Design optimization of clutch cushion disc with the integration of finite element analysis and design of experiments

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Abstract: In recent years, growth of automotive market and the need for competent design of components has developed an over-reliance on advanced CAE tools. Design objectives of these automotive components are evaluated through simulations that are expensive in terms of money, resources and time. In such cases, evaluating all the design variables types and arriving at an optimized design makes it very computationally exhaustive. To overcome this complication and arrive at the optimized design, design of experiment (DOE) with combination of response surface method (RSM) has been adopted. One of the most important components in an automobile power transmission is clutch system, its main function is to permit soft and steady engagement of the torque transmission through its axial stiffness. The progressive axial stiffness is achieved by a cushion disc placed between the two friction facings. The undulating model of the cushion disc acts like a spring, thus providing gradual stiffness during engagement and disengagement of the clutch system. This work presents an approach to the design optimization of the clutch cushion disc with the integration of FEA and design of experiment to achieve the target cushion curve and minimize the stress induced during the action using Ansys Design explorer.

Keyword(s): Clutch cushion disc, Design of experiments (DOE), Response surface methodology (RSM)

1. Introduction

Structural analysis of the automotive components and assemblies is performed through simulations/experiments that are expensive in terms of money, resources and time. In such cases, evaluating all the design variables types and arriving at optimized design makes it very computationally exhaustive and intractable. Design of experiment is a methodical approach that helps the designers to determine the effect of each individual parameter that affects the output results of the process or design. DOE also provides a full understanding of the interaction between the design parameters and the output response of the design. The meta-models obtained through design of experiment and response surface method captures the relationship between the input parameters and the output response efficiently and helps in evaluating the objective functions and constraints. There are several versions of DOE schemes but the basic idea behind
every design type is to spread out the design samples in the design space such that the design space can be explored in the most efficient way. The motive is to obtain the required information with minimum number of samples.

1.1 Clutch Cushion Disc

Clutch is a mechanical element which makes a momentary engagement with the gear box and the vehicle engine. Clutch disc assembly is responsible for the transmission of torque. It not only transmits torque but also absorbs torsional vibrations. For drivers’ comfort and drivability soft and gradual transmission of torque must be ensured. This soft and gradual reengagement of torque transmission is achieved through the cushion disc in the clutch disc. Cushion disc provides the required axial elastic stiffness to the clutch disc for gradual transmission of torque.

The cushion disc is placed in between the friction facings through rivets (Figure 1). It has an undulating surface which provides it a spring characteristic during engagement and disengagement. Without cushion disc the clutch engagement is jarring and uncomfortable for the driver, it may even lead to engine stalling. The load-deformation curve, also known as cushion curve is obtained by compressing clutch disc between the two plates, representing pressure plate and flywheel. It is one of the important design constraint prescribed by the car manufacturers. The design of the cushion disc must meet the prescribed cushion stiffness target and minimum stress criteria.

![Figure 1. Clutch cushion disc](image)

Literature on the cushion disc is quite limited. Only few researchers have carried out the study on the load deflection characteristic curve of the clutch disc. Literature describing the finite element modeling of the clutch cushion disc have been found and studied. Sfarni et al. [1] performed the parametric model study of the clutch cushion disc to identify the significant geometrical parameters. Sfarni et al. [1,2] proposed a finite element riveted clutch disc model in order to predict the cushion curve. Kaya [3] performed shape optimization of an automobile clutch cushion disc using differential evolution method. But they did not take into account the stresses developed during clutching mechanism. N Capetti [6] studied how temperature affects the cushion stiffness curve. Hagerodt A [7] reviewed how the proper design of the cushion springs can improve the transmission. Purohit R [8] performed static structural analysis of clutch disc assembly using Ansys software. Gunst [4] and Christine M[5] explained in their work how design of experiments and response surface optimization can be implemented in product design optimization. ANSYS [9] design
explorer offers various DOE schemes and response surface types that allows user to perform parametric optimization.

Design of the clutch cushion disc to achieve the specified cushion target is dependent on designer’s experience. It is achieved through trial and error method. Manual parametric iterations are performed by the designer, thus making it a time consuming and a costly process. In this study, a methodology is proposed, using design of experiment and response surface optimization algorithms to obtain the optimal design that meets the prescribed cushion target and minimum stress criteria.

2. Methodology

The present work deals with the determination of an optimized design of clutch cushion disc taking into account load deflection characteristics and stress distribution with the integration of the design of experiment and FEA in Ansys workbench. The main objective is to have an optimized design that meets the required cushion specifications (i.e. target stiffness curve) and has minimum stress distribution.

The primary step of the design optimization through response surface optimization using Ansys design explorer is to develop an initial simulation model. Initial simulation model is used to identify and define the parameters that need to be investigated. Parametrical variations are performed to anticipate the effect of cushion parameters.

A parametric model is created in Ansys design modeler. A sword drapo profile is considered for the optimization (Figure 2). Initial model is prepared based on the measurements from the existing design, in order to anticipate the effect of assembly on the cushion curve. Bending widths and the altitude of the profile are chosen as the important cushion parameters for design optimization. Outer diameter and inner diameter are kept constant.

![Figure 2. Parametric model of cushion disc](image1)

![Figure 3. Geometry of cushion disc (single paddle)](image2)

Computation is split in two static structural analysis systems: (a) for computation and estimation of cushion, which is made in comparison with initial disc measurements (without considering the facing rivets) (b) for computation and estimation of stress levels in the disc which is made including a simulation of the facing rivets.

The desired output response parameters are chosen from the simulation results. Once the initial simulation is completed and parameters defined, design space is defined. Design space is defined by
specifying the upper and lower bound of the input design parameters. In this study Box-Behnken design techniques is used to conduct design of experiment. Box-Behnken algorithm permits to perform parametric variations with extreme factors combinations. It requires fewer design points than other algorithms. Kriging with auto refinement is used for the response surface computation. It refines by creating additional design points based on its internal error prediction until accuracy is achieved and is highly suited for the non-linear responses. Goodness fit metrics obtained from this algorithm is always good.

Once the response surface is obtained, goal driven optimization is performed to find the optimum design point. As the optimization is a multi-objective problem, multi objective genetic algorithm (MOGA) is used for optimization. It is suited for continuous parameters, can handle multiple goals and helps in evaluating the global optima. Pareto optimum candidate points are predicted from the optimization. Ansys through its multi decision criteria predicts 3 good candidates points from pareto optimum points. Stars are allotted to these design points based how well they meet the objective. Candidate with maximum number of stars is chosen as the optimum design point.

3. Finite element modeling of the clutch cushion disc

Taking into account the symmetry of the clutch cushion disc, blade alone is considered for finite element calculation. Blade is meshed with shell elements (shell181). Mesh around the rivet holes are mapped mesh. Thickness of the cushion disc is 0.7mm. Facing rivets heads were imprinted in the model. Meshed model of the blade is shown in the figure below (Figure 4).

Interface between the friction facings and the cushion disc is represented by two rigid dummy bodies (Figure 5). Two frictionless contact pair is scoped manually, between the top and bottom surface of the cushion disc and the two rigid bodies. Augmented Lagrange is used as the contact formulation. Bottom facing is constrained in all directions. Top facing is constrained in all direction except in axial direction (UZ direction). Inner diameter of the cushion disc is locked to restrain rigid body motion. Clamp load is applied axially on the top surface. Force is applied in two load steps, preload is also considered. For stress level computations, facing rivets are considered. Bonded contact is defined between the cushion disc rivets head and the facings. Interference fit is simulated. Cyclic symmetry boundary conditions are also applied.

Figure 4. Meshed model of cushion disc.  
Figure 5. Top and bottom facing.
Initial simulation for cushion curve and stress computation is updated for the initial cushion disc design. Initially we have 3 data sets: a) target measurement which is the required cushion target, b) load-deflection characteristics of the initial disc only obtained from simulation, and c) initial assembly measurement which is known for the initial design. Since we need to define FEA results in terms of assembly results, the same difference which exists in initial disc only and initial assembly measurement data is applied to the other variations in order to anticipate the effect of the assembly on the final cushion.

Deflection values and force reaction values are obtained for plotting the progressive stiffness curve. Reaction force is used to check whether the analysis or design point is solved correctly or not. Deflection and reaction force values are parameterized at number of sub steps for cushion curve computation. Similarly, maximum stresses developed on the gear box side (i.e. top surface) and flywheel side (i.e. bottom surface) are obtained as output response. The results for the initial design are shown below:

![Figure 6. Progressive stiffness curve for initial design](image)

4. **Design of Experiment and Response surface optimization**

Once the initial simulation is completed and the output response defined, design of experiment and response surface optimization is carried out. Input parameter description are shown in Figure 2, A-F are the bending position, Z1 and Z2 is the height of the profile. Lower bounds and upper bounds are described for each parameter as shown in Table 1. These bounds were defined based on the geometry of the initial model. It was kept in mind that the model update should not fail within the defined bounds of the parameter. A parametric study was also done to identify the influencing parameters. Two iterations were performed to achieve the cushion target each considering different number of parameters:
Table 1. Upper bounds and lower bounds of parameter

| Parameters | Initial value (mm) | Lower bound (mm) | Upper bound (mm) |
|------------|--------------------|------------------|------------------|
| P1-A       | 6                  | 5                | 8                |
| P2-B       | 17                 | 16               | 19               |
| P3-C       | 29                 | 29               | 32               |
| P4-D       | 40.8               | 38               | 42               |
| P5-E       | 66.5               | 64               | 69               |
| P6-F       | 76.5               | 74               | 75               |
| P7-Z1      | 0.65               | 0.6              | 0.7              |
| P8-Z2      | 0.85               | 0.8              | 0.9              |

4.1 Iteration 1

Three parameters were considered for this study. Bend distance (A, D, and F) were defined as the input cushion design parameters. Height of the profile, thickness and other parameters was kept constant. Parameters were chosen based on the parametric study. 13 design points were generated through Box-Behnken design. Refinement points were generated to improve the response surface accuracy in prediction. Goodness of fit (Figure 7) chart was extracted to get the information regarding the data fitting. From the local sensitivity chart (Figure 8), it was observed that on increasing the parameters A and F cushion deflection decreases, and on increasing the parameter D cushion deflection decreases. The adequacy of the response surface was checked through the verification points. Optimization problem was defined as the objective set to seek the target cushion curve and minimize the stress distribution, subjected to the constraints.

Objective: Seek target stiffness curve, Minimize stress levels.

Constraints: Stress ≤950 MPa (@7000N), lower bounds and upper bounds of the parameter

Three optimum design points were generated from the MOGA optimization. Number of stars and cross are displayed next to each of output response parameter to indicate how well it meets the stated objective. The candidate with maximum no of stars was selected as the optimum design point. The shift in the bending position between the initial and optimized model is shown in Figure 18. The optimum result obtained from iteration 1 is shown below:
Figure 7. Goodness of fit for iteration 1.
Figure 8. Local sensitivity of parameters.

Figure 9. Progressive stiffness curve for iteration 1.
Figure 10. Representation of computed GB side stress under clamp load for iteration 1.

Figure 11. Representation of computed FW side stress under clamp load for iteration 1.

It was observed that the calculated cushion curve shifted near to the cushion target but did not fit well. It fits the required cushion target at medium clamp load (3000N-5000N), and deviates at low and high clamp loads (Figure 9). However, the stress levels decreased in the optimized cushion disc model as compared to the initial model (Figure 10 and Figure 11). Since required objective was not meet, another design of experiment was conducted considering more number of cushion parameter in order to achieve the required cushion target.

4.2 Iteration 2

In this study eight cushion parameters were considered. Bend distance (A, B, C, D, E and F) and height of the profile (Z1 and Z2) was defined as the input cushion design parameters. Thickness of the cushion disc and was kept constant. Same algorithm and objective as used for the case study 1 was used to conduct design of experiment and response surface optimization. Lower bounds and upper bounds were defined for each parameter as mentioned in the Table 1. 65 design points were generated and simulated through Box-Behnken design. Goodness of fit metric obtained from response is good as observed from Figure 12. Sensitivity of each parameters was studied from the local sensitivity chart as show in Figure 13. The optimum result obtained from the optimization is shown below:
Figure 12. Goodness of fit for iteration 2.

Figure 13. Local sensitivity of parameters.
As seen in Figure 14, the optimum design obtained from the iteration 2 meets the cushion requirements. The cushion curve is very near to the required cushion target at low and high clamp load value. The accuracy of the fit was checked by chi square goodness of fit test. The stress level distribution is also below the stress criteria as seen in Figure 15 and Figure 16.

Comparison is shown between the optimized design obtained from the two studies in Figure 17. It is evident from the stiffness curve comparison and stress plots that the optimized design obtained from the second iteration is the best one. Thus this approach of design of experiment and response surface optimization using Ansys Design explorer was effectively applied in the design optimization of the clutch cushion disc.
Figure 17. Progressive Stiffness curve comparison for iteration 1 and iteration 2.

Figure 18. Overlapped model comparison between the initial and optimized design (itr 1).

Figure 19. Overlapped model comparison between the initial and optimized design (itr 2).

5. Results and Conclusion

With the parametrical variations of bending distance and altitude of the profile it is possible to meet the specified cushion stiffness curve. The design point generated from the design of experiment and the response surface optimization in Ansys meets the required cushion target and minimum stress criteria. It saves lot of manual work. Solving time for conducting the design of experiment and response surface optimization is less than the manual optimization and thus reduces the trial and error efforts. Global mesh size used for cushion disc was 0.6 mm. It can be shown that it is not necessary to maintain such a small mesh size if progressivity calculation is the only aim of calculations. The proposed methodology can be applied for the parametric design optimization of similar automobile components.

There are various different DOE algorithms available in Ansys design explorer which can be investigated for performing parametric design optimization of automobile components. It is necessary to
understand the mathematical backgrounds for each of the available algorithms and with different algorithm combinations, required objective and accuracy can be achieved.

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