Optimization of Rolling Resistance of Non-Pneumatic Tyre With Three Dimensional Spokes

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Abstract- *The effects of geometry parameters of a non-pneumatic tyre on overall performance of the NPT is investigated. Parametric study, design of experiments (DOE) and sensitivity analysis are conducted with finite element model to determine effects of design variables: i) the thickness of spokes ii) the shear band thickness on rolling resistance and vertical stiffness. Results from the DOE are used to create Surface Response Models (RSM)for both the objective function (minimal RR) and a constraint on vertical stiffness. Result indicate that both variables have significant effect on rolling resistance. The results are taken from the optimizationit shows that the Non-Pneumatic tyre has high shear band thickness with low rolling resistance while rolling.*

Keywords- Rolling resistance, Deflection, Non-Pneumatic tyre, Optimization, Design of experiment

I. INTRODUCTION

[1] The concept of a non-pneumatic tyre going back to the 1920s, has received much attention because of the potential advantages over pneumatic tires, especially including no catastrophic damage, such as flat tires and lower maintenance requirements. NPT consists of flexible spokes, shear band, tread, inner and outer rings. [2] The principle of the shear band is, the shear modulus of shear layer is very substantially, lower than the tensile modulus of two membranes while being sufficient to be able to correctly transmit the force from one membrane to other and to thus make said band work in shear mode. [3] The spokes and shear band constructed from polycarbonate with lower viscoelastic energy loss. The system experiences low rolling resistance. The use of hyperelastic material such as Polycarbonate is important because their properties positively impact the flexibility, energy loss, damping, and contact pressure distribution between the NPT and road. [4] The rolling resistance of the tire is the most important factor contributing to the vehicle flue consumption and it also raises the temperature of tyre. Use of polycarbonate having low viscoelastic energy loss than that of synthetic rubber, the energy loss of the NPT may reduce and this may result in the design of fuel-efficienttyre. The usage of material and their volume play an important role as they help in reduction of cost and rolling resistance without compromising the stiffness of the structure[5] Rolling resistance consumes only four to seven percent of the total energy originating by combustion. The statistics show that a ten-percentage increase in fuel economy. [8] The main component which contributes to the energy loss of the NPT is the shear band due to the shear loading at the contacting area. Hence the shear band acts as the key component in determining the energy efficiency of the NPT.

II. MATERIAL PROPERTIES OF NPT

The NPT includes of tread made of rubber, strong outside steel ring, an Inner ring made of Aluminium alloy 7075-T6 and spider web spokes made of polycarbonate. The two-circular arm connected the spider web spokes and it gives extra shear flexure to spokes. Property of material is used to decide their application. Material selection is one of the mainareas in research and engineering field. Here Rubber, Steel, AL 7075 T-6, Polycarbonate are selected tomaking a tyre.

A.Constraints and interaction

The rigid hub, the spokes, the inner ring, the shear band, the outer ring and the tread are assembled together with a bond constraint. The road is modeled in creo and is constrained in all degree of freedom. A node to surface contact interaction in ANSYS is assigned between the road and the outer edge of the road. The value of coefficient used for the friction is 0.15. The value is chosen typically to avoid slip during rolling simulation in ANSYS.

B. Rolling Resistance

During free rolling the force opposing the direction of rolling, neither breaking nor accelerating and not applying longitudinal force. That opposing force is known as rolling resistance force (F_R). It is defined as a resistive force due to the deformation of the loaded tire on the flat road. By energy dissipation, RR is defined as energy dissipated per distance rolled.

$F_R = W_d / D$

$W_d = \sum_{i=1}^{N} \tau\, W \tan\delta$

F_R – Rolling resistance W_d – Energy dissipated D – Distance Rolled by tyre

W – Sum of multiplication of elemental strain energy $\tan\delta$ – Dissipation Factor.

C. Load and Boundary Condition

The objective of the problem is to numerically measure the rolling resistance per unit distance F_R and the vertical stiffness of the NPT for different values of the geometric design variables. The NPT is subjected to a vertical load of magnitude 3000 N at the hub centre and rolled to a distance of 1 metre. The analysis of two steps namely load and roll step. In the first step, the static vertical load is applied and maintained in the second step. The second step is time-dependent in NPT. Two boundary conditions namely centre and ground. In first step Centre is set free in the y-direction and rests of all DOF's are constrained. In second step rotation DOF (around z-direction) and translational (y-direction) are set free and translational DOF (x-direction) is set to a value of 1 metre. The ground is constrained in all DOF for bothanalysis. The deflection is measured from output data and rolling resistance numerically calculated by strain energy.

D. Parametric Study

The parametric study is conducted to determine the effects of each geometric design variable, spoke thickness and shear band thickness on the rolling resistance response and vertical deflection defined by K = (3000 N) / δ.In the first parametric study, the shear band thickness is varied with a fixed spoke thickness of 3mm. Figure 1 variation of RR with respect to the change in shear band thickness. It is observed that the F_R of the NPT is reduced with the increase in shear band thickness. This implies that when more volume of material in the shear band is used, the NPT becomes more resistant to the shear effect and less energy is lost while rolling.

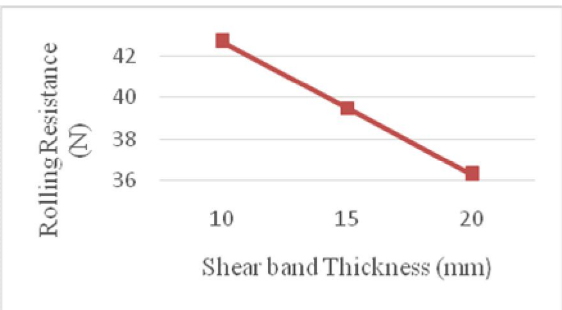

Figure 1 variation of RR with respect to the change in Shear band thickness

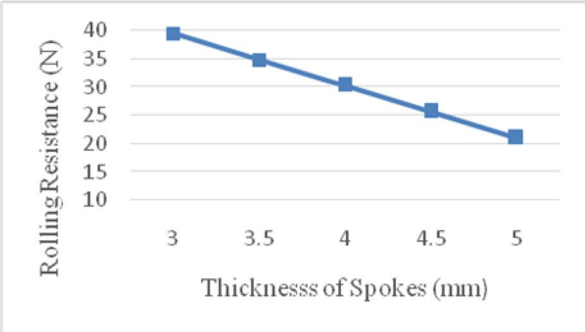

Figure 2 variation of RR with respect to the change in Spoke thickness

Figure 2 variation of RR with respect to the change in spoke thickness with fixed shear band thickness of 15mm. Similar effects can be observed in the spoke thickness variation.

III. OPTIMIZATION

The aim of the present work is to conduct a geometric size optimization of shear band thickness and spoke thickness of the NPT by minimizing the Rolling Resistance subject to a constraint on vertical stiffness as measured by the vertical deflection.

Objective Function: Minimize F_R

Constraint: 6 mm $< \delta <$ 9 mm

Design Variable Limits:

3 mm < x < 5 mm

10 mm < y < 20 mm

Where $F_R$is the Rolling Resistance, δ is the vertical deflection, x is the thickness of the spokes and y is the thickness of shear band.Before performing the optimization, a design of experiments (DOE) is conducted by running several numerical experiments over the design space defined by the limiting values of the design variables. A response surface model (RSM) is then generated as an approximate analytical function relating the design variables and the output response parameters. The RSM and Optimization is done using MINITAB a statistical tool and optimization tool.

A. Design of Experiments and Design

Sensitivity Study

Design of Experiments (DOE) is conducted to observe the response of RR and vertical deflection for combination of the design variables. The DOE technique used here is Response Surface method and Central Composite Design is performed for nine design points. The results (Rolling Resistance and vertical deflection) for corresponding design are shown in Table 3

Table 1 Data from the DOE

Thickness of Spokes (mm)	Thickness of Shear Band (mm)	Deflection (mm)	Rolling Resistance (N)
3	15	9.742	45.34
3.3	11.5	7.471	37.28
3.3	18.5	6.283	36.15
4	10	6.488	31.56
4	15	6.239	27.32
4	20	5.815	23.46
4.7	11.5	5.98	26.32
4.7	18.5	5.75	21.26
5	15	4.89	20.41

A sensitivity study is connected to study the influence of the design variables on the response parameters namely the Rolling Resistance. The effect of the design variables on the response parameters is studied using the Pareto chart of standardized effects. It determines the absolute value of the effects which is indicated by the red line on the chart. Effect of any parameter which extends past the line indicates that the parameters are potentially important. The line indicating the absolute value corresponding to alpha = 0.05 which means that the effects have been calculated at 95% confidence level.

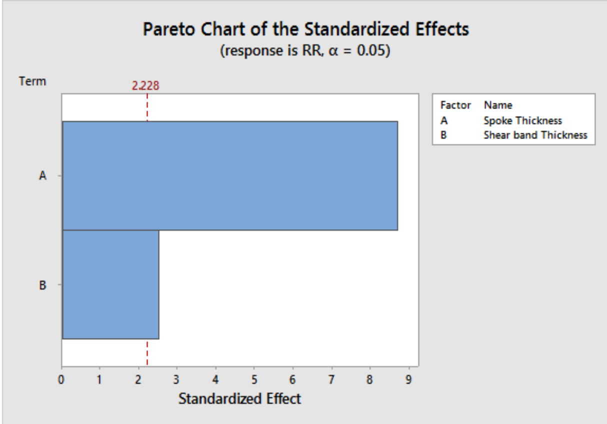

Figure 3 Pareto chart of standardized effects

The figure 3 shows that both the design variables play a significant role in affecting the response parameters (RR) with thickness of spoke having greater effect. Since both design parameters have significant influence on the RR response, the optimization is performed with both.

B. Response Surface Model (RSM)

The response surface model is developed based on a regression approach. The tabulated results from DOE are used to create response surface model for the RR and vertical deflection. The figure shows that the thickness of spokes and shear band are decreases the value of Rolling Resistance is increases.

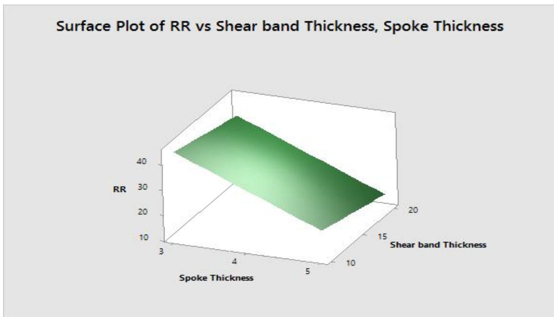

Figure 4 Surface Plot

C. Optimization Process

The RSM of both RR (objective function) and the deflection (Constraint) appears as a Uni-modal function with the design space. The optimization generated by Sequential Optimization. This is mostly used for solving the nonlinear constrained optimization problem. From the DOE and RSM, the optimized value is Spoke Thickness 3.5 mm and Shear Band Thickness is 20 mm.

IV. SURROGATE MODEL

[16] Generally engineering applications, the evaluation of a performance function iscomputationally expensive. Uncertainty analysis needs a number of such evaluations.One solution to this problem is to create a surrogate model to replace the originalexpensive performance function. The evaluation of a surrogate model is much cheaperthan that of the original performance function.The basic idea is to perform a number ofexperiments (numerically or physically) at different design points (or inputs), and thenthe performance function values and corresponding inputs are used to fit the simplifiedsurrogate model.

Here X1 is Spoke Thickness and X2 is Shear Band Thickness these input variables are known as Design variables and Y is Rolling Resistance is an output variable is called by Response Variable. Design variable boundary limits are

Table 2 Design Limits

Limits	-1.414	-1	0	1	1.414
Spoke Thickness	3	3.3	4	4.7	5
Shear Band Thickness	10	11.5	15	18.5	20

From the DOE number of the experiment is tableted.

Table 3 DOE experiments

X1	X2	X1 * X2	Yexp
0	0	0	27.32
-1.414	0	0	45.34
-1	1	-1	36.15
1	-1	-1	24.68
1.414	0	0	20.41
0	1.414	1.414	23.46
0	-1.414	-1.414	31.56
-1	-1	1	41.21
1	1	1	22.26

The generalized Equation for linear function Rolling Resistance Y is

$Y = \beta_0' + X1' \beta_1' + X2' \beta_2' + X1'{*}X2'{*} \beta_{12}'$
$X_i' = [\, 2(X_i - X_{imin}) / X_{imax} - X_{imin} \,] - 1$
X_i' – Continues Design Variable
$\beta_0' \beta_1' \beta_2' \beta_{12}'$ – Unknown coefficients

To find **β_0'** (**β_0'** - Average of the response)

$\sum_{i=1}^{9} Yexp$ = 1/9(27.32+45.34+36.15+24.68+20.41+23.36+31.56+41.21+22.26)

= 30.266

$\beta_1'\beta_2'\beta_{12}'$is calculated from the main effect. The main effect Ei is computed as the difference between the average value P_i^+ of the response at the Xi' high level (+1) and average value P_i^- of the response at the Xi' low level (-1) for **$X_i'\beta_1'$**is computed as follows.

The average response at X'1 high level (+1)

$P_{1-} = 1/3\ (Y_2^{exp} + Y_3^{exp} + Y_8^{exp})$
$= 1/3\ (45.34 + 36.15 + 41.21)$
$= 40.9$
$P_{1+} = 1/3\ (Y_4^{exp} + Y_5^{exp} + Y_9^{exp})$
$= 1/3\ (24.68+20.41+22.26)$
$= 22.45$
$E1 = P_{1+} - P_{1-} = 22.45 – 40.9 = -18.45$
$\beta_1' = E1 / 2 = -9.225$

Follow the same procedure for **β_2'**and **β_{12}'.** Finally, the equation becomes,

Y = 0.132 X1X2 – 11.205 X1 – 1.0378 X2 + 82.73

V. RESULT AND DISCUSSION

The multivariable, Single constrain optimization was performed and the result of the optimization is shown in Table. The results then validated in ANSYS and Surrogate model by setting the design variables to the optimized. The output from ANSYS and Surrogate model is shown in the tabulated column.

Table 4 Result of Optimization

Parameter	Optimum Values	Validation Using ANSYS	Validation Using Surrogate Model
Thickness of Spokes (mm)	3.5	3.5	3.5
Thickness of Shear band (mm)	20	20	20
Deflection (mm)	6.76	7.05	7.6
RR (N)	31.52	32.1	31.99

VI. CONCLUSION

A constrained design optimization was conducted to determine optimal values for spoke thickness, and shear band thickness to achieve minimum rolling resistance of the NPT with constrained on the vertical stiffness. The influence of the two design variables on the response parameters were also studied. Sensitivity analysis shows that the spoke thickness has a greater effect on the RR. Both the design variables play a significant role in affecting the response parameters. The optimized result shows a 30 % decrease in spoke thickness and 33.33 % increase on shear band thickness to a reference design used in previous study. The optimized result in a 29.2 % reduced in energy loss compared to the initial value with nearly the same value of stiffness.

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