Design and analysis of an impact energy absorbing steering system

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Abstract: In a country that continues to hold the record for high road deaths every year, it is important to have reliable safety system in vehicles which is an absolutely crucial pre-requisite for driver safety. The latest tests, conducted by Global NCAP (New Car Assessment Program), showed that in an accident, most budget cars would leave the driver with possible life-threatening injuries. For such cars with insufficient or unreliable safety devices, this paper deals with the design of an impact absorbing steering column, used to achieve controlled deceleration of a restrained/unrestrained occupant to reduce the impact forces and thus reducing the chances of fatal injuries.

Keywords: impact absorbing systems; steering systems; driver safety.


1 Introduction

India has a large population in the middle class bandwidth. In the cars bought by an average middle class family, the safety systems in such cars fall short in the NCAP (New Car Assessment Program for India) tests.

In most cases, frontal collisions are a major cause of fatality. The steering wheel and rigid steering column components are the major reasons for fatal injuries to the driver (Hen, 1998; Mohamed and Yusuff, 2007). Figure 1 shows the safety protection for the front passenger and the driver.

The forward push during a frontal crash is the source for rib-damage and several front end injuries (NHTSA, 2010).

Literature review provides the information on existing safety systems, their advantages and shortcomings. This helped in fixing the parameters for which the mechanism had to be designed (NHTSA, 2009; Shaikh et al., 2015).
Following are the safety systems already present in automobiles:

1. **3-point seat belt**: A seat belt functions to reduce the likelihood of death or serious injury in a traffic collision by reducing the force of secondary impacts with interior strike hazards, by keeping occupants positioned correctly for maximum effectiveness of the airbag (if equipped) and by preventing occupants being ejected from the vehicle in a crash or if the vehicle rolls over (Engineering ToolBox, 2011; Du Bois et al., 2004).

   **Limitations:**
   - A 3-point seat belt has inability to avoid fatal injuries at high velocities.
   - Cases of burns and injuries are seen due to the friction between the occupant body and seat belt.

2. **Airbags**: The airbag module is designed to inflate rapidly then quickly deflate during a collision or impact with another object or a sudden deceleration.

   **Limitations:**
   - Airbags are designed to deploy once only, and are ineffective if there are any further collisions after an initial impact. Multiple impacts may occur during certain rollover accidents or other incidents involving multiple collisions, such as many multi-vehicle collisions.
   - In an under-ride collision, the car’s crush zones designed to absorb collision energy are completely bypassed, and the airbags may not deploy in time because the car does not decelerate appreciably until the windshield and roof pillars have already impacted the trailer bed.
   - Even delayed inflation of airbags may not be of any use because of major intrusion into the passenger space, leaving occupants at high risk of major head trauma or decapitation in even low speed collisions.
   - Typical airbag systems are completely disabled by turning off the ignition key.
   - Cost of the system is high.

After having identified the gaps in existing car safety technology, this paper highlights the lack of reliable safety systems in budget cars and taking that up as a cause, and discusses the design, analysis and possible reduction in fatal forces.
2 Field of research

2.1 Construction and working

The steering system designed is an impact absorbing type. The apparatus consists of two interference fit shafts coupled for telescopic movement under impact axially applied thereto, the upper shaft being solid and is called the steering rod and the lower shaft being hollow and is called the steering column/tube. In addition to these it also consist of splines provided along the outer periphery of the steering rod and the inner periphery of the steering column. It is shown as Figure 2.

Figure 2 Actual modelled mechanism

Two bracket members are provided, one on each shaft so as to hold the two torsional springs which are designed to absorb the impact energy by controlled deflection of the spring when an impact load is exerted against the steering rod.

Once the collapsible action starts, further impact energy absorption means are provided inside the steering column by placing a fixed quantity of absorbing material for controlled deceleration and substantial reduction of forces on the driver via impact and shock absorption properties of the material used.

The total force absorbed by this mechanism is due to the stiffness and deformation of the spring, frictional resistance during telescopic movement of the two shafts and the energy absorbed due to the energy absorption material.

$$ F_{\text{total}} = (F_{\text{spring}}) + (F_{\text{friction}}) + (F_{\text{absorption material}}) $$

The resistance of spring, together with a frictional resistance between the shafts and the energy absorbed by the material used, absorbs a substantial amount of the impact force which, in the absence thereof, would be transmitted undiminished to the driver resulting in fatal injuries.

Model was prepared to study the effect of the proposed idea. The same is discussed.

- Material selected for shafts: Mild Steel C45 (Commercially cold rolled).
- Young’s modulus, E=210 MPa
- Torsional yield stress = 100 MPa
- Factor of safety = 3.5
Material selected for springs: Due to its high tensile strength and its ability withstand higher stresses under repeated loading than any other spring material – Music Wire ASTM A228

Absorption material: Duocel aluminium foam

2.2 Design of mechanism

Using Newtonian physics, forces on the occupant during impact were calculated for various speeds from 40 kmph to 100 kmph and upper torso weights of the unrestrained occupant varying from 40 kg to 70 kg (Global NCAP, 2016).

All the parts of the system were designed theoretically, and permissible range of stresses in the mechanism was also calculated.

2.3 Modelling and analysis

The theoretically designed parts of mechanism were individually modelled on Catia V5R20 and various constraints were given to the parts during assembly.

The assembled part was imported on the static analysis module on Ansys Workbench. The materials that were selected during the designing phase were to be added to the engineering library for future access. Once the geometry has been imported, Ansys structural software tools automatically detect and perform setup for contacts or joints between parts of an assembly.

The auto detection of contacts led to inaccurate results as the maximum contact stiffness was too large, compression of spring wasn’t observed and hence to avoid this issue all auto generated contacts were deleted and contacts were established manually.

3 Contact analysis

Manual bonded contact was established between the ends of the spring and faces of the mounting brackets so as to couple or bond them together.

- It was done by specifying the target bodies and target surface.
- This allowed compression of the torsional springs as there was proper bonded contact between the two springs and brackets.
- Frictionless support environment is used in analysis setting for the internal splines and the internal periphery of the steering column.
- This boundary condition is used to prevent any flat or curved faces from moving or deforming in the normal direction. The normal direction is relative to the selected geometry face. No portion of the surface body can move, rotate, or deform normal to the face.
- The problem of maximum contact stiffness being too large was solved by this method.
Meshing involves division of the entire model into small pieces called elements. Meshing was done locally on different volumes due to varying sizes. This is called hybrid grid meshing due to use of varying element size and shapes.

4 Analysis settings

- Load that was calculated was applied directly to the front end of the upper shaft for linear actuation, i.e., collapsibility of the steering system.
- A vector of a load was applied to selected geometry, and this was done to resemble force imparted by the occupant on the steering.
- Fixed support boundary condition prevents flat or curved faces from moving or deforming, vertices from moving.
- It was used on the lower brackets and the end of steering column to prevent any motion and restrict them in all DOF.

Directional deformation and Von-Mises stresses were obtained. It was found that the maximum stress and deflections were in the permissible range. The designed mechanism was safe for all load ranges calculated.

The results were calculated at all speeds and weights. The results shown here are for two speeds of 56 kmph and 64 kmph, which are the standard speed values for crash tests conducted recently by Global NCAP.

1. The velocities and maximum displacements are used to calculate value of acceleration.
   - Final velocity, \( v = 0 \).
   - Initial velocity, \( u = \) speed of the vehicle.
   - Maximum displacement for calculating deceleration, \( = 1.5 \text{ feet} = 0.4572 \text{ m} \) (it is the maximum stretch distance of the seat belt).
   - We know that, \( v^2 - u^2 = 2as \)
   - Decelerations are calculated, using values of \( v, u \) and \( s \).

2. Forces are calculated for these acceleration values at different masses ranging from 40 kg to 70 kg.
   - We know that, \( F = ma \)

3. The average value of the distance between the occupant and the steering wheel is 15” that is 0.381 m.
   - Impact energy is determined using the force and the distance.
   \[ E_{\text{impact}} = W = Fd \]
It is the impact energy that is applied on the steering wheel by the occupant when the occupant collides with the steering wheel.

The part of this energy has to be absorbed by the mechanism in order to reduce the impact and save the occupant.

4 The impact energy is absorbed by the displacement of the spring.

The spring stiffness can be calculated from the dimensions of the spring.

\[ k = \frac{E d^4}{64 D r^3} \text{ N} \]

\[ k = 69.2138 \text{ N/m} \]

The force created due to the deceleration causes the deflection \( X \) in the spring.

\[ X = \frac{F}{k} \]

These two values can be used to generate the results for Impact energy absorbed by the spring.

\[ E^i = \frac{1}{2} k X^2 \]

5 The energy absorbing material absorbs some more part of the energy.

The impact energy absorbed can be calculated by calculating the area below the stress strain curve of the absorbing material.

By trapezoidal rule, the formula for area, impact energy absorbed is calculated,

\[ E'_{\text{impact}} = 6,462,758 \text{ J/mm}^3 \]

The volume of the absorption material used in the mechanism,

\[ V = \frac{\pi}{4} d^2 h \]

Here, \( d = 30 \text{ mm} \)

\[ h = 177.8 \text{ mm} \]

Hence the total energy absorbed by this volume,

\[ E^i = E'_{\text{impact}} \cdot V \]

\[ E^i = 812.2356 \text{ J} \]

6 The total energy left out after the absorption,

\[ E = E'_{\text{impact}} - E^i - E^2 \]
The force is then calculated in terms of \( G \).

\[
    \text{Force}(G) = \frac{E}{9.81 \times m \times s}
\]

where, \( E \) is energy left after the absorption
\( m \) is mass
\( s \) is distance for deceleration; 0.5334 m or 21”.

The table below shows the force on the occupant

<table>
<thead>
<tr>
<th>Mass of occupants</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 kmph With Mechanism</td>
<td>15.38</td>
<td>15.81</td>
<td>16.15</td>
<td>16.44</td>
<td>16.67</td>
<td>16.87</td>
<td>17.04</td>
</tr>
<tr>
<td>%Reduction in Force</td>
<td>43</td>
<td>41</td>
<td>40</td>
<td>39</td>
<td>38</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>64 kmph With Mechanism</td>
<td>21.27</td>
<td>21.7</td>
<td>22.05</td>
<td>22.33</td>
<td>22.56</td>
<td>22.76</td>
<td>22.93</td>
</tr>
<tr>
<td>64 kmph Without Mechanism</td>
<td>35.23</td>
<td>35.23</td>
<td>35.23</td>
<td>35.23</td>
<td>35.23</td>
<td>35.23</td>
<td>35.23</td>
</tr>
<tr>
<td>%Reduction in Force</td>
<td>40</td>
<td>38</td>
<td>37</td>
<td>37</td>
<td>36</td>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

It can be seen that all the forces obtained after energy absorption are less than 60G. This clearly signifies the prevention of fatality.

The percentage reduction in force is plotted for test velocities.

Figure 6 presents the percentage reduction in impact energy is also calculated.

Figure 3 Variation of force at 56 kmph
Figure 4  Variation of force at 64 kmph

Figure 5  Percentage reduction in impact force variation for 56 kmph and 64 kmph

Figure 6  Percentage impact energy absorbed variation at 56 kmph and 64 kmph
5 Conclusion

1. The design is capable of complete torque transmission and zero power loss.
2. The system is easy to manufacture because fewer parts are involved.
3. The system is ergonomically feasible. It is light, compact and needs no extra provisions.
   a. The dimensions are so designed that there is no need of changing the available interiors design of the vehicle.
4. The system is a completely mechanical linkage built system. Hence it doesn’t affect the basic automobile engine performance. It doesn’t require any external power supply to actuate.
5. The system is more cost effective than other available systems like airbag.
6. The system reinstalling cost is zero. The system can be used several times. The unlocking of ratchet-pawl mechanism enables the system to come back to its original position and ready to work condition.
7. The mechanism takes care of various limitations of other available systems. It is designed for working under all impact conditions generated up to a speed of 100 kmph and mass of 70 kg in the available space according to automobile ergonomics.
8. The mechanism absorbs the kinetic and impact energy and reduces the chances of fatality efficiently up to speeds of 100 kmph and 70 kg of occupant masses.
9. Speeds more than 100 kmph can cause fatal conditions with this mechanism. The constraint of working for this mechanism is the space available for deformation. If an extra space is provided by automotive manufacturers for redesigning of steering column, the fatality at higher speeds also can be prevented with small modifications in the existing design.
10. The system serves the purpose of providing the safety to the driver in budget cars by incorporation of the proposed economic and efficient impact energy absorbing steering system.

References


