International Journal of Computational and Experimental Science and Engineering (IJCESEN)
Vol. 1-No.2 (2015) pp. 16-19
http://dergipark.ulakbim.gov.tr/ijcesen

***ISSN:* 2149-9144**

Research Article

Weight Optimization and Reliability Prediction of an Automobile Torque Arm Subjected to Cyclic Loading

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Presented in "2nd International Conference on Computational and Experimental Science and Engineering (ICCESEN-2015)"

ABSTRACT

The demands for lightweight, high-performance, low-cost structures are dramatically increasing, and that draws attention to research in the field of structural optimization. Designs of lightweight structures have become more important, especially in the automobile industry. The goal of this study is to obtain the optimum shape of an automobile torque arm and predict its reliability. Torque arm, part of the rear suspension, is subjected to cyclic loading. The stresses developed in the structure should not exceed the allowable stress, and fatigue life is another constraint due to cyclic loading. The optimization of torque arm requires calculation of the stresses and the fatigue life many times; therefore surrogate models (response surface approximations and Kriging) are used in this study to reduce the computational cost. Surrogate based optimization of the torque arm is performed by using the Optimization Module of ANSYS Workbench. After the optimum shape is determined, the reliability prediction of the torque arm is performed. In reliability prediction, tail modeling method, an adaptation of a powerful result from extreme value theory in statistics related to the distribution of exceedances, is utilized.

KEYWORDS – Weight Optimization, Surrogate Models, Tail Modeling.

1. Introduction

The limit-state function of a mechanical system is usually evaluated through performing computationally expensive finite element analyses. The simulation techniques such as Monte Carlo method or its advanced variants (e.g., importance sampling, Melchers [1]; adaptive importance sampling, Wu [2]; directional simulation, Nie and Ellingwood [3]) require a large number of limit-state evaluations; hence they are not suitable for highly safe mechanical systems. Alternatively, the analytical methods such as first-/second- order reliability methods (FORM/SORM) are computationally efficient, but their accuracy diminishes as the limit-state function becomes nonlinear. In order to overcome the drawbacks of these traditional methods, the techniques based on tail modeling have been successfully used by many researchers, including Castillo [4], Caers and Maes [5] Kim et al. [6], and Ramu et al. [7] for reliability assessment of highly safe mechanical systems.The demands for lightweight, high-performance, low-cost structures are dramatically increasing, and that draws attention to research in the field of structural optimization. Designs of lightweight structures have become more important especially in automobile industry. The torque arm is a suspension component that mounts on a rear-wheel drive vehicle's rear-drive axle. This component allows the vehicle to accelerate in a straight line without rotating the rear axle. The torque arm also assists the vehicle in braking by applying force to the braking system. The torque arm is primarily used in what designers call a three-link suspension system. In this study, the optimum shape of an automobile torque arm is obtained by using optimization techniques and then the reliability of the optimum configuration is predicted by using tail modeling. The torque arm is subjected to cyclic loading, and it is designed such that the stresses developed in the structure should not exceed the allowable stress, and fatigue life is another constraint due to cyclic loading. The optimization of torque arm requires calculation of the stresses and the fatigue life many times; therefore surrogate models are used in this study to reduce the computational cost.

2. Problem Definition

In this study, the weight of the torque arm is minimized under stress and life constraints and then its reliability is predicted. The baseline geometry and loading conditions are shown in Figure 1. The torque arm is fixed at the left end to the chassis and the cyclic loads transferred from rear-wheels are applied at the right end. For the loads, a factor of safety of 2.0 is used. For instance, the expected vertical load on the torque arm is 633.25 N, so 1266.5 N vertical load is used in the analysis.

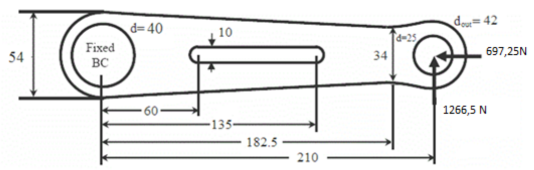

Figure 1. Baseline Geometry and Boundary Conditions Dimensions are in mm.

Based on static and fatigue failure considerations, the optimization formulation can be stated as presented in Eq. (1) and the design variables are shown in Figure 2.

Find d_1, d_2, d_3, d_4, d_5

Minimize $mass\ (d_1, d_2, d_3, d_4, d_5)$

S.t. *Max Von-Mises Stress* $(d_1, d_2, d_3, d_4, d_5) - \sigma_{bl} \leq 0$ (1)

Fatigue lifetime $nf\ (d1, d2, d3, d4, d5) - (nf)bl \leq 0$

where σ_{bl} and $(n_f)_{bl}$ are the maximum von-Mises stress and the fatigue life of the baseline design, respectively. These values are obtained through structural analysis by using ANSYS Workbench Structural Analysis Tool. For fatigue analysis stress-life method [8] is used. The optimization of this problem is performed by using Response Surface Optimization module of ANSYS Workbench. Polynomial response surface (PRS) approximation and Kriging models are used. After the optimum shape is determined, the reliability prediction of the torque arm is performed using tail modeling.

3. Optimization Results

As noted earlier, PRS and Kriging surrogate models are

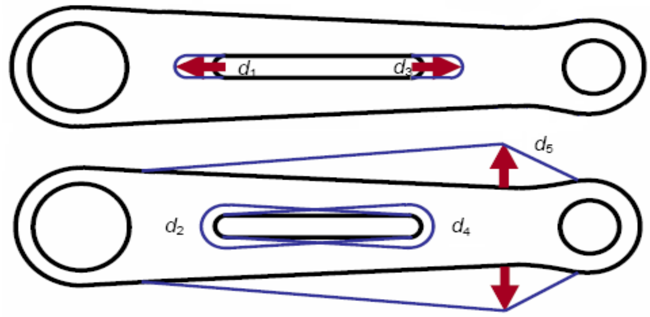

Figure 2. Design variables for the optimization of torque arm

used in this study to relate the maximum von-Mises stress and fatigue life to the design variables. It is found that Kriging surrogate model has smaller RMSE (for both fatigue life and maximum von-Mises stresses) than PRS model, therefore optimization is performed by using Kriging models. Von-Mises stress distribution at the baseline design and the optimum design can be seen in Fig. 3. The values of the design variables, maximum von-Misses stress, fatigue life, and weight of the baseline and the optimum design are given in Table 1. Optimization results indicated that the weight of the torque arm can be reduced by 26% through optimization.

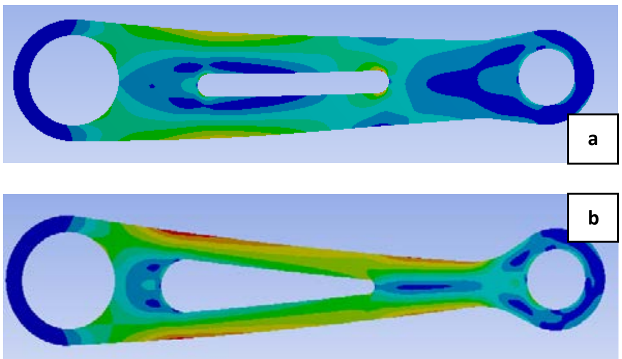

Figure 3. von-Mises stress distribution at (a) the baseline design, (b) the optimum design

4. Reliability Prediction

After obtaining the optimum design, reliability prediction is performed. Random variables are listed in Table 2. The mean values of the geometric random variables are taken as the optimum design dimensions and standard deviation is taken as 1 mm for all geometry random variables. For fatigue life estimation, stress life parameters are strength coefficient (σ_f) and strength exponent (b), and they are taken as random variables. Coefficients of variation values for these parameters are selected based on our experience. Coefficient of variation for load is taken as 0.1 as in [9].

Table 1. Optimization Results

	Baseline Design	Optimum Design
Dimensions (mm.)		
d1	60	51
d2	5	11
d3	135	129
d4	5	3
d5	10	18,5
Mass (kg)	0,196	0,145
Max. Von Mises Stress (MPa)	319,6	295,7
Fatigue Life (cycle)	8658	11122

Table 2. Random Variables

Random Variables	Distribution Type	Mean	Standard Deviation
Geometry variables			
d1 (mm)	Normal	51	1
d2 (mm)	Normal	11	1
d3 (mm)	Normal	129	1
d4 (mm)	Normal	3	1
d5 (mm)	Normal	18.5	1
Load Components			
Random Variables	**Dist. Type**	**Mean**	**Standard Deviation**
Fx (N)	Normal	348.625	34.8625
Fy (N)	Normal	633.25	63.325
Fatigue Life Parameters			
Random Variables	**Dist. Type**	**Mean**	**Standard Deviation**
σ_f (MPa)	Lognormal	1043	83.44(Cv=0.08)
b	Normal	-0.107	0.0107(Cv=0.10)

4.1 Reliability Prediction

In this study, tail modeling is used for reliability prediction of the torque arm. Tail modeling method is an adaptation of a powerful result from extreme value theory in statistics related to the distribution of exceedances. The conditional excess distribution above a certain threshold is determined using the *generalized Pareto distribution* (GPD). The distribution parameters of the GPD are found through maximum likelihood estimation [10]. After the distribution parameters are found, the reliability is calculated by using Eq. (2)

$$P_f = 1 - \left(1 - F(g)\right) \left\langle \left(1 - \frac{\xi}{\sigma} g\right) \right\rangle_+^{\frac{-1}{\xi}} \quad (2)$$

where ʒ is the shape parameter, σ is the scale parameter of GPD, and *g* is the selected threshold value. For reliability prediction M=500 samples are created according to distribution types, mean and standard deviation values and structural analyses for these samples are performed to obtain fatigue life values. Since the torque arm fails because of fatigue, limit state function is written in terms of fatigue lifetime. The limit state function has the form of

$$g = log(N_c) - \log(N) \quad (3)$$

where system fails g>0 condition, N_c is the critic life determined by finite element analysis of optimum design, and N is the random fatigue life values. Reliability predictions are listed in Table 3. In tail modeling prediction, parameters are calculated using maximum likelihood and least square estimation. The average values of these two methods are also shown.

Table 3. Reliability Prediction

Methods	Reliability
Maximum Likelihood Estimation	0.997
Least Square Estimation	0.993
Average	**0.995**

5. Conclusion

This study is mainly concerned with minimization of the weight of an automobile torque arm under stress and fatigue life constraints as well as the reliability prediction of the optimum design. Surrogate based optimization approach is followed to obtain the optimum torque arm configuration. Polynomial response surface approximations and Kriging metamodels are used, and it is found that Kriging metamodels are more accurate than polynomial response surface approximations. Therefore, Kriging model is further used in used in optimization, which is performed by using Optimization Module of ANSYS Workbench. Optimization results indicated that the weight of the torque arm can be reduced by 26% through optimization. Furthermore, optimum design has better features in terms of maximum von Mises stress and fatigue life. After the optimum design is found, its reliability is predicted by tail modeling technique.

Acknowledgement

The authors gratefully acknowledge the support provided by The Scientific and Technological Research Council of Turkey (TÜBİTAK), under award MAG-214M205.

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