Study of crash energy absorption characteristics of inversion tube on passenger vehicle

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Abstract. This article studied the energy absorption characteristics of the inversion tube and acquired the inversion tube design key dimensions under theoretical conditions by performing formula derivation in the quasi-static and dynamic state based on the working principle of the inversion tube: free inversion. The article further adopted HyperMesh and LS-Dyna to perform simulation and compared the simulation result with the theoretical calculating value for comparison. The design was applied in the full-vehicle model to perform 50km/h front full-width crash simulation. The findings showed that the deformation mode of the inversion tube in the full-vehicle crash was consistent with the design mode, and the inversion tube absorbed 33.0% of total energy, thereby conforming to the vehicle safety design requirements.

1. Introduction
The energy absorber with the inversion tube as the energy absorption component, which is designed by using the plastic deformation principle, has wide applications in automobile crash buffering, helicopter crashed seats, aircraft soft landing and other personal protection aspects, also attracting an extensive attention in actual engineering of ocean platforms, highway barriers and nuclear power stations. The reason why the inversion tube attracts an extensive attention lies in its stable bearing capacity and energy absorption characteristics [1]. Under axial crushing, the round metal tube will have free inversion outwards or inwards. Numerous experimental studies at home and abroad showed that the axial force of the inversion tube is stable in the inversion process [2-4]. In automobile safety design, especially in front crash design, the acceleration borne by the passengers should be hopefully constant. Such demand characteristics fit the deformation energy absorption characteristics of the inversion tube well.

2. Working principle of inversion tube
See the following figure for the free inversion process of the inversion tube. P is the axial tension in Figure 1. Energy absorption working principle of the inversion tube: when the graphic inversion tube has inward-inversion deformation under axial tension, the initial radius of curvature of the section $AB$ is $r$, and the radius of curvature of the section $AO$ is infinite before deformation. After deformation, the radius of curvature of $A'B'$ is increased to be infinite, and the radius of curvature of $A'O'$ is reduced to be the radius $r$. At the moment, the deformation force of the inversion tube is constant. The key dimensions of the inversion tube are shown as Table 1.
3. Study of starting load of inversion tube

3.1. Study of starting load under quasi-static impact condition

According to references, the starting load $P_e$ formula under the quasi-static condition of the inversion tube is $^{[6]}$:

$$P_e = \frac{\pi D R e t}{\sqrt{3}} \left[ \ln \frac{D}{d} + \ln \left( 1 + \frac{t}{2r} \right) \right]$$  \hspace{1cm} (1)

Wherein, $D$ is the outer diameter of the inversion tube, $d$ is the inner diameter, $t$ is the thickness, $r$ is the radius of curvature, and $R_{el}$ is the yield strength of the low carbon steel material. Based on the design space and dimensions, $D = 80\text{ mm}$, $d = 60\text{ mm}$, $r = 5\text{ mm}$, because the thickness of the inversion tube has the maximum effect on the starting load, $t$ is selected as the theoretical study value.

3.2. Study of starting load under dynamic impact condition

The article studies the application of the inversion tube under the vehicle crash condition, so the static load impact formula needs to change. According to the theory in the references, the effect of material strain rate characteristics on load should be considered. Cowper-Symonds formula $^{[7-9]}$ is often used to deduce the structure crash problems

$$\frac{\sigma_d}{\sigma_0} = 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{q}}$$  \hspace{1cm} (2)

In the formula (2), $\sigma_0$ is the yield strength of the material, $\sigma_d$ is the strength under dynamic impact, $\dot{\varepsilon}$ is the strain rate, and $C$ and $q$ are material constants, respectively 40 and 5. For the free inversion process of the inversion tube, the free inversion process of the low carbon steel inversion tube in the reference $^{[10]}$ is equivalent to the circumferential stretching process, and the material strain rate formula is:

$$\dot{\varepsilon} = V \ln \left( 1 + \frac{2b}{r} \right) / 2\pi b$$  \hspace{1cm} (3)

Wherein, $V$ is the impact velocity, $r$ is the tube radius $d$ in the figure, and $b$ is the transition radius of the inversion tube. The formula is shown as follows:

$$b = \frac{\sqrt{rt}}{2}$$  \hspace{1cm} (4)

Wherein, $t$ is the tube thickness, the values are as follows after substitution:

| Parameters | Material | Yield strength | Inner diameter $d$ | Outer diameter $D$ | Thickness $t$ | Radius of curvature $r$ |
|------------|----------|----------------|-------------------|-------------------|----------------|------------------------|
| Value      | SPPS38   | 220 Mpa        | 60 mm             | 80 mm             | 2.5 mm        | 5 mm                   |
\[ b = 5.477 \,, \dot{\epsilon} = 0.0677 \,; \text{substitute the values into the formula (2) to obtain the following formula:} \]

\[ \frac{\sigma_d}{\sigma_y} = 1 + \left( \frac{\dot{\epsilon}}{C} \right)^{1/q} = 1.279 \]

The low carbon steel with the yield strength \( \sigma_y \) of 220 Mpa is adopted, and \( \sigma_d \) is 281.38Mpa at the moment, i.e. \( R_c = \sigma_y = 281.38 \text{ Mpa} \) in the formula (1).

### 3.3. Deduction of starting load under ideal dynamic impact

Under crash impact of the vehicle and the rigid wall, the theoretical formula is deduced as follows:

\[ F = ma \quad (5) \]

Under the vehicle full-load condition, \( m = 650 \text{ kg} \); because the crash condition in the article is the front full-width crash, the theoretical set acceleration \( a = 40 \text{ g} \), and \( F = 254800 \text{ N} \).

There are 2 crash energy absorption tubes, so the impact force on the single side is:

\[ F' = F / 2 = 127400 \text{ N} \,; \text{i.e. } P_e = F' = 127400 \text{ N} \text{ in the formula (1).} \]

Substitute all the above parameters into the formula (1) to obtain the theoretical thickness design value of the inversion tube under the front full-width crash condition:

\[ t = 2.405 \text{ mm} \,; \text{t is first set to be 2.5mm in the following simulation.} \]

### 4. Front crash simulation study of inversion tube

#### 4.1. Build crash simulation model of inversion tube

The overall modeling of the inversion tube is shown as Figure 2. HyperMesh and LS-DYNA software is adopted to perform simulation analysis. The simulation mesh generation adopts 8mm units and MAT2 low carbon steel materials. Part 1 is the rigid wall, part 2 is the inversion tube, part 3 is the flange, part 4 is the front rail, and part 5 is the connecting tube. All the crash energy absorption parts can be fixed by fixing the tail end of the front rail. The crash simulation speed of the rigid wall is 50 km/h, the additional mass is half of the full-load vehicle weight, i.e. 325kg, and the simulation calculation time is 50ms.

**Figure 2. Inversion tube simulation modeling**

**Figure 3. Inversion tube simulation condition**

#### 4.2. Inversion tube crash simulation result analysis

The inversion tube crash simulation process is displayed as Figure 4:

**Figure 4. Inversion tube crash simulation process**

(a) \( t=10 \text{ ms} \)  \hspace{1cm} (b) \( t=50 \text{ ms} \)

The period of 0–20 ms shows the inward inversion process of the inversion tube, which is very stable. After 20 ms, the front rail enters the crumpling stage. At the moment, the speed of the rigid wall is not reduced to 0, thus the front rail will be crumpled continuously later. The connecting tube
part between the inversion tube and the front rail is free of obvious crumpling, because the inversion tube and the connecting tube are connected in a welding mode, and the rigidity of the connecting part is higher than the other part.

The crash acceleration curve of the rigid wall is shown as Figure 5. The period of 0~20 ms is the crumpling process of the inversion tube, and the average value is 38g after the acceleration is stable.

![Figure 5. Inversion tube crash simulation acceleration graph](image)

The crash process is analyzed as follows, the period of 0~20 ms is the crumpling process of the inversion tube, and its crumbling figure is shown as Figure 6.

![Figure 6. Inversion tube crash simulation process](image)

See Figure 7 for the inversion tube impact force graph. The stable inversion tube impact force is 121729 N.

![Figure 7. Inversion tube crash simulation impact force graph](image)

See Table 2 for comparison and error analysis of the theoretical calculating value and the simulation calculating value. The comparison analysis error is small, indicating that the simulation calculation result is available. Therefore, the discussed inversion tube dimensions are appropriate, and the dimension values will be further applied to the following full vehicle model crash.

|                      | Average acceleration | Inversion tube impact force |
|----------------------|----------------------|-----------------------------|
| Theoretical calculating value | 40 g                | 127400 N                    |
| Simulation calculating value | 38 g                | 121729 N                    |
| Error                | -5.00%               | -4.45%                      |
The appropriate dimensions of the inversion tube are obtained after analysis. However, parts like bumper and crash box are also designed in the vehicle crash parts, which will absorb certain energy in the early stage of crash, thus the thickness of the inversion tube used in the vehicle crash simulation is smaller than the thickness designed in the section.

5. Vehicle crash simulation analysis

The design of the inversion tube is applied to a full vehicle to perform the vehicle crash simulation. The simulation condition is subject to GB11551-2014 "The Protection of the occupants in the Event of a Frontal Collision for Motor Vehicle", front full-width crash is adopted, with the impact speed of 50 km/h and the overall weight of 650 kg. The finite element mesh generation includes the following procedures: CAD geometric data inputting, geometry clearing, mesh generation and mesh quality adjustment. Theoretically, the small the model mesh dimensions area, the more the meshes are, the higher the quality is, the longer the solving operation time is, the higher the accuracy is. However, too many too dense meshes will also enhance the requirement for computer's capacity while prolonging the computer operation time. The 8 mm×8 mm unit mesh generation is adopted in this study, and the unit mesh density of the parts is consistent.

![Figure 8. Inversion tube application full vehicle simulation model](image)

5.1. Vehicle crash deformation analysis

Seen from the vehicle crash deformation analysis, the inversion tube deformation mode is kept consistent with the design model, and no plastic hinge bending deformation is generated. By means of the stable inversion process, the inversion tube absorbs energy and reduces vehicle speed, thereby ensuring the vehicle crash safety characteristics.

![Figure 9. Full vehicle simulation analysis](image)

5.2. Energy absorption analysis

Analysis of energy absorption conditions of key energy absorption parts in simulation is shown as the following table, wherein the parts absorbing energy most are the inversion tubes on the left and right sides, with the energy absorption amount accounting for 33.0% of the total crash energy. The energy absorption amount of the main energy absorption parts in the vehicle accounts for 60.0% of the total energy, indicating that the inversion tube can absorb 33.0% of the energy of the fully electric vehicle, thus the design aim can be achieved.
Table 3. Key part energy absorption analysis

| Left energy absorption part | Absorbed energy (kJ) | Right energy absorption part | Absorbed energy (kJ) |
|-----------------------------|----------------------|-----------------------------|----------------------|
| Front bumper                | 2.497                | Crash box                   | 1.576                |
| Crash box                   | 1.578                | Crash box                   | 1.576                |
| Inversion tube              | 10.671               | Inversion tube              | 10.309               |
| First front rail            | 5.733                | First front rail            | 5.752                |

Energy absorbed by energy absorption part (kJ) 38.166
Total crash energy 63.600
Energy absorption percentage 60.0%

6. Summary
This article studied the crash energy absorption characteristics of the inversion tube. First, the theoretical formula deducing was performed according to the references to determine appropriate inversion tube dimension parameters. The front full-width crash simulation simplified model was built in HyperMesh to verify whether the theoretical design values are feasible by means of inversion tube simulation to further apply the designed inversion tube parameters into the front full-width crash simulation. The designed inversion tube was applied to the full vehicle to perform 50km/h crash simulation under the front full-width condition. The crash simulation was completed in HyperMesh to verify energy absorption and stability effect of the designed inversion tube on the full vehicle crash safety to demonstrate that the designed inversion tube structure complies with the requirement for safety.

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