Research Article

Design Optimization for Weight Reduction of Locomotive Wheel using Response Surface Methodology

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I N F O

A B S T R A C T

Manufacturing cost of locomotive wheel largely depends on mass of locomotive wheel, and to reduce mass of wheel, design optimization is necessary. In this research, the design of the locomotive wheel is optimized considering hub radius and hub width as input parameters to DOE (Design of Experiments). Initially, finite element analysis is performed under static structural loading conditions to determine equivalent stress and safety factor, which is followed by design optimization using Response Surface Methodology. The software used for design and analysis is ANSYS.

Keywords: Locomotive wheel, weight reduction, FEA, ANSYS

Introduction

A train wheel or rail wheel is a type of wheel specially designed for use on rail tracks. A rolling component is typically pressed onto an axle and mounted directly on a rail car or locomotive or indirectly on a bogie, called a truck. Wheels are cast or forged (wrought) and are heat-treated to have a specific hardness. New wheels are trued, using a lathe, to a specific profile before being pressed onto an axle. All wheel profiles need to be periodically monitored to ensure proper wheel-rail interface. Improperly trued wheels increase rolling resistance, reduce energy efficiency, and may create unsafe operation. A railroad wheel typically consists of two main parts: the wheel itself and the tire around the outside. A rail tire is usually made from steel and is typically heated and pressed onto the wheel, where it remains firmly as it shrinks and cools. Monoblock wheels do not have encircling tires, while resilient rail wheels have a resilient material.

Nomenclature of different regions of locomotive wheel can be seen in figure 1 above. Tread and flange are the regions that come into immediate contact with the rail track.
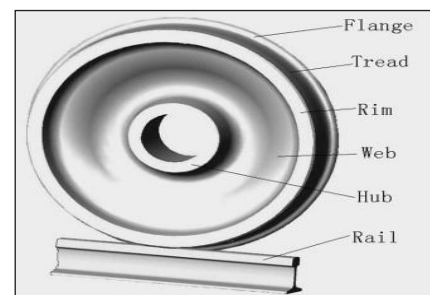

Figure 1.Locomotive wheel[1]

Problem Description

Structural and fatigue life analysis of railway wheels is done using the finite element method. The method involves three stages of analysis, i.e., preprocessing, solution, and postprocessing.

- The preprocessing stage involves CAD modeling, meshing into elements and nodes (discretization), assigning loads, and boundary.
- The solution stage involves matrix formulations, matrix inversions and multiplication, and assemblage of element stiffness. matrix, global stiffness.

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• The postprocessing stage involves viewing results, contour plots, vector plots, and optimization of input.

The base design reference is taken from the KLW data sheet, which provides a range of dimensions of hub, tread, flange, rim, and web. The dimension ranges of these parameters are provided in figure 2 below.

Table 1 below shows the material properties of wheel and axle loads. The axle load specified in Table 1 below is used for structural and fatigue life analysis.
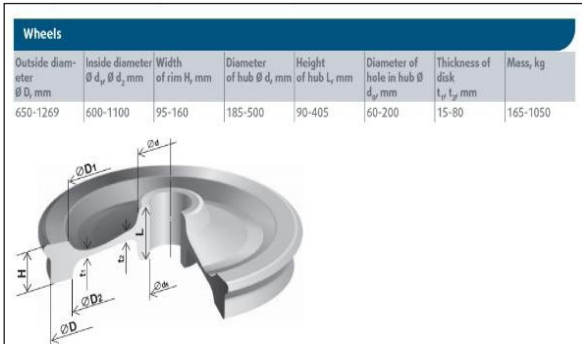

Figure 2.Wheel Dimension Range[4]

Table 1.Material properties and Loads

Axle Load	146.2 KN
Young's Modulus	205GPa
Density	7850 Kg/m^3
Ultimate Strength	450MPa
Yield Strength	250MPa

Finite Element Analysis

The CAD model of a locomotive wheel and track is modeled using the data reference ranges provided in figure 3. The CAD model developed is 1/4th of the actual size to save computational time in meshing and solution.

The model is meshed using hexahedral elements and fine sizing as shown in figure 4 below. The number of elements generated is 27461 and the number of nodes generated is 4988. Smoothing is set to medium, inflation set to smooth transition, transition ratio.272.
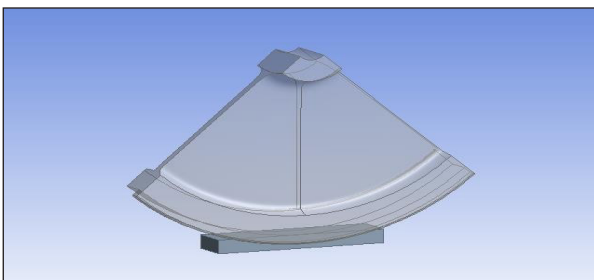

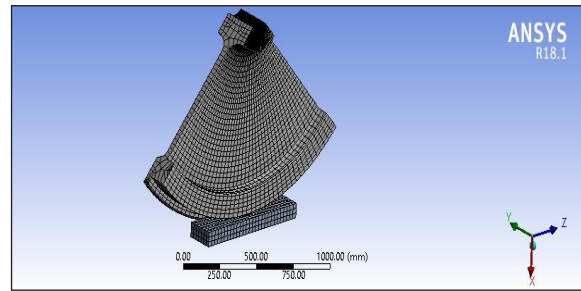**Figure 3.CAD model of wheel and track**

Figure 4.Meshed model of wheel and track

The bottom surface of the track is provided with fixed support [c], and the right surface of the wheel is provided with frictionless support [A]. A downward direction force of 146200N is applied to the hub as shown in figure 5 below.

The fatigue life analysis is performed under fully reversed load as shown in figure 6, and the safety factor along with fatigue life is determined. Life is determined in terms of the number of cycles.

Safety factor is determined, and the minimum value of safety factor obtained is 3.21, as shown in figure 7 below.
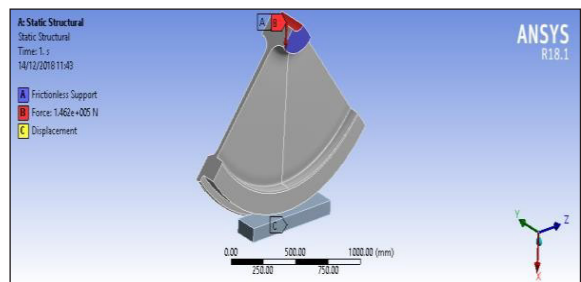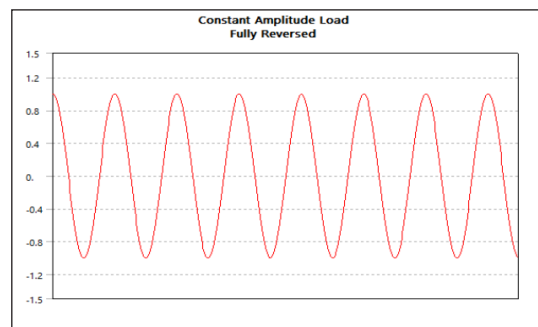

Figure 5.Loads and Boundary Conditions

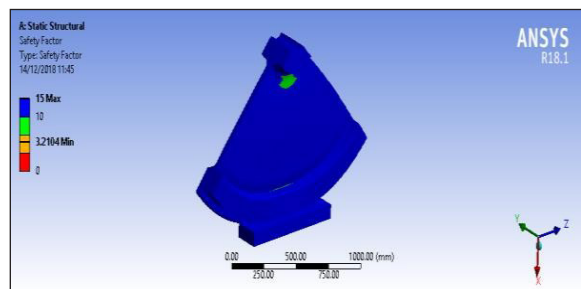

Figure 6.Equivalent stress plot

Figure 7.Safety Factor

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Optimization Using Response Surface Methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building[5]. By careful design of experiments, the objective is to optimize a response (output variable) that is influenced by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify reasons for changes in the output response. When behavior (response, y) that should be taken into consideration for design is determined as a function of multiple design variables (x_i), the behavior in the response surface method is expressed by the approximation as a polynomial y = f(x) on the basis of observation data. A quadratic response function with two variables and a regression model is expressed by

$$y=\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta x^2 + \beta x^2 + \beta_5 x_1 x_2$$

where β_0, β_1, β_2, β_3, β_4, and β_5 are the regression coefficients.

The optimization is performed on 2 design parameters, i.e., hub width (x_1) and hub radius (x_2), using response surface methodology. Fig 8. The response surface method (RSM) is a statistical and mathematical method to model approximately and analyze the response surface with the design variables when the interesting responses are influenced by various design variables. RSM was to use regression methods based on least squares methods. In the study, RSM was used to determine the optimum design for the minimization of the weight within the specific life. The significant process variables were identified by using the central composition design (CCD), which is a kind of design of experiments (DOE). Central composite design is the default DOE type. It provides a screening set to determine the overall trends of the meta model to better guide the choice of options in Optimal Space-Filling Design. The CCD DOE type supports a maximum of 20 input parameters.

	A	B	C	D	E	F
1	Name	P12 - hubwidth (mm)	P13 - hubradius (mm)	P4 - Safety Factor Minimum	P5 - Equivalent Stress Maximum (MPa)	P8 - Geometry Mass (kg)
2	1	123.75	80	3.2102	26.852	676.12
3	2	112.5	80	2.7564	31.273	675.85
4	3	135	80	3.0888	27.907	676.44
5	4	123.75	72	3.0369	28.384	677.81
6	5	123.75	88	2.7566	31.27	673.53
7	6	112.5	72	2.7123	31.781	677.66
8	7	135	72	3.1722	27.173	678.04
9	8	112.5	88	3.2214	26.842	673.27
10	9	135	88	2.7597	31.235	674.45

Figure 8.Hub Width and Hub Radius with Optimization

In Central Composite Design (CCD), a rotatable (spherical) design is preferred since the prediction variance is the same for any two locations that are the same distance from the design center. However, there are other criteria to consider for an optimal design setup. Among these criteria, there are two that are commonly considered in setting up an optimal design using the design matrix. The degree of non-orthogonality of regression terms can inflate the variance of model coefficients. The position of sample points in the design can be influential based on their position with respect to others of the input variables in a subset of the entire set of observations.

After DOE, a response surface is generated for all the input and output values using the least squares methodology. The data points are fitted with a standard 2nd order model. The points generated on the response surface are then used to perform the optimization. The goodness of fit plots for all the subsystems are shown below in Fig 9.

"Goodness of Fit" of a linear regression model describes how well a model fits a given set of data, or how well it will predict a future set of observations. An X-Y Scatter plot illustrating the difference between the data points and the linear fit.
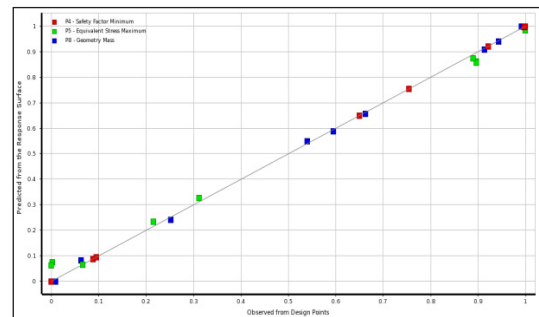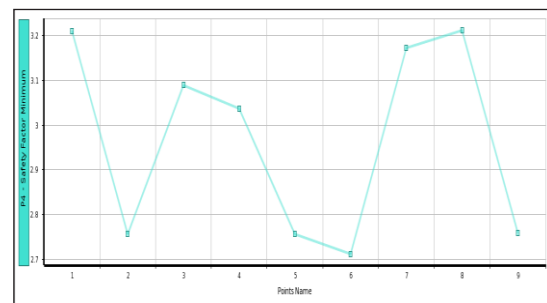

Figure 9.Goodness of fit curve

Figure 10.Safety factor at different design points

The above graph [Fig 10] shows the safety factor at different design points (x_1: hub width and x_2: hub radius). The safety factor is found to be maximum at design point number 8, for which hub width is 112.5mm and hub radius is 88mm. The safety factor is minimum for point number 6, for which hub width is 112.5mm and hub radius is 72mm.
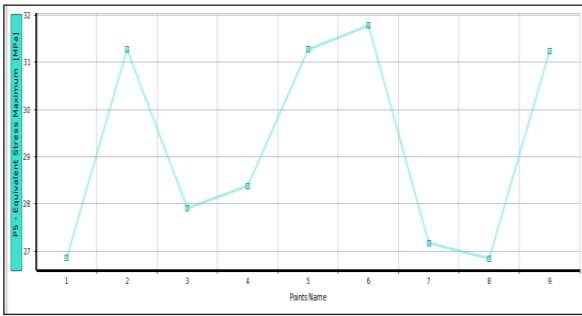
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Figure 11.Equivalent stress at different design points

The equivalent stress is found to be maximum at design point number 6, for which hub width is 112.5mm and hub radius is 72mm, and minimum at design point number 8, for which hub width is 112.5mm and hub radius is 88mm (Fig. 11).

The geometric mass of the wheel is found to be maximum (678.04 kg) at design point 7, for which hub width is 135 mm and hub radius is 72 mm. The geometric mass is minimum (673.27 kg) at design point 8, for which hub width is 112.5 mm and hub radius is 88 mm. Contour plots developed through RSM analyze the effect of an input variable with respect to one output variable, keeping all other variables fixed. The effects of tread depth and tread width on loco-motive wheels are analyzed with contour plots (Fig. 12).
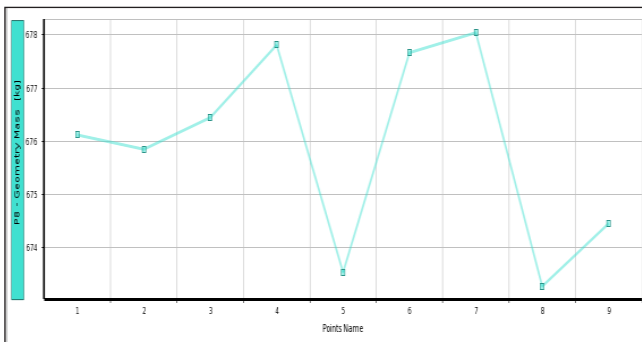

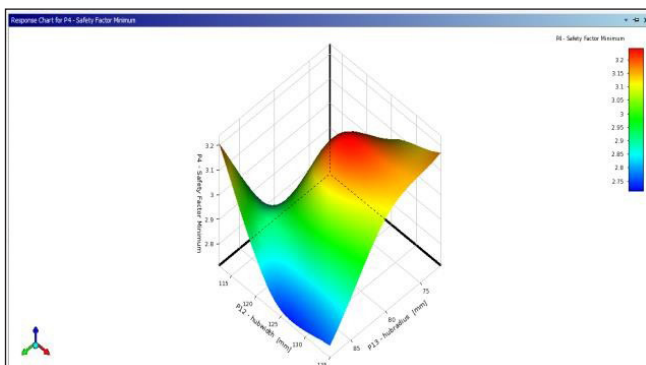**Figure 12.Geometric mass at different design points**

Figure 13.Response surface chart for safety factor output
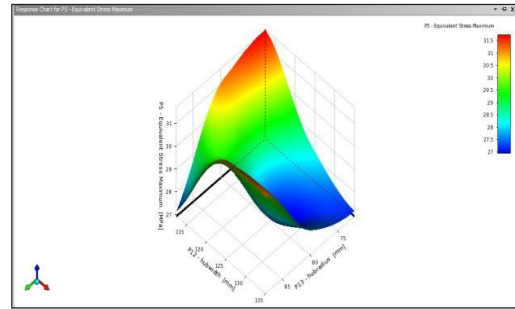

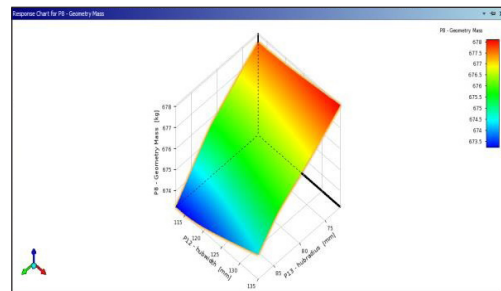**Figure 14.Response surface chart for equivalent stress output**

Figure 15.Response surface chart for mass optimization

Sensitivities charts are used to graphically view the global sensitivities of each output parameter with respect to the input parameter. The global, statistical sensitivities are based on a correlation analysis using generated sample points, which are located throughout the entire space of input parameters.
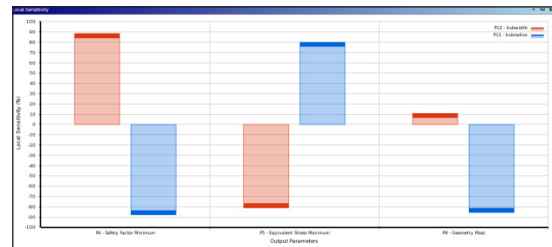

Figure 16.Local sensitivity graph for safety factor and equivalent stress

A local sensitivity graph [Fig 16] is plotted for all three output variables (i.e., safety factor, equivalent stress, and geometric mass). For safety factor, hub width has a slightly higher contribution as compared to hub radius. For equivalent stress, hub width has a higher contribution as compared to hub radius. For geometric mass, hub radius has a much higher contribution as compared to hub width.

Table 2: Results from response surface Maximum and minimum values of output variables (safety factor, equivalent stress, geometric mass) are generated and shown in table 2 above. The minimum geometric mass calculated from RSM is 673.22 kg, and the maximum geometric mass is 678.08 kg.

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Conclusion

Finite Element Analysis of locomotive wheels is performed using the ANSYS 18.1 software package. The design of locomotive wheels is optimized using response surface methodology, and input parameters for optimization are tread depth and tread width. The output parameters are equivalent stress, safety factor, and geometric mass. The minimized geometric mass is 673.22 kg.

References

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