Research on the Influence Factors of Automotive Door Closing
Energy and Performance Improvement

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Abstract. In order to decrease the minimum of door closing effort for a SUV, influence factors are comprehensively analyzed, which involve door cabin-pressure, seal stiffness, compression load, door weight, door latch force, door hinge and door opening limiter friction effect, etc. Applying influence factor separation method, door closing energy is tested to analysis the main influencing factors. Then, according to the main factors, rod contour line of the door opening limiter and slider spring stiffness are designed and optimized by CAE, improve programme is proposed and carried out. Test results show that door opening limiter is the main influence factor on door closing energy and velocity, and the improve programme has good effect for decreasing the minimum of door closing effort. It shows that the minimum of door closing energy decreases from 6.96J to 2.83J and the minimum of door closing velocity decreases from 1.05m/s to 0.7m/s, which indicate the significant improvement for door closing comfort.

Introduction

The minimum of door closing energy and velocity are important indexes for vehicle quality. Generally speaking, good feels of door opening and closing are inclined to light, smooth and clear sense of gear position. Contrarily, if a large and blocked effort is needed to close the door, the vehicle appears of poor quality, which is directly linked to a strong displeased door closing sound as door closing velocity increases. Therefore, automobile manufactories have paid more and more concern to improve the door closing quality without sacrificing the vehicle air tightness and acoustic insulation requirements.[1]

In order to develop the method for improving door closing effort, this paper includes the detail study of various design parameters which are responsible for door closing effort. Combined with door closing energy and velocity test equipments, individual parameters contribution is measured in the form of energy consumption. Based on this case study, CAE optimization is carried out by adjusting main parameters. Improve programme is proposed and verified by vehicle tests to improve customer experience in door closing effort.

Minimum Door Closing Energy Influence Factors

The minimum of the door closing energy is the result of the interaction of the different parts of the car door and body system, such as whole vehicle tightness, door cabin-pressure, door opening limiter, hinge axis, moment of inertia, lock, seal and so on [2]. However, the door closing quality should be balanced with vehicle air tightness and the acoustic insulation.

The minimum of the door closing energy is defined as the minimum energy required for the door to close from a certain degree and stationary state to the door completely closed under the external force. So the motion of the door satisfies the conservation of energy, as follows

\[ E_{\text{closing}} + E_{\text{air}} + E_{\text{seals}} + E_{\text{latch}} + E_{\text{doorcheck}} + E_{\text{potential}} + E_{\text{hinges}} + E_{\text{bodydeformation}} + E_{\text{doordeformation}} = 0 \] (1)
Considering the vehicle body and door are high stress and deformation resistance system, they're supposed to be rigid and don't deform during the closing. Thus, the above equation could be simplified as

\[
E_{\text{closing}} + E_{\text{air}} + E_{\text{seals}} + E_{\text{latch}} + E_{\text{doorcheck}} + E_{\text{potential}} + E_{\text{hinges}} = 0
\]

(2)

**Door Cabin-Pressure**

The energy sink due to the cabin air pressure is a substantial contributor to the overall door closing effort. During up glass position, air is pushed inside the cabin during door closing, is also known as air bind phenomena. Majority of the air escapes through door gaps and vent holes in the vehicle cabin. As the door gap area approaches zero during seal compression, air is compressed rapidly inside the cabin. Pressure spikes during air compression and eventually drops as air escapes out of the vents. More vent area or mid/down glass condition will have negligible air bind effect. [3]

Air starts compressing inside the cabin when the door gap area starts decreasing (shaded region) in figure 1. Door gap area and cabin vent area aid outflow of air. Pressure rises due to compression of air and pressure drops due to leakage of air. This creates a net positive pressure gradient across door surface. Work done can be calculated as a function of pressure, door area and angular displacement.

Typical C-segment car with partially opened up glass door at ajar position is shown in figure 1.

![Figure 1. Representation of vehicle cabin door opened at ajar position.](image1.png)

**Door Latch**

Door latch helps to secure the door in locked position. Latch consists of an assembly of pawl, ratchet, latch bumper and torsional springs. Latch locking takes place in two latching positions which are primary (full latch) latching and secondary (partial latch) latching. Striker is mounted on body pillar and Latch assembly is mounted inside the door. Figure 2 shows door latch and striker assembly details.

![Figure 2. Schematic of a latching system.](image2.png)

Latch is a major energy sink parameter for door slam durability. Detailed latch mechanism in CAE is necessary for simulation of the door dynamics. Latch assembly consists of latch housing, pawl,
ratchet, torsion spring for pawl and catch (ratchet), latch and catch bumpers. Latch and striker assembly is shown in figure 2 in door ajar position; only parts related to latch kinematics are shown.

When the door is dynamically closed from ajar (partially open) position, catch interacts with striker and it rotates around striker until it gets locked by the pawl. Pawl holds the catch in two stages, for initial travel of door, pawl partially holds the catch, which is known as secondary latching (partial latching). Further travel of door enables pawl to hold the catch completely in full latching condition, which is also known as primary latching or known as the door in design position. The corresponding door velocity to reach primary latch condition is known as minimum door closing velocity.

**Seal Stiffness**

Seal stiffness is one of the important entities for design of door. Seal aids in absorbing part of kinetic energy during door closing phenomena. It also provides a soft engagement for the door. In abusive door closing conditions, seal stiffness plays very important role to avoid contact between door and body panel (to avoid paint chipping). Typical door and body seal for swing door is shown in Figure 3 [4].

Seal compression behavior is approximated to a linear spring system. Average compression of each seal segment is calculated in design position of the door. The compression energy is calculated on the basis of seal design compression, seal length and seal force per 100mm seal strip. Spring compression energy is calculated as sum of individual seal segment energy contributions. Graphical representation of the seal spring model is shown in figure 4.

![Figure 3. Schematic of the door-seal-body system.](image)

![Figure 4. Baseline primary seal CLD curve.](image)

**Seal Air Cavity**

Seal air cavity is another energy sink parameter, this need to be accounted in the door closing energy calculation. Seal has a hollow seal air cavity along the seal strip length. Seal orifices are located along the circumference of seal. Air inside the seal cavity escapes gradually through the seal orifices during door closing phenomena when door makes contact with the seal. This phenomenon gives a non-linear damping effect.

For the seal orifice model, the rate of compression of seal in lateral direction is assumed constant with the average velocity. Seal bulb is modelled as a rectangular strip with equivalent cross-sectional area and an orifice pitch length ‘p’. Steady, linear and vortex free flow conditions are assumed inside the cavity. Pictorial view of seal air cavity is shown in figure 5.

![Figure 5. Seal air cavity.](image)
Door Weight

Door rotation about a tilted axis produces the torque and this aid to close the door. Position of COG monitored before and after door closure. COG position rises or drops depending on hinge positions. COG shift is close to zero in rear doors, owing to nearly vertical placement of the hinges.[5]

When the door hinge axis is not vertical, the door weight, \(-mgk\), will generate a torque, \(T\) weight = \(T\) weight (\(\theta\)), around the hinge axis, which may help to close the door (see Figure 6).

![Figure 6. Schematic of door weight effort model.](image)

Energy sink can be calculated by measuring door weight and rise or fall of COG from initial position.

\[
E_i = m_{\text{door}} g (h_f - h_i)
\]

\(h_f\) -final position of door CG

\(h_i\) -initial position of door CG

Hinge Friction

Total door weight is borne by the door upper and lower hinges with each carrying half of the total door weight. Frictional torque is created at the door hinge pin, its magnitude depends on location of COG, distance between hinges, hinge radius, coefficient of friction at hinge interface and mass of door assembly. Refer figure 7 for door hinge friction schematic.[5]

The door weight is assumed to be carried equally by the upper and lower hinges with each hinge carrying half of the door weight. Because the door mass center is at a distance \(r_{cm}\) from the hinge axis, there is a moment due to reactions \(r_{cm} \cdot h \cdot mg\) at the two hinge pins which balances the door moment \(mg \cdot r_{cm}\). If the hinge pin has a radius \(r_h\), and the hinge friction coefficient is \(\mu_h\), the torque from the two hinge pin sides is

\[
T_{\text{hinge}} = 2\left(\frac{r_{cm}}{h} + 1\right)\mu_h mgr_h
\]

The energy sink from hinge friction is

\[
\Delta E_{\text{hinge}} = T_{\text{hinge}} \Delta \theta
\]

\[E_{\text{hinge}} = E_{\text{hinge}0} + \Delta E_{\text{hinge}}\]
Door Checkstrap

Door checkstrap is also called as checklink. Door checkstrap is an important design entity for automotive door design. It assists the door opening and closing with the help of check arm profile (roller path), rollers and springs.

One end of the link connects to the door and the other connects to the body, the position of check link mounting is typically between the hinges of the door. Checklink doesn’t carry any door weight. It is an assembly of rollers fitted with sleeve and springs, travelling on check arm profile. Check arm profile provides intermediate stops for the door when opened or closed slowly. Design detail of checkstrap model is shown in figure 8.

Door checkstrap consumes and releases energy as the rollers travel up and down the check arm slope.

Check link torque data is available through physical test data. Check link contribution can be calculated as a function of door open angle. Figure 9 shows checkstrap opening and closing effort for a corresponding door opening angle[5].

From T - Ø data, energy contribution can be calculated as area under the graph for partial opening position to latched position.

\[ E_i = \sum_{i=0}^{n} T_i \Phi_i \]  \hspace{1cm} (6)

Where Ø varies from initial door open angle to zero (Design Position).

Problem Validation

There are two methods for detecting door closing effort, one is keeping the door closing energy consistency and detecting the velocity, another is keeping the door closing velocity consistency and detecting the energy. Here we select the second method. The tested vehicle is completely stationary without load and windows closed. Keeping the door in full open state and the maximum opening angle is 75°, then it is closed at 1.2m/s by special speedometer, and the varies closing velocity with time will be collected by a speedometer.

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Due to the door weight, hinges and lock can't be verified by manual methods, so this experiment does not take into account. The improvement of other performance and parts is as follows

1. Seal: A circle o-type rubber strip is added though the inside of the door seal to increase the stiffness. Moreover, increasing the number of open hole and enlarge the area to double of original.

2. Airflow resistance in cabin: The first method is plugging pressure relief valve to prevent the air inside the vehicle exhausting at the moment of closing the door. The second method is falling window 1/3 height to help the air inside the vehicle exhausting.

3. Door opening limiter: Disconnect the door opening limiter with the door and the body.

Table 1. The door closing velocity at 1.2m/s.

<table>
<thead>
<tr>
<th>Verified items</th>
<th>Door closing energy J</th>
<th>Falling energy difference J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original state</td>
<td>6.96</td>
<td>/</td>
</tr>
<tr>
<td>Increasing seal stiffness</td>
<td>6.51</td>
<td>0.45</td>
</tr>
<tr>
<td>Enlarging the area of the seal open hole</td>
<td>8.13</td>
<td>-1.17</td>
</tr>
<tr>
<td>Plugging pressure relief valve for vehicle body</td>
<td>8.3</td>
<td>-1.34</td>
</tr>
<tr>
<td>Falling window 1/3 height</td>
<td>4.86</td>
<td>2.10</td>
</tr>
<tr>
<td>Disconnecting door opening limiter</td>
<td>2.13</td>
<td>4.83</td>
</tr>
</tbody>
</table>

As shown in Figure 11 and Table 1, when the door closes at the same speed, door opening limiter has the greatest influence on closing energy, the second is airflow resistance, and the seal stiffness and open hole have the least influence. The energy will fall down from 6.96J to 2.13J with the door opening limiter disconnected. And in terms of subjective evaluation, the closing effort also decreased significantly. Thus, the door opening limiter is the key optimization object in next section.

**CAE Optimization**

The type of the selected vehicle's door opening limiter is spring, so the main arm profile and stiffness are the main parameters for door closing effort.

On the premise that the gear position is clear and open and close operation smoothly, main arm profile of the door opening limiter is optimized. First, the depth of fiber groove is increased from 0 to 0.5mm. Then, the inflection point position is smoothed, as shown in Figure 12.
The other optimization is reducing spring stiffness. Ensuring the initial spring length is 26.4mm, different spring stiffness, such as 49.7N/mm, 45.28N/mm, 40.85N/mm, 36.425N/mm and 32N/mm are selected to get better results. Spring unit of the limiter is simulated by a sliding pair and load is added though matching stiffness and length.

Table 2. Optimization data of door opening limiter.

<table>
<thead>
<tr>
<th>Spring stiffness N/mm</th>
<th>original</th>
<th>reduce range mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>49.7</td>
<td>46.9</td>
<td>30.2</td>
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<tr>
<td>45.20</td>
<td>42.5</td>
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<td>38.5</td>
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<tr>
<td>36.42</td>
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<td>34</td>
</tr>
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<td>32.00</td>
<td>16.4</td>
<td>29.5</td>
</tr>
</tbody>
</table>

Figure 13. Bar chart showing simulation torque of checkstrap before and after improvement.

As shown in Table 2 and Figure 13, according to CAE analysis, it could be concluded that profile and spring stiffness of the door opening limiter have significant influence on door closing effort. So the optimization programme is carried out by designing the profile and spring stiffness. Here specific programme of deepening the fiber groove 0.3mm and changing the spring stiffness 40.85N/mm are executed.

**Effect Validation**

**Effect of Door Opening Limiter Improvement**

According to the proposed optimization programme, actual sample is manufactured showed in Figure 14.
Torque tests of the door opening limiter are carried out applying professional test rig. The test results in Figure 15 show that the torque of the improved limiter is obviously reduced.

**Figure 15. Door checkstrap characteristic curve before and after improvement.**

**Effect Validation for Door Closing Effort**

The improved vehicle door closing efforts are tested by two methods. One is keeping the door closing velocity 1.2m/s, the minimum of closing energy is detected, results show obvious decrease of the door closing energy from 6.96J to 2.83J. Another is imposing minimum force on the premise that the door lock is completely locked, the minimum of closing velocity is detected, results also show obvious decrease of the door closing velocity from 1.05m/s to 0.7m/s.

The tests results both prove that the improve programme based on profile and spring stiffness of the door opening limiter has good effect on door closing quality. Here we also confirm the effect by subjective evaluation, the increased value from initial 4 point to finally 7 point also definitely indicates the significant improvement for door closing comfort.

**Conclusion**

(1) According to the analysis of design parameters influence on door closing energy, main factors are obtained by separation method, and optimized object is confirmed. It is clearly concluded that door opening limiter has the greatest influence on closing energy, which introduces new insight into the door closing effort analysis.

(2)Based on CAE simulation, a improve programme involves deepening the fiber groove and changing the spring stiffness is proposed. Though door closing tests with the programme, the results show that it has good effect on decreasing door closing effort and improving door closing comfort.

(3) Review the whole work process, objective test combined with subjective validation is proved to be an efficient method for door closing effort evaluation, so it could provide a reference for the development of vehicle NVH.
References


