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Design Optimization of A Rotating Flywheel Under High Centrifugal Forces using Response Surface Method

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Abstract. Flywheel is a mechanical device specifically designed to efficiently store rotational energy. Flywheels resist changes in rotational speed by their moment of inertia. In automotive clutch system, flywheel rotates at high speed under the influence of rotational force which may result in severe crack. In this study, finite element analysis was used to predict equivalent stress of the flywheel at different rotational speed. Taking 8000 rpm as the maximum rotational speed, the layout of the flywheel was then modified. This is done not only to reduce the maximum equivalent stress, but also reduce the mass of the flywheel. The comparison between the original layout of the flywheel and the modified one is shown in this work.

1. Introduction

An automotive component in clutch system like flywheel may experience high rotational motion [1-3]. The induced severe radial and circumferential stress may result in crack and damage. It is the intention of this work to investigate the maximum equivalent stress using Finite Element Analysis. The original design was then modified by introducing a series of slot segment within the flywheel with the aim to reduce the original equivalent stress beside reducing the weight of the flywheel.

Previous work [3] investigated the stresses and deformation of the frictional clutch components using finite element analysis. This work clearly suggested the importance of the optimal design of the flywheel in order to reduce stress. Otherwise, improper design may lead to initial crack and breakage due to high rotational speed. Other than that, the weight of the flywheel was also considered [4] to suggest optimal design of a flywheel.

In this work, response surface method was used to propose new modified design of the flywheel by considering the equivalent stress. By introducing the slot segments within the flywheel, the weight of the flyweight can be reduced besides reducing the equivalent stress at certain rotational speed. In this work, the optimal dimensions of the flywheel are based on the maximum 8000 rpm speed rotational motion.

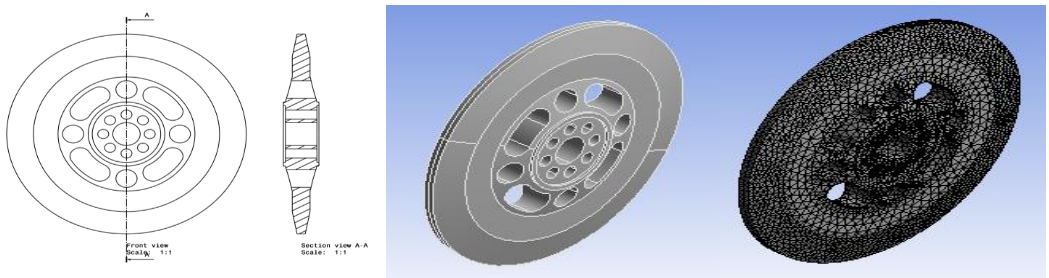
2. Finite element model and response surface method

In this study, finite element analysis is used to analyze the flywheel under different rotational speeds. The objective is to investigate the changing of the stress with respect to the rotational speeds. The pattern is expected to follow the trend in [5]. The flywheel design is to withstand at 8000 rpm to simulate the high rotational speed condition. The boundary condition in the finite element model is similar to Ref. [2]. The material properties of the flywheel are shown in table 1.

Table 1. Material Properties.

AISI 316 Stainless Steel	
Elastic Modulus	196 GPa
Poisson Ratio	0.27
Yield Stress	205 MPa
Density	7999 kg/m

In order to propose the optimal design of the flywheel, the response surface method is used [6-8]. Central Composite Designs is adopted in the design process using quadratic model. The mathematical model is created that best fits to the obtained data using FEA. The objective function is constructed as a second order degree polynomial.



(a) (b) (c)

Figure 1. Original Flywheel Design before modification
(a) cross section, (b) CAD model (c) FEA model.

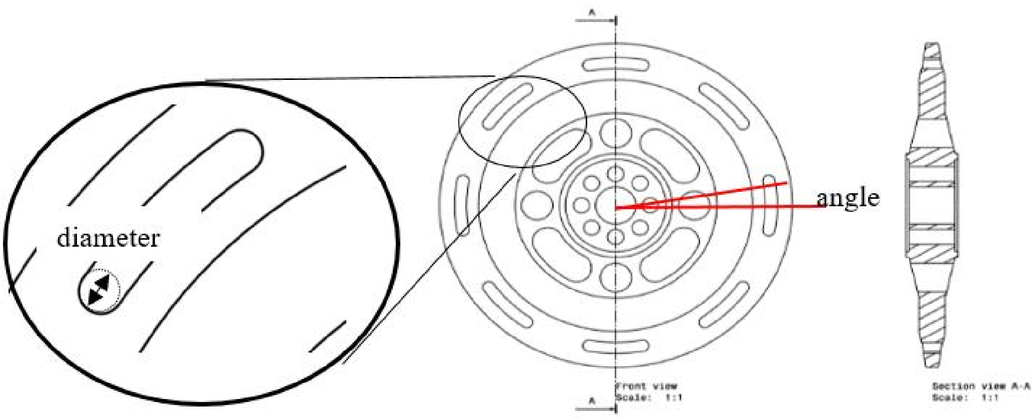


Figure 2. Modified flywheel.

The simulation results provide data of equivalent stresses for each design. In this study, the original flywheel is re-designed with a series of slot profile. The diameter of the slots is purposely varied from the range of 6mm to 12mm. The profile of the slots is also defined with respect to the given angle from the central point between the range of 10 degrees to 20 degrees. The target design can be formulated as follows;

Objective	Minimize Maximum Equivalent Stress	(1)
Subject to	6mm < diameter of slot < 12mm	(2)
	10 degree <Slot size (angle from center point) < 20 degree	(3)
Constraint	High Rotational Speed 8000 rpm	(4)

The response surface method is used in this study by adopting central composite design method. The objective function is defined as a function of two second-order quadratic terms as follows;

$$y = \beta_0 + \beta_1 x_0 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon \quad (5)$$

This second order model is the basis for the response surface designs. This model provides a good approximation to the surface near the maximum or a minimum. For k = 2 there will be a 22 design with center points, which is required for the first order model. The star or axial points are, in general, at some value α and -α on each axis. The 22 design create a box, and adding the axial points outside of the box gives a spherical design where $\alpha = \sqrt{k}$ as shown in figure 3. It is an advantage to use central composite design. This computation is often used when the design plan calls for sequential experimentation because these designs can include information from a correctly planned factorial experiment.

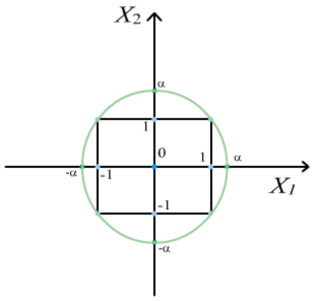


Figure 3. Central Composite Design.

3. Analysis and discussions

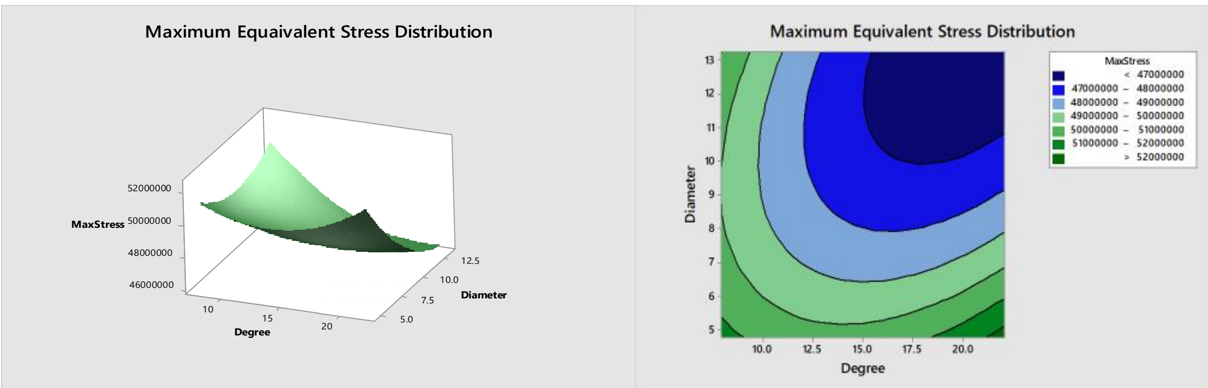


Figure 4. 3D and 2D surface plots for variations in diameter ($X1$) and angle ($X1$) at constant maximum 8000 rpm.

The result obtained from the equation (5), were analyzed and shown in figure 4 and figure 5. The 3d surface plots for variation of diameters and the angle profile (in degree) of the slot as shown in earlier figure 2, show the changing trend of the maximum equivalent stress or Von Misses Stress. It can be observed that the maximum equivalent stress tends to decrease with the increasing of the diameter and angle profile. It can be easily concluded that by increasing the diameter and the angle profile will decrease the maximum equivalent stress. However, in this optimization process, the design is subjected to the limitation as defined in equation 2. Not only that, it is also can be seen from figure 5 that by simply increasing the diameter and the angle profile, the maximum equivalent is not continuously decreasing. The changing trend start to show an increment after certain point of minimum value of maximum equivalent stress. The interaction of the changing parameters is also shown in the same figure.

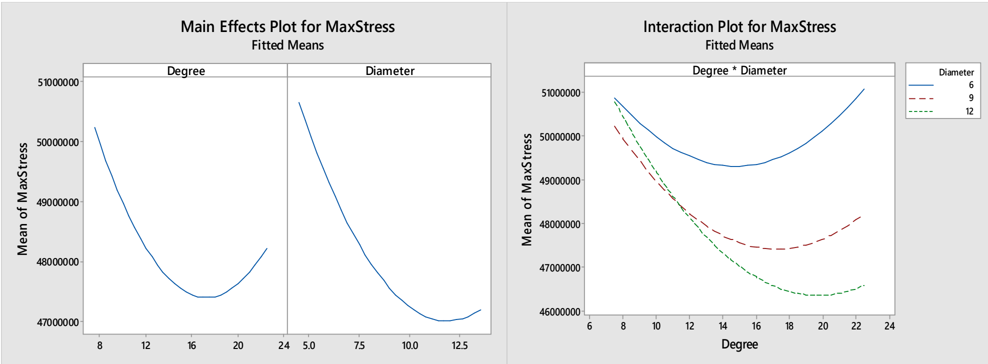


Figure 5. The effect of Maximum Equivalent Stress with the changing of the size of slot (degree) and diameter of the flywheel.

By searching the optimum value of the diameter and the angle profile of the slot, the optimal dimensions of the slot is decided which satisfy the target design. The comparison of the maximum equivalent stresses at different rotational speeds are also show on figure 6. During the optimization process, even though the high rotational speed is constrained, the maximum equivalent stress will also decrease at different rotational speeds.

Table 2. Comparison between the original and Modified Design of flywheel.

Comparison	Volume m³	Mass kg	Slot Profile	Maximum Stress at 8000 rpm
Original Design	$2.6411(10^{-4})$	2.1126	No Slot	50908000 Pa
Modified Design	$2.3061(10^{-4})$	1.8447	Diameter = 12mm, Degree = 19.7°	45422000 Pa

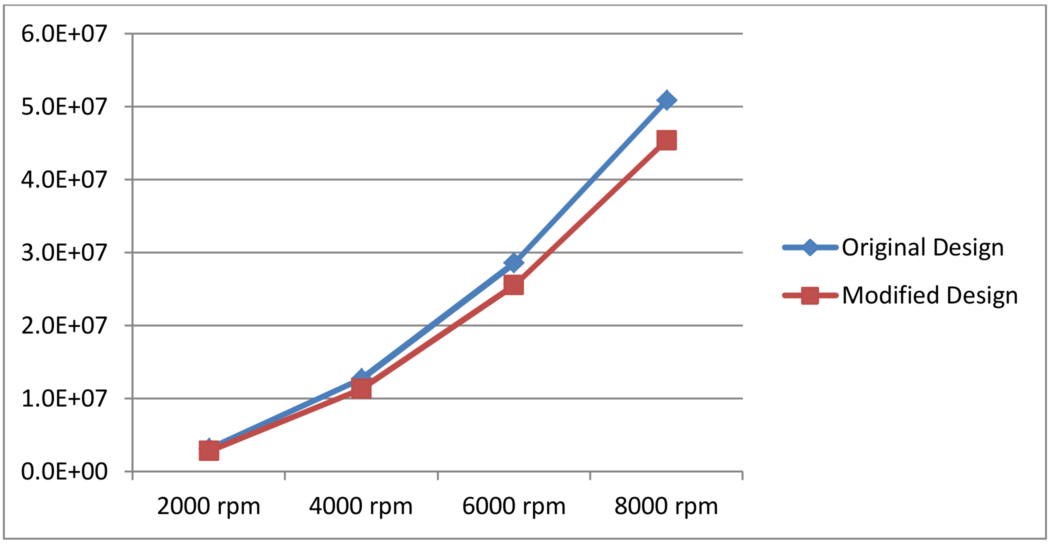


Figure 6. Comparison of the maximum equivalent stress [Pa] between original and modified design at different rotational speed [rpm].

4. Conclusion

The Response Surface Method is useful for the design of experiments investigating the effect of the two evaluated factors (diameter of the slots and slot size) on the response parameter (equivalent stress). This computational experimental design not only investigates the variation of the changing response, but also able to identify the optimal dimensions of the evaluated factors with respect to the equivalent

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stress. This structural modification not only reduces maximum equivalent stress but also the weight of the flywheel itself.

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