DESIGN, ANALYSIS AND MATHEMATICAL MODELLING: EFFICYCLE

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Abstract- Efficycle is an energy efficient entirely human powered three-wheeled vehicle which is ergonomically and aerodynamically stable. Present study has been carried out with regard to the static analysis of a chassis with delta structure, under certain variable factors. For this, static analysis is conducted using Simulation software, for three impacts: Front, Rear and Side. Weight of the vehicle, number of nodes, material of the chassis has been studied in the present case, and a mathematical model has been formulated linking them to the displacement of chassis. The design of experiments is done using 2^3 full-factorial method. Significance of individual factors as well as their interactions is examined using Design Experts Software. Analysis of Variance (ANOVA) method is used to predict proficiency of the model.

Keywords– ANOVA, Design of Experiments, Efficycle, Static Analysis

I. INTRODUCTION

With the never-ending increase in population and need for transportation vehicles, rate of consumption of conventional fossil fuels poses a threat to the existence of life on earth. It is high time to develop alternate and greener modes of transportation for a sustainable future.

The Effi-cycle was designed to be an electrically assisted, dual-human powered tricycle, which is ergonomically and aerodynamically stable. Different topologies were analyzed and based on the factors such as turning radius, load carrying capacity, handling, spacious and ease of maneuvering; delta design was adopted with one wheel at the front and two at the back.

II. DESIGN CONSTRAINTS [1]

- The vehicle must have three wheels that should not be in a straight line.
- The vehicle must be within the dimensions of 100 inch x 55 inch (L x B).
- The vehicle must be capable of carrying two riders, of at least of 190.3 cm (6’3”) height and weighing 113.4 kg (250 lb.).
- There should be a clearance of minimum 3 inches between driver and any component of the vehicle, in static and dynamic conditions.

III. PROCESS FLOW CHART

The step wise process, that has been considered for this project has been documented as given in below flow chart.

Figure 1: Process flow chart

IV. DESIGN METHODOLOGIES

A. Chassis/Frame Design
The purpose of the chassis is to provide attachment points which will not yield within the car’s performance envelope. The frame configuration selected was Delta. Tubular space frame is chosen to be the baseline chassis type. Space frames are a series of tubes which are joined together to form a structure that connects all of the necessary components together [2]. The design of the chassis is shown in figure 2.

![Figure 2: Design of the Chassis](image)

B. Material used
A thorough research on a suitable material in terms of its mechanical properties, weld-ability and cost was done. Stainless steel AISI 1020 and carbon steel ASTM A36 was shortlisted compared and analysed. AISI 1020 is the most versatile and widely used stainless steel in the market. ASTM A36 can easily be bent and offers good tensile strength.

<table>
<thead>
<tr>
<th>Factors</th>
<th>AISI 1020</th>
<th>ASTM A36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>395 N/mm²</td>
<td>520 N/mm²</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>200 GPa</td>
<td>190 GPa</td>
</tr>
<tr>
<td>Density</td>
<td>7870 g/cc</td>
<td>7800 kg/m³</td>
</tr>
</tbody>
</table>

C. Static Analysis
A static analysis is used to calculate the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. Solidworks software was used for designing the chassis, keeping in mind some desirable factors:
- To make it ergonomically stable,
- Decrease the cost and weight of the vehicle,
- Increase rider safety
The stability of the chassis was then checked by using Simulation software. The static analysis was carried out, in which the deformation of the chassis was calculated, in three impact conditions- front impact, rear impact and side impact, which gives us the maximum stress and maximum displacement results. Software was so chosen due to its optimised speed and accuracy for simulations. Also, it eliminates the need for physical prototypes by providing with practical results. The simulations runs are as shown in below figures.

![Figure 3: Front Impact](image)

![Figure 4: Rear Impact](image)

![Figure 5: Side Impact](image)

V. MATHEMATICAL MODELING
To study the effect of process parameters and their interactions on the response, i.e. displacement, 2³ full factorial method is used for Design of Experiments (DOE) [4]. The main focus of this paper is to derive equations of impact, that link various variables to displacement.
On varying levels of tensile strength, weight of the vehicle will remain constant due to similar densities of the materials. The higher and lower settings of factors included in this experiment are tabulated in the Table II.
A series of simulations were carried out using Solidworks, for each combination of process parameters, tabulated in Table III.

<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Low Level (-1)</th>
<th>High Level (+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (A)</td>
<td>3750</td>
<td>4750</td>
</tr>
<tr>
<td>Nodes (B)</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Tensile strength (C)</td>
<td>395</td>
<td>520</td>
</tr>
</tbody>
</table>

Table III: Process Parameters

Analysis of variance using partial sum of squares type III is carried out on the 2^3 factorial model using Design Expert software. The results for all the three impacts are displayed in Table IV and Table V.

For side impact, the degree to which the designed chassis is stable is quite high. So, deformation produced due to process parameters is insignificant, therefore not considered in further studies.

Table VI & VII enlists the change that response data undergoes as factors changes from their low (-1) to higher (+1) level and their contribution in the same.

<table>
<thead>
<tr>
<th>Coded Factors</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>-1</td>
<td>+1</td>
</tr>
<tr>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table III: Response matrix

The relationship between the factors and the response is given below by the coded equation, which is useful for identifying the relative significance of factors. Final Equations in Terms of Coded Factors are as follows-

Displacement (Front Impact)\[= +24.80 \cdot 0.31 \cdot A + 2.92 \cdot B - 3.23 \cdot C + 0.043 \cdot AB - 0.039 \cdot AC - 0.38 \cdot BC\]

Displacement (Rear Impact)\[= +0.82 \cdot 9.812e-4 \cdot A + 0.007 \cdot B - 1.887e-3 \cdot C - 0.019 \cdot AB - 0.019 \cdot BC\]

Significance and Diagnostics of model: R2 tells us how this model fits the observation. It always increases when a new term is added, whether it is significant or not. PRESS (Predicted Residual error Sum of Squares) is a measure of how the model fits each point in the design. It is used to calculate pred. R-squared. The Adeq-Precision measures the signal to the noise ratio. A ratio greater than 4 is desirable.

The Pareto Chart (figure 6) displays the various factors affecting the displacement in order of their significance, for front Impact i.e. B, C, BC, A, AB, AC. From the chart we can conclude that the factor B is most significant while AB and AC do not affect much.
For rear impact, the Pareto Chart (figure 7) displays the order of significance, i.e. C, B, BC, A, AB, AC. From the chart we can conclude that the factor C is most significant while AB and AC do not affect much.

Contour is a two dimensional representation of the response across the factors displayed on the axis. When there are more than two actors, 2D graph displays a slice through factor shape. Contour graph for front impact is as shown in fig 8.

For Rear impact, contour graph is shown in fig 9.

VI. OPTIMIZATION

In Numerical Optimization, the goal is to minimize the displacement of chassis, while allowing the process parameters to assume any value in between their levels. The goal seeking begins at a random starting point and proceeds up to a maximum point. The optimized results obtained from the modelling are tabulated as follows.

Table VI: Optimization Results

<table>
<thead>
<tr>
<th>Impact</th>
<th>Weight</th>
<th>Nodes</th>
<th>Tensile Strength</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>3750</td>
<td>4</td>
<td>520</td>
<td>18.8033</td>
</tr>
<tr>
<td>Rear</td>
<td>3750</td>
<td>4</td>
<td>520</td>
<td>0.576</td>
</tr>
</tbody>
</table>

CONCLUSION

With the help of DOE, following conclusions were made to support the significance of the model.

For front impact,
- The Model F-value of 129987.43 implies the model is significant. There is only a 0.21% chance that an F-value this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C and BC are significant model terms.
The "Pred R-Squared" of 0.9999 is in reasonable agreement with the "Adj R-Squared" of 1.0000; i.e. the difference is less than 0.2.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 983.582 indicates an adequate signal. This model can be used to navigate the design space.

For Rear Impact,

- The Model F-value of 173297.01 implies the model is significant. There is only a 0.18% chance that an F-value this large could occur due to noise.
- Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, C and BC are significant model terms.

- The "Pred R-Squared" of 0.9999 is in reasonable agreement with the "Adj R-Squared" of 1.0000; i.e. the difference is less than 0.2.
- "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 1088.991 indicates an adequate signal. This model can be used to navigate the design space.

REFERENCES

[3] Product Data Sheet 304/304L Stainless steel, AK Steel