at the force application point as shown in Figure 4.

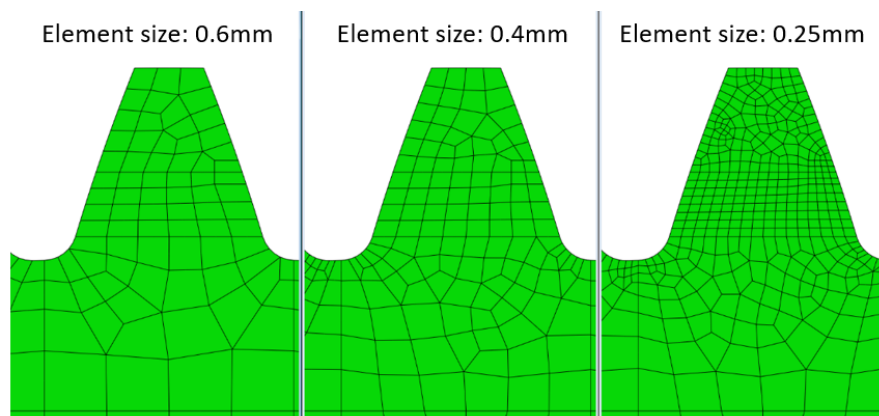


Figure 3: Mesh convergence

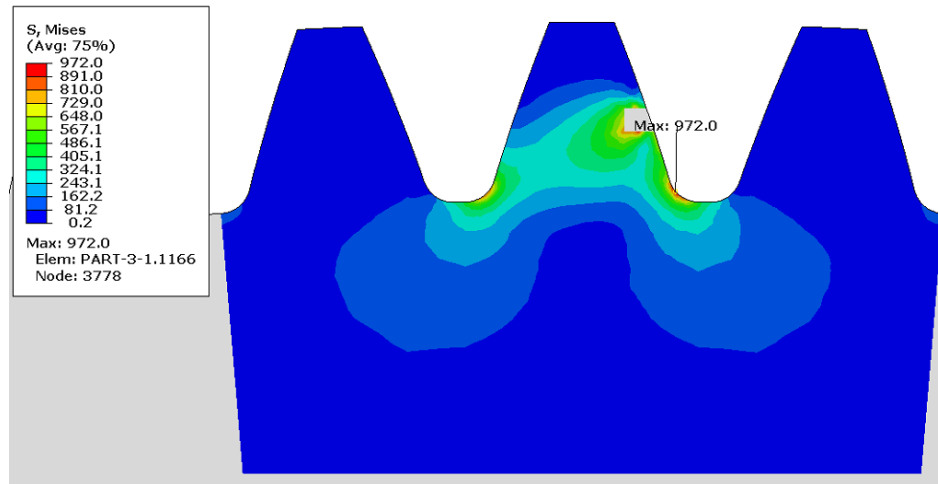


Figure 4: Stress concentration areas of the gear

DESIGN OF EXPERIMENT (DOE)

DOE is performed before optimization study on the process of lightening of the gear weight. Main aim of this study is to determine which parameters are more effective on the process of lightening of the gear weight and is to determine the relations between these parameters. Aimed weight is achieved with fewer iterations via determining suitable intervals for design parameters by using DOE results.

Design Variables

First of all, design variables are determined for the DOE study of lightening of the gear weight. Predetermined geometrical values of gear are defined as design variables. Diameter of lightening holes (R_h), circular position of these holes (R_p) and diameter of shaft hole (R_s) are defined as design variables. These definitions are transferred to Isight via Abaqus. Defined parameters are shown in Table 3. A continuous and linear design space is created with these design variables.

Variable of Design	Lower limit (mm)	Original value (mm)	Upper limit (mm)	Type of variable (mm)
R_s : Radius of the shaft hole	20	25	50	Continuous
R_h : Radius of the lightening holes	20	30	50	Continuous
R_p : Circular position of the holes	70	90	120	Continuous

Table 3: Variables of Design

Constraints of Design

At the process of DOE, it is aimed that maximum von Mises stress is kept below the yield strength of the material, while weight of the gear is reduced. Since yield point value is not sufficient for safety, it is aimed that maximum stress is lower than 850 MPa with 1.35[9] factor of safety. This constraint of design is defined at below in this case.

$$g(x) < 850 \quad (1)$$

This constraint of design hold gear harmless by constraining the objective function.

Objective Function

Main aim of the changes at the geometry of gear is reducing weight of gear. In this study %25 weight reduction is aimed. Since using of objective function at DOE is not needed, this description is not used in this study. Objective function is used to determine suitable intervals for design parameters by comparing weight values which are obtained from DOE results.

DOE Process

In this study DOE is performed while it is aimed that the stresses are below the yield strength on a gear which is under load of torque while the gear's weight is reduced. ISIGHT 2017 software is used for DOE analysis. Stress analysis is done at Abaqus after that fem model and its results are used as input values for DOE study before DOE model is created. DOE is performed for gear by running these two software simultaneously. DOE cycle is given at Figure 5.

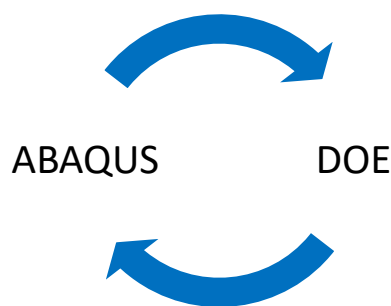


Figure 5: DOE cycle

Analysis are performed with four different DOE methods (Latin hypercube, Full Factorial Design, Central Composite Design and Box-Behnken). The intervals which are given at Table 3 are used for design variables.

Findings of DOE

The best results are obtained by Latin Hypercube method among these four method. Fifty line design matrix is created for fifty point and analyzed with this method. Eleven out of this fifty iteration is completed successfully. Since there are two iterations which provides the aimed stress and aimed weight reduction (iteration 42 and iteration 45). Iteration results which provides the aimed weight reduction is given at Table 4, Figure 7 and Figure 8.

Iteration	Radius of the lightening holes	Circular position of the lightening holes	Radius of the shaft hole	Mass	Mises_Max
9	24.9	115.92	24.9	0.0243528	841.665
11	26.12	84.29	27.96	0.0238864	844.466
13	27.35	113.88	20	0.023938	821.341
18	30.41	103.67	31.63	0.0224746	821.162
19	31.02	85.31	23.06	0.0227517	834.584
20	31.63	76.12	29.18	0.0222482	834.752
25	34.69	73.06	28.57	0.0212819	896.621
33	39.59	94.49	32.24	0.0192667	885.244
42	45.1	99.59	20.61	0.0175708	821.776
45	46.94	92.45	22.45	0.0166574	823.893
46	47.55	90.41	32.86	0.0158057	850.856

Table 4: Successful iterations which are obtained by Latin Hypercube Method

Relations among variables according to DOE are shown at Figure 6. The most crucial parameter is diameter of the lightening hole according to the results. The second important parameter is the square power of diameter of lightening hole and the last important parameter is diameter of the shaft hole.

When the parameters which effects to stress are viewed, it is seen that square power of diameter of the gear is the most effective factor and second effective factor is seen as square power of diameter of lightening hole.

DOE Results

Started on Wed Mar 27 15:10:27 EET 2019
 Completed on Wed Mar 27 15:20:30 EET 2019
 Technique: Latin Hypercube
 Number of experiments: 50

Normalized Effects (0-100%)

This table lists the *estimated* relative effects that the various factors had on each response:

Sources	Step_1_Mass	Step_1_S_mises_max
Model_1_Part_3_Cevre_CirRad_1_sketch	-80.03594664	9.232741515
Model_1_Part_3_Cevre_CirRad_1_sketch-Model_1_Part_3_Cevre_RadLen_1_sketch	0.007590889824	7.14439972
Model_1_Part_3_Cevre_CirRad_1_sketch-Model_1_Part_3_Merkez_CenRad_sketch	0.001907486721	8.602727772
Model_1_Part_3_Cevre_CirRad_1_sketch^2	-12.51019552	-14.96893589
Model_1_Part_3_Cevre_RadLen_1_sketch	0.004909094416	11.93672917
Model_1_Part_3_Cevre_RadLen_1_sketch-Model_1_Part_3_Merkez_CenRad_sketch	0.001380097793	-12.67612259
Model_1_Part_3_Cevre_RadLen_1_sketch^2	0.003754147544	-4.304700118
Model_1_Part_3_Merkez_CenRad_sketch	-6.62351698	5.167539684
Model_1_Part_3_Merkez_CenRad_sketch^2	-0.8107991506	-25.96610355

Figure 6: Relations among parameters according to DOE results

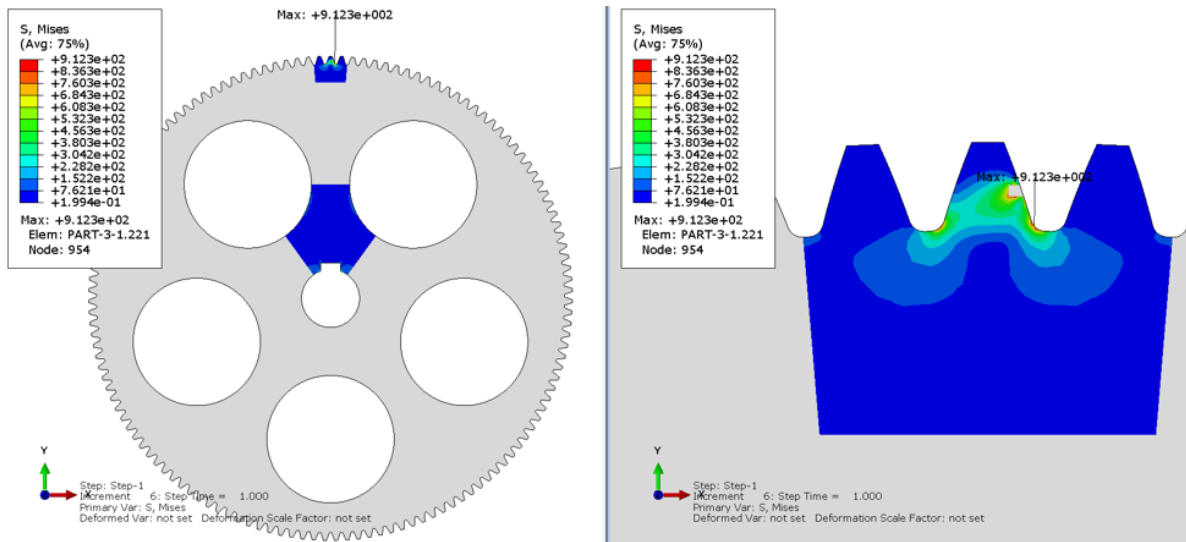


Figure 7: Distribution of stresses for iteration 42 (weight reduction is %23.5)

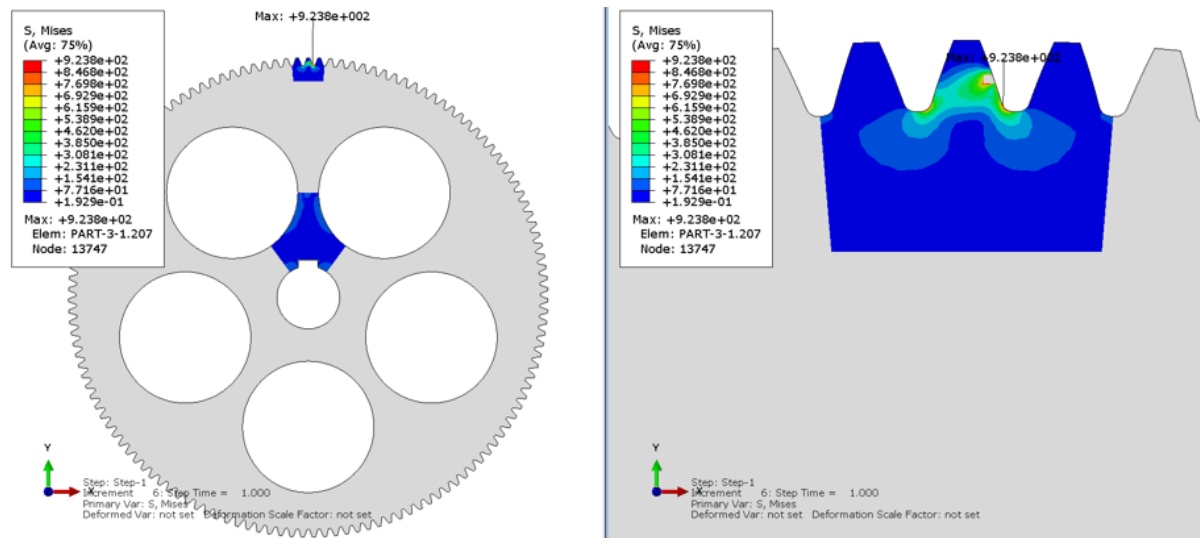


Figure 8: Distribution of stresses for iteration 45 (weight reduction is %27.5)

OPTIMIZATION WITH ISIGHT

Optimization Model

In this study, the stresses on a spur gear under torque load are lightened so that they remain below yield strength. ISIGHT 2017 software was used for optimization analyzes. Stress analysis was first performed with Abaqus 2017 before creating the model. After that, the effects of design variables on the optimization process were determined by performing experimental design. The model, which is created by using Abaqus, and the result file were entered as input to the program. According to the results obtained from the experimental design, the design variables were narrowed and then were defined to the model. The design constraint used in the experimental design was also used in the optimization model. Unlike the experimental design, the objective function is defined. The objective function is determined from DOE study. According to DOE results, objective function is defined as reducing weight of the gear up to 25%.

Since the design variables, space and constraints are linear and there are few design variables in the model, the optimization process is performed by SQP (Sequential Quadratic Programming) method.

Narrowing the spacing of the design variables allowed optimization to run in a narrower range and in less time. The two softwares worked together to get lighter the gear. Figure 9 shows the optimization cycle.

Variable of design	Lower limit (mm)	Original value (mm)	Upper limit (mm)	Type of variable (mm)
$\varnothing_s$: Shaft radius	20	25	30	continious
$\varnothing_h$: Radius of holes	25	30	48	continious
$\varnothing_p$: Circular position of holes	87	90	95	continious

Table 5: Narrowed intervals of design variables according to DOE results

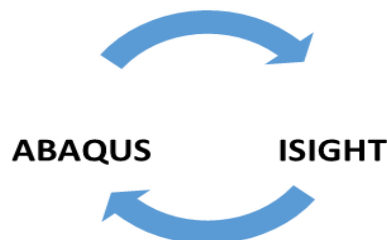


Figure 9: Optimization cycle

Optimization Results

In the optimization model, analyses were performed by using different methods. Since the best and shortest convergence is obtained with SQP method, optimization analysis has been performed with this method for the problem. Table 6 shows the values obtained at the end of the optimization analysis.

According to the obtained values, the increase in hole diameter decreases the weight under the determined constraint even though the decrease in shaft diameter. As the lightening hole diameter increases, the decrease of the shaft diameter reduces the gear weight, since the excessive increase in the lightening hole diameter does not provide the stress constraint. According to the experimental design findings, by narrowing the range of the design variables, the targeted gear weight under the desired stress constraint was very close. Gear weight was reduced by 23.6%. In addition, optimization analyses were completed with fewer iterations.

Øh: Radius of holes	Øp: Position of holes	Øs: Shaft radius	Weight (kg)	Reduction (%)	Stress (MPa)
30	90	25	23	-	867.6
45	90	25	17.4	24.3	868.9
29.98	87	20	23.2	¹ (increased)	821
45	88.5	22.5	17.54	23.6	823.8

Table 6: Weight and stress values which are obtained by optimization analyses

Figure 10 shows the stresses on the optimized gear. In the optimization process, the maximum value (867.6 MPa) of von Mises calculated at the integration points is used. The distribution shown in the figure shows the average stress values. The maximum stress at the integration point is 823.8 MPa.

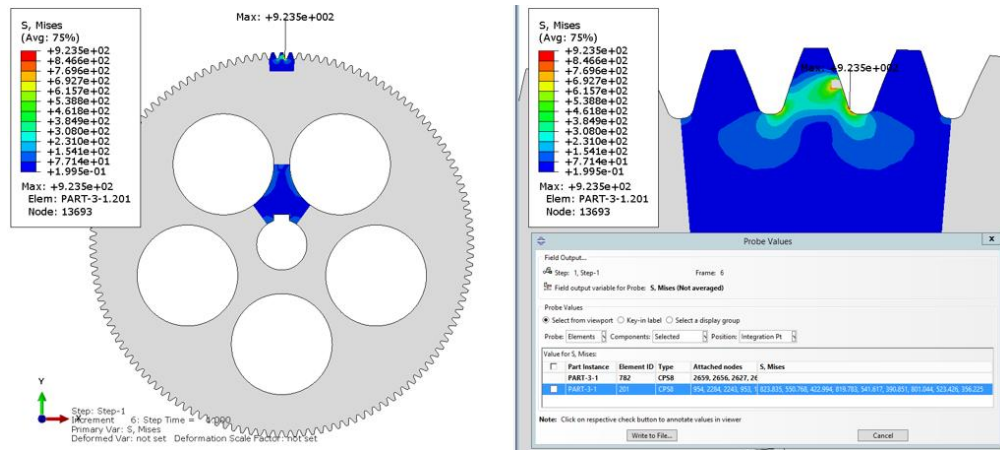


Figure 10: Gear geometry and stress distribution which are obtained by optimization analyses

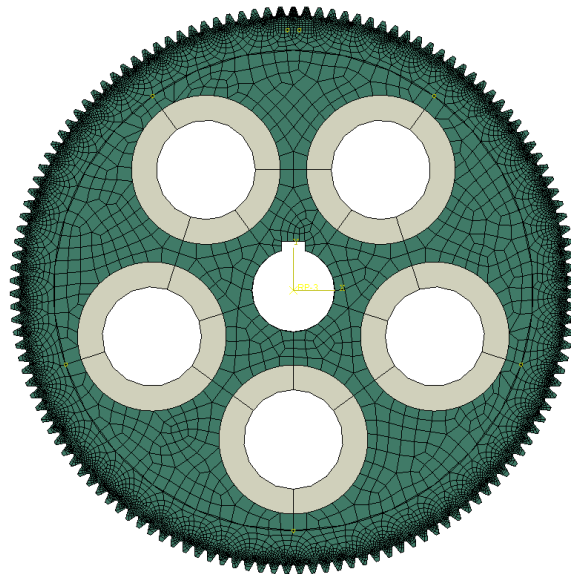


Figure 11: Comparison of the original gear geometry and optimized gear geometry

Conclusion

In this study, the optimization of geometric position of the lightening hole, the radius of the lightening holes and the radius of the gear shaft used in a spur gear in aircraft engines were performed. The optimization problem is solved by using ISIGHT 2017. According to obtained DOE and optimization results, the following conclusions are drawn:

- Due to the experimental design analyses made with different methods, the best results were obtained with Latin Hypercube method.
- According to the experimental design results, the most important parameter affecting the weight is the diameter of the lightening hole by 80%. The square power of the lightening hole diameter of 12.5% is second and the diameter of the gear shaft hole with a values of 6.5% is last effective parameter in reducing the weight of gear.
- When the parameters affecting the stress are examined, it is seen that the square power of the gear shaft hole diameter is the most influencing factor with 25% and the

square power of the lightening hole diameter is the second factor affecting the stress with 15%. Finally, the third factor affecting the stress is the multiplication of the gear shaft hole diameter by 12% and the distance between the gear shaft hole and the lightening hole.

- As a result of the optimization analysis performed with the design variable ranges determined according to the experimental design, the gear weight was reduced by 23.6%, and the maximum stress was calculated as 823.8MPa below the target value (850MPa).

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