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Structural Optimization of Alloy Wheel Rim using Design of Experiments

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ABSTRACT:

Automobile wheel is a key component of the automobile. The optimization design for aluminium alloy wheel was implemented using Design of Experiments (DOE) in this paper. On wheel, the parameters affecting the overall efficiency such as strength, stiffness and weight are selected, and simulation experiments are completed using Minitab software according to the Box-Behnken Design. The response surface model is obtained from the Response Surface Method (RSM) and then static analysis was done by using ANSYS for each design with different combination of parameters produced by response surface model. As a result, the optimal parameters of the wheel are determined by finding the minimum value of the response model. A shape of an optimized wheel is determined by the response surface model and validity is confirmed by analysing and comparing the characteristic of wheel with the baseline design. Lastly, transient thermal analysis of the optimized alloy wheel is aimed at evaluating the performance of alloy wheel of a car under static conditions specifically in hot weather.

KEYWORDS:

Alloy Wheel; Design of experiment; Box-Behnken design, Response surface method; Finite element analysis

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NOMENCLATURE:

RSM	Response Surface Method
CAD	Computer Aided Design
CAE	Computer Aided Engineering
DOE	design of experiment
ANSYS	Finite Element Software
OPTIII	Optimization Program

1. Introduction

In the past, steel wheel rim was applied in most of the cars due to the steel material properties. However nowadays, alloy wheel is used primarily in automotive industries because they offer suitable properties such as low weight, high strength and many more. However, still some of the alloy wheel designs failed to produce a proper result due to the complexity of designs. Therefore, these failure designs must undergo an optimization process that can utilize an alternative with the most cost effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing the undesired ones. However, in typical optimization problem, the goal is to find the values of controllable factors that determine the behaviour of design or system which maximizes the productivity and minimizes the waste. The design of structural system has two categories: design a new structure, and improving the existing structure to perform better. The design engineer's experienced and creative ideas are required in the development of new structure [1]. Nowadays, many engineers started to use the mathematical model and computational tools like Computer Aided Design (CAD) and Computer Aided Engineering (CAE) to develop the designs. Then, these designs were analyzed using structural optimization to obtain the optimal design. In structural optimization, the variables are generally the sizes of structural elements and the quantities that define the geometry or shape physical system.

Structural optimization is divided into three optimization processes such as size, shape and topology optimization. Some basic optimizations of these have been carried out in various applications [2-4]. Wheel rim is one of the important parts which a function to move the vehicle. In 2010, methods of fatigue life prediction and structural strength of steel wheel under the bending conditions were detailed by Li et al [5]. They assume that steel wheel is a heavy part due the material used and suggested wheel must undergo a size optimization process to obtain an optimal design. Therefore, the problem was overcome by applying size optimization method on the styling holes of steel wheel to obtain an optimum size which can lead to weight reduction. Even though the steel wheel structural weight has been reduced a little, it still did not accomplish the needed requirement. Therefore, alloy wheel rim has been introduced to overcome these problems.

Utilizing the zero order optimization methods in ANSYS, a wheel as the object with the bending test condition, Zhou [6] has used the composite materials such as magnesium alloy to optimize the design of lightweight structural dimensions of the wheel rim thickness, wheel installation flange thickness and the contours of the wheel and thereby minimised the weight of the wheel. Research on structural optimization of the aluminium alloy wheel was also done using OPTIII method [7]. The OPTIII has the characteristics of high convergence rate and the lightweight design of a wheel may be realized based on the optimization design. In this paper, the optimization process was carried out on the aluminium alloy composite wheel. An alloy wheel of Proton Persona with 7 spokes was chosen to be optimized by using design of experiments (DOE).

2. Means and methods

Three parameters are chosen to be optimized in the alloy wheel shown as Fig. 1. DOE is a method to find an optimal condition in a combination of parameters. Then, these combinations of parameters are analysed using Response Surface Method (RSM). RSM is an optimization method introduced by Box and Wilson in the early 1950s. It consists of a group of mathematical and statistical techniques used in the empirical study of relationship between one or more measured responses and input factors. Given a response y, and a vector of variables x influencing y, the relationship between x and y is given by,

$$y = f(x) + \varepsilon \tag{1}$$

$$\hat{y} = g(x) \tag{2}$$

where ε is, a random experimental error assumed to have a zero mean. Since the true response function $f(x)$ is usually unknown, the estimated response $g(x)$ is created to approximate $f(x)$.

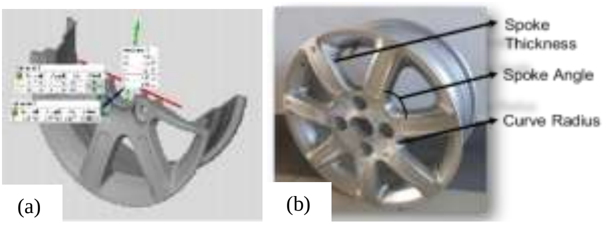

Fig. 1: (a) Dimension acquisition using GOM (b) Actual alloy wheel

The most widely used response surface approximating functions are low-order polynomial models. The 1st and 2nd order models are,

$$\hat{y} = b_0 + \sum_{i=1}^{k} b_i x_i \tag{3}$$

$$\hat{y} = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j}\sum b_{ij} x_i x_j \tag{4}$$

where k is the number of parameters in fitted model, b_0 is the constant coefficient, b_i is the linear coefficient, b_{ij} is the interaction coefficient between x_i and x_j, and b_{ii} is the quadratic coefficient of x_i. Generally, the procedure of RSM consists of the following steps:

1) Experiments are screened to reduce the number of variables to those that are the most influential to the response, when the number of variables is large or when the experimental burden is heavy.
2) Designing and conducting a series of experiments to get adequate & reliable response measurements.
3) Developing mathematical models of the first and second order response surface with the best fittings.
4) Finding the optimal set of design parameters that produces a max. or min. value of the response.

Once the optimized design is obtained from the RSM, the transient thermal analysis is carried out. This is because during a hot weather, the wheel is exposed to the high surrounding temperature and will have an effect on the alloy wheel due to static conditions [8].

3. DOE using Box-Behnken Design

The model of alloy wheel was created in Catia V5 by using the dimensions that are collected from the GOM software. The objective function for the optimization design of alloy wheel is to maximize overall efficiency by reducing weight and increase/maintain the strength. Spoke thickness, spoke angle and curve radius were chosen on alloy wheel which may affect the efficiency of alloy wheel. The shape of alloy wheel change when these parameters change at the same time. Thus, the relationship between all these parameters is treated as dependent. Table 1 presents the actual value and range of each design parameter. Based on these parameters, a RSM is carried out from the DOE. These parameters are inserted in Box-Behnken Design to get more information from fewer experiments. Then, three factors and three response variables were chosen to produce 15 runs with different values of each factor using Minitab16 and those values are presented in Table 2.

Table 1: Range of design parameters

Design Parameters	Actual Value	Min. Value	Max. Value
Spoke Thick. (mm)	25.68	20	30
Spoke Angle (°)	50.35	45	60
Curve Radius (mm)	5.2	1	8

Table 2: Box-Behnken design results

Run Order.	Std Order	PtType	Curve Radius (mm)	Spoke Thick. (mm)	Spoke Angle (°)
1	10	2	4.5	30	45.0
2	1	2	1.0	20	52.5
3	12	2	4.5	30	60.0
4	3	2	1.0	30	52.5
5	8	2	8.0	25	60.0
6	14	0	4.5	25	52.5
7	15	0	4.5	25	52.5
8	6	2	8.0	25	45.0
9	4	2	8.0	30	52.5
10	5	2	1.0	25	45.0
11	9	2	4.5	20	45.0
12	11	2	4.5	20	60.0
13	7	2	1.0	25	60.0
14	2	2	8.0	20	52.5
15	13	0	4.5	25	52.5

4. Finite element model and analysis

After creating all the alloy wheel designs from Box-Behnken Design result using Catia V5, each model is imported into the ANSYS. Then, the mesh of the model is created. Based on a mesh sensitivity study, a mesh size of 2mm was chosen. The number elements and nodes in the mesh are 410688 and 710747 respectively. The mechanical properties of aluminium alloy used for the modelling are given in Table 3. There are two kinds of load; static load and dynamic load acting on the automotive wheels. In this paper, the automobile wheels are subjected to static load only. The total magnitude load of 2930 N was obtained from the total mass of Proton Persona of 11720 N is divided into four wheels. Fig. 2(a) indicates the total magnitude load of vehicle, 2930 N acting downwards on the four holes at the wheel centre. Fig. 2(b) indicates the fixed constraints around the hub surface due to the region where automobile wheel contacts on the ground.

Table 3: Mechanical properties of aluminium alloy

Density (kg/m^3)	Modulus of Elasticity (Pa)	Poisson Ratio	Tensile Yield Strength (Pa)
2770	7.1E10	0.33	2.8E8

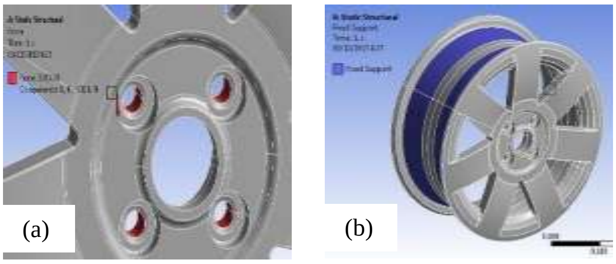

Fig. 2: (a) Load of vehicle acting on four holes at wheel center (b) Fixed boundary conditions application

5. Results and discussion

From the result of Static Structural Analysis on the baseline model, the magnitude of maximum deformation is 2.8947E-6 m and the maximum stress is 3.6061 MPa. The total weight of baseline model is 11.305 kg. Figs. 3(a) and (b) show the total deformation and Von Mises stress results of alloy wheel respectively. The strength and weight were optimized using RSM. The output from RSM analysis is given in Table 4. When the baseline model was analysed using RSM, no optimal solution is found because the value of total deformation is too low, and the Von Mises stress is too high. Fig. 4 shows the optimization response on the parameters according to the RSM. The goal of RSM is to optimize an alloy wheel performance by minimizing the weight and strength. Fig. 4 shows the minimum design parameters that can minimize the strength and weight compared with the datum model. It also indicates The minimum predicted total deformation and Von Mises stress responses are 2.5517 µm and 3.1305 MPa respectively. The mass of the optimal design is 11.1619 kg.

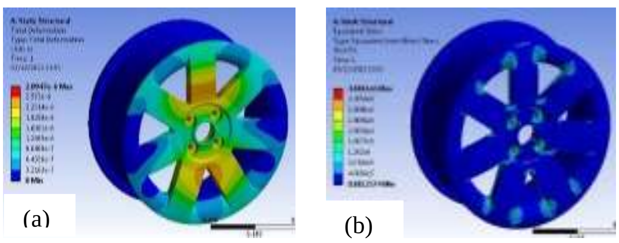

Fig. 3: Baseline design simulation results - (a) Total deformation (b) Von Mises stress

Table 4: Design parameter and response variable value

Run Order.	Max. total deformation (µm)	Max Von Mises stress (MPa)	Mass (kg)
1	1.8233	2.4489	12.457
2	5.3275	4.8319	11.37
3	2.1068	2.6375	11.685
4	1.9435	2.6971	12.031
5	3.4373	4.0796	10.818
6	3.1562	3.5562	11.132
7	3.1560	3.4662	11.132
8	2.8964	3.8277	11.462
9	1.9062	2.8205	12.054
10	2.9555	3.3055	11.441
11	5.4498	4.9226	10.485
12	6.4682	5.1027	9.9947
13	3.4982	3.9010	10.798
14	5.8224	5.1440	10.233
15	3.1554	3.8653	11.132

```
Response Optimization

Parameters

        Goal     Lower   Target   Upper  Weight  Import
total   Minimum  1.8233  1.8233   2.900       1       1
von     Minimum  2.4489  2.4489   3.600       1       1
mass    Minimum  9.9447  9.9447  11.306       1       1

Global Solution

curve radius   =   4.04040
spoke thickn   =  28.0808
spoke angle    =       60

Predicted Responses

total  =   2.5517 ,  desirability =  0.323457
von    =   3.1305 ,  desirability =  0.407902
mass   =  11.1619 ,  desirability =  0.105826

Composite Desirability = 0.240799
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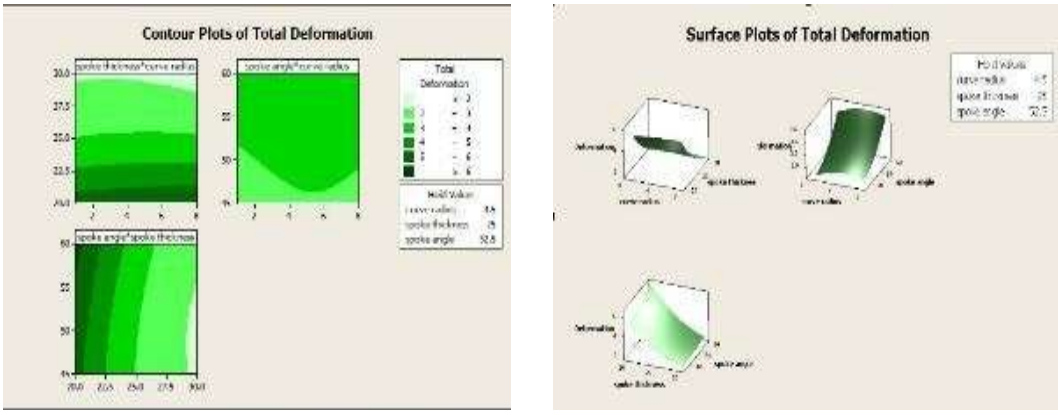
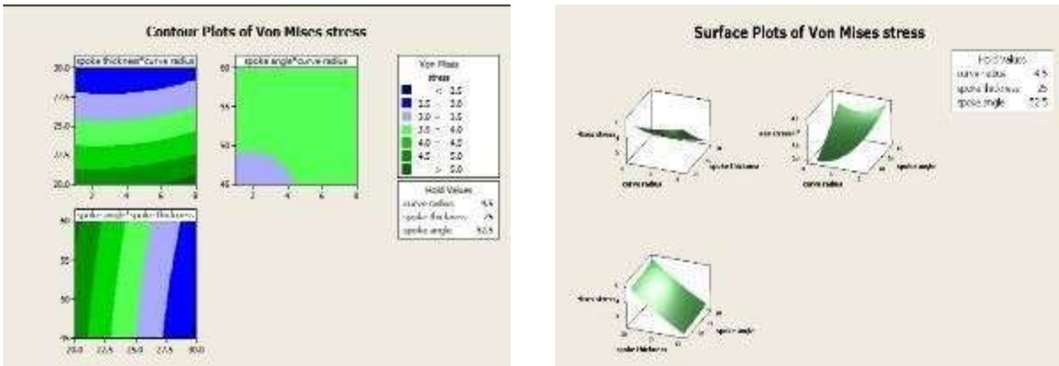
Fig. 4: Response optimization

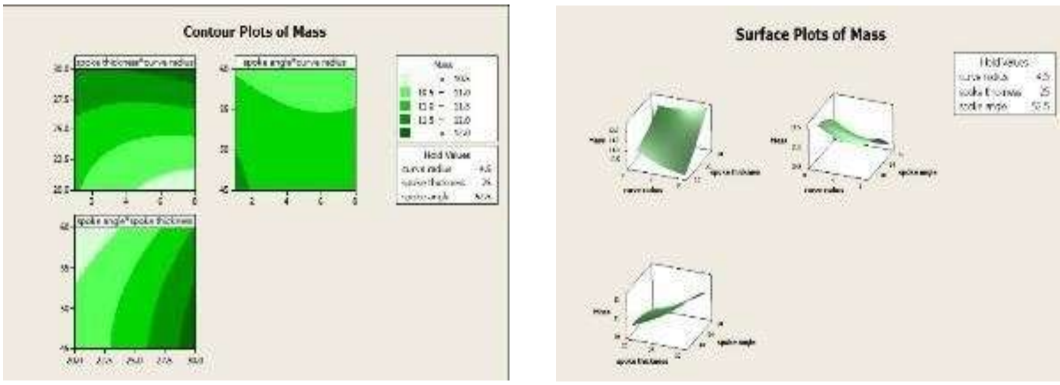
Fig. 5(a) shows the contour plot of total deformation distribution between the design parameters. From the graphs of spoke thickness vs. curve radius and spoke angle vs. spoke thickness, the minimum contour line for total deformation is 2 µm and 3 µm for the graph of spoke angle vs. curve radius. Fig. 5(b) shows the contour plot of Von Mises stress distribution between the design parameters. From the graphs of spoke angle vs. spoke thickness, the minimum contour line for Von Mises stress is 2.5 MPa, 3.0 MPa for the graph of spoke thickness vs. curve radius and 3.5E MPa for the graph of spoke angle vs. curve radius. Fig. 5(c) shows the contour plot of mass distribution between the design parameters. From the graphs of spoke thickness vs. curve radius and spoke angle vs. spoke thickness, the minimum contour line for mass is 10.5 kg and 11.0 kg for the graph of spoke angle vs. curve radius. Therefore, all the optimal value parameters obtained from the response optimization are proven. Figs. 6(a) and (b) show the total deformation and Von Mises stress result of optimal alloy wheel. The comparison results of total deformation, Von Mises stress and the weight of baseline and optimal designs were recorded in Table 5. The optimal design has a slightly low strength compared to the baseline model, but is lighter then baseline model. Total deformation of optimal design is also lower than the baseline model. Therefore, the optimal design is more efficient than the baseline model.



(a) Total deformation distribution between spoke thickness, spoke angle and curve radius



(b) Von Mises stress distribution between spoke thickness, spoke angle and curve radius



(c) Mass distribution between spoke thickness, spoke angle and curve radius

Fig. 5: Overall responses distribution between spoke thickness, spoke angle and curve radius

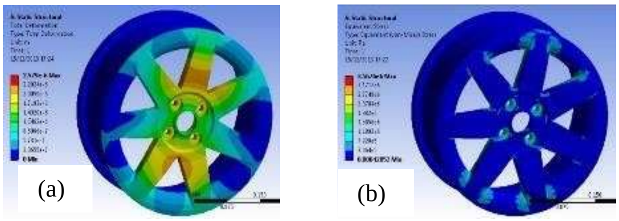


Fig. 6: Optimal design simulation results - (a) Total deformation (b) Von Mises stress

Table 5: Result of total deformation, Von Mises stress and weight of baseline model and optimal design

Design	Total deformation (μm)	Von Mises Stress (MPa)	Weight (kg)
Datum model	2.8947	3.6061	11.305
Optimal design	2.5790	3.567	11.047

Finally, a transient thermal analysis is carried out using ANSYS to investigate the temperature variation across the optimized alloy wheel. This is because when the alloy wheel in a static condition, the front surface of alloy wheel is exposed to the surrounding high temperature on a hot weather. Therefore, the temperature effect on optimized alloy wheel can be obtained by transient thermal analysis. The natural convection and radiation is assumed to happen on the optimized alloy wheel. During the analysis, the surface of the alloy wheel is assumed to be sphere. Other than that, the surface temperature of alloy wheel is 37 ºC and the surrounding temperature is changed from 33 ºC to 40 ºC. Fig. 7(a) shows the thermal loading on the alloy wheel. Fig. 7(b) shows the thermal distribution result from the transient thermal analysis. The temperature distribution is very small because the analysis is done only for 10s and the effect on the alloy wheel by the surrounding temperature of 40 ºC is significant. The temperature difference is only 0.117 ºC and accepted with not much effect to optimal design.

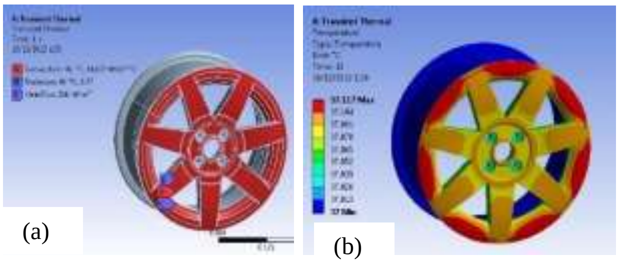


Fig. 7: Optimal design transient thermal simulation results - (a) Thermal loading (b) Temperature distribution

6. Conclusion

Various design parameters - spoke thickness, spoke angle and curve radius all influence the alloy wheel design. DOE was successfully proposed the optimal design parameters. The designs were analysed under static structural load using ANSYS to validate the optimal parameters finding, and the objective was met. Overall efficiency of alloy wheel which are its strength and weight were optimized using RSM. An optimal design was obtained from RSM that is providing almost equal strength and reduction in weight compared to the baseline design. The optimized alloy wheel is analysed for the transient thermal effects. It was found that the temperature difference is significantly small and almost equal to the thermal performance of the baseline model.

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