Structure Design and Research on a New Tire Emergency Inflation System

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Abstract. Tire burst is huge harmful, a new tire emergency inflation system was put forward based on the airbag technology to reduce the harm of tire burst in this paper. Firstly, the pyrotechnic gas generator and its matching wheel hub were designed, the tire emergency inflation system model was established and the inflation process was simulated. The results show that the numerical model of tire emergency inflation system can well simulate the inflation process after tire burst. The peak time of gas production has little effect on the peak pressure of gas in the airbag after inflation. The peak time of gas production is different, but the final pressures in the airbag are all about 250 kPa, meeting the performance requirements. Therefore, the function of tire emergency inflation system designed can be realized.

1. Introduction

In highway traffic accidents, 46% of them are related to tires, of which tire burst accounts for 70% [1]. According to a test, if the car speed is more than 160 km/h when the tire blows out, the death rate of drivers and passengers is 100%. Tire burst has become the terrible killer of driving safety at high speed [2]. How to prevent tire burst has become an important issue for safety traffic.

At present, tire burst-proof technologies mainly include prevention before tire burst (before-technology) and emergency disposal after tire burst (after-technology). The prevention technologies before tire burst mainly include tire pressure monitoring [3], tire repair [4], tire pressure regulation [5, 6], etc. The prevention technologies before tire burst have certain effect on tire burst-proof, but they can not avoid tire burst, so the emergency disposal technologies after tire burst are particularly important.

The Run Stability Control (RSC) tire is one of the after technologies and can support car traveling a certain distance normally after tire burst. RSC tires mainly include three types of self-sealing, self-supporting and auxiliary supporting [7]. The self-sealing type has high cost and is difficult to replace, which limits its application. The self-supporting type is widely used at present, but it's not economical. The auxiliary supporting type can’t match the existing standard rims, so only few vehicles are equipped.

The tire emergency inflation device based on airbag is another after technology, which can inflate the tire or spare tube in an emergency to keep stable driving after tire burst [8-11]. Due to advantages of rapid response, controllable inflation pressure and so on, this technology has attracted people's attention. It can well deal with the situation of tire pressure sudden change and large tire deformation after tire burst.
In this paper, a new tire emergency inflation system was put forward based on the airbag technology. The system adopted the gas generator of mechanical ignition, which avoided the unreliability of electric signal ignition. The gas generator was installed in the center of the wheel hub, avoiding the impact on the wheel rotation balance. Firstly, the gas generator structure and its matching wheel hub were designed, the system working principle was explained. The inflation process CFD simulation of the system was carried out to study its feasibility.

2. Structure design of the tire emergency inflation system

There are three types of airbag gas generators for automobiles: pyrotechnic type, gasholder type and hybrid type [12]. Pyrotechnic gas generator has advantages of simple structure, rapid inflation, good safety and long-term storage [13], and also its gas production mass is controllable [14], so the pyrotechnic gas generator was used here. The ignition of generator is mechanical. The generator three-dimensional structure diagram is shown in Figure 1.

![Figure 1. Three dimensional structure diagram of gas generator](image)

The elastic component is a diaphragm that will deform under pressure, for example a corrugated diaphragm [15]. The gas generator with mechanical ignition was installed in the center of the wheel hub. The airbag was treated as the spare inner tube and was installed on the wheel rim. Together with the hollow spoke, they formed the tire emergency inflation system. The tire emergency inflation system structure diagram is shown in Figure 2.

![Figure 2. Structure diagram of tire emergency inflation system](image)

Working principle: assemble the gas generator according to the design and install it in the hub center. Inflate the tire to the normal tire pressure, and then inflate the gas generator to the preset pressure (the tire burst warning pressure, taken as 200 kPa in this paper) through the inflation hole. After inflation,
the tire pressure is greater than the gas generator pressure, so the elastic component is convex towards
towards the gas generator, making connection key separate the striker and the ignition powder.

Elastic component and connection key can be fixed by thread. Once the tire blows out, the tire
pressure drops suddenly till to smaller than the gas generator pressure, the elastic component is deviation
from the gas generator under the effect of the internal and external pressure difference, pulling out the
connection key so that the striker pops out, strikes and ignites the ignition powder. Then the ignition
powder ignites the main powder, generating gas. The gas enters the hub through the nozzle and one-way
air outlet hole, then inflates the airbag installed on the rim through the hollow spokes, completing the
emergency inflation after the tire burst. Finally, a new inner tube is formed, making the vehicle not out
of control and providing enough handling time for driver, which reduces or avoids the harm of tire burst
accident.

3. Simulation of emergency inflation process

The key to achieve emergency inflation is that after ignition, the generated gas can inflate the airbag to
the specified tire pressure within the specified time. Due to the limitation of spoke structure, high
inflation pressure, and short inflation time, the gas flow through the spoke hole is easy to cause choking
phenomenon, which affects the inflation process. Therefore, in this section, a tire emergency inflation
system model was established to simulate the inflation process to study whether it can meet the inflation
requirements.

3.1. Modeling and Verification

(1) 3D Modeling

An actual vehicle is used in this paper, its hub size parameters are shown in Table 1.

| Table 1. The hub size parameters |
|-------------------------------|
| **Hub parameters** | **Tire parameters** |
| Diameter /mm | 381 |
| Width /mm | 177.8 |
| Offset ET/mm | -30 |
| Center Hole Diameter/mm | 110.2 |
| Width /mm | 215 |
| Aspect Ratio | 75 |

According to the above design, the 3D tire emergency inflation system model consist of gas generator,
hollow spoke and tire system was established (fluid part), as shown in Figure 3.

![Figure 3. The tire emergency inflation system model (fluid part)](image)

(2) Model Verification

Due to the limited test conditions, it is difficult to verify the model with the actual inflation process
of the wheel system. The reliability of the numerical model mainly depends on the accuracy of the
geometry and model parameters such as boundary condition, turbulence model, etc, and the model
parameters are universal in the scope of their application. Therefore, the accuracy of model parameters was verified through typical tank test and then the verified model parameters were applied to the established tire emergency inflation system model for simulation.

A 60L cube tank model was established, the grids were refined at the entrance. The mesh model (fluid part) is shown in Figure 4.

![Figure 4. Mesh model of tank](image)

The model parameters in the simulation were as follows: flow boundary was set at the inlet, k-ε turbulence model was adopted, standard wall function was used in the near wall area, simple was used for discretization, and the residual values were 10⁻⁴.

The boundary conditions were obtained by differentiating the p-t curve of typical tank test [16]. The p-t curve of typical tank test of gas generator [17] is shown in Figure 5.

![Figure 5. Typical tank test p-t curve](image)

When the powder reacts completely, the pressure in the tank reaches its peak value, and then the pressure drops slightly due to the dropping temperature. In order to avoid the negative value of the mass flow, the differential calculation on the p-t curve was only performed before the peak pressure, and the gas production mass curve was obtained as shown in Figure 6.
Firstly, the grid independence of the model was verified. The numerical results will be more accurate with the grid getting refined, but basically will not change with further refined when the grid is refined to a certain extent which is the suitable grid size. The trial simulations of different sizes of grids were carried out. The meshing scheme is shown in Table 2.

**Table 2. Meshing scheme**

| Scheme | Basic size/mm | Refined Size/mm | Number of Grids |
|--------|---------------|-----------------|-----------------|
| 1      | 8             | 4               | 140600          |
| 2      | 6             | 3               | 315400          |
| 3      | 4             | 2               | 1014600         |
| 4      | 4             | 1               | 1387900         |
| 5      | 4             | 0.5             | 3966500         |

Trends of peak pressure and computing time with the grid number are shown in Figure 7.

It can be seen that with the increase of grid number (that is, the grid size gradually decreases), the peak pressure gradually converges. When the grid number is greater than 1381900 (that is, the grid size is less than 1 mm), the peak pressures are basically the same, but the computing time increases sharply. Considering the accuracy and computing time of simulation, meshing scheme 4 is the best.
Then numerical $p$-$t$ result with meshing scheme 4 and the test $p$-$t$ result are shown in Figure 8.

![Figure 8. Numerical p-t result and test p-t result](image)

As can be seen from the Figure 8, the trend of the numerical $p$-$t$ curve is the same as that of the test $p$-$t$ curve. They both increases first and then decreases slowly. The peak pressure time is around 70 ms. The numerical peak pressure is about 193.12 kPa, the test peak pressure is about 185.39 kPa, and the error is 4.17%. At the end time, the numerical pressure is about 190.36 kPa, the test pressure is about 179.77 kPa, and the error is 5.89%. The results show that the numerical model is accurate and reliable, so the model parameters can be applied to the tire emergency inflation system model for further study.

3.2. Simulation of emergency inflation process

(1) Determination of inflation mass and spoke diameter

According to the design, the airbag was inflated from the initial state (assuming the amount of substance is $n_0$) to the pressure $p$ (assuming the amount of substance is $n_t$), setting the total cross-sectional area of the spoke hole as $A$, the length as $L$, and the fully expanded volume of the airbag as $V_t$. The ideal gas state equation is

$$p \cdot V_t = n \cdot R \cdot T \quad (1)$$

Where $p$ is the gas pressure, the standard inflation pressure of the tire in this paper is 250 kPa, so $p$ is 350 kPa (absolute pressure value); $V_t = V_i + A \cdot L$ ($V_i$, $L$ are read by the software as 0.050 m$^3$, 0.135 m respectively); $R$ is the gas constant of 8.314; $T$ is the gas temperature, in order to ensure sufficient inflation quality, $T$ is taken as 293.15 K at room temperature after inflation. After inflation, the mass of the air filled into the airbag is

$$m = \rho \cdot v \cdot A \cdot t = M \cdot (n_t - n_0) \quad (2)$$

Where, $\rho$ is the gas density; $v$ is the gas velocity; $t$ is the inflation time; $M$ is the gas molar mass. For inflation time $t$, assuming that the wheel hub sinks freely after the tire burst, half height $h$ of the tire is taken as the sinking height so that $t = 0.127$ s. Considering the delay time of gas production, $t$ is taken as 0.1 s. According to references [18] and [19], the gas pressure in the tire drops to atmospheric pressure in about 800 ms after tire burst, so the inflation time $t$ can ensure the inflation efficiency. For gas velocity $v$, according to the choking phenomenon of gas dynamics, when the gas velocity in the pipeline reaches sound velocity, the mass flow rate is the maximum under this stagnation pressure and temperature. Therefore, in order to ensure enough gas mass passing through the spoke hole within a specified time, the following relationship should be met

$$\rho_{st} \cdot c_{st} \cdot A \cdot t \geq M \cdot (n_t - n_0) \quad (3)$$
Where, the formula of sound velocity is
\[ c_{cr} = \sqrt{\frac{k P}{\rho}} = \sqrt{k \cdot R \cdot T} \]  
\[ (4) \]

\( \rho_{cr} \) is the gas density at sound velocity; \( k \) is the adiabatic index, sodium azide is used in this paper. The gas produced by sodium azide is mostly the diatomic molecule nitrogen, so the adiabatic index \( k \approx 1.41 \).

In order to ensure the spoke holes have sufficient flow capacity at any working condition, it is necessary to make the cross-sectional area of spoke holes meet equation (3) at any working condition, that is, the minimum product of \( \rho_{cr} \) and \( c_{cr} \) should be selected to determine the cross-sectional area of spoke holes. However, the minimum product of them is difficult to determine, so the minimum \( \rho_{cr} \) and \( c_{cr} \) was selected respectively.

For \( c_{cr} \), the sound velocity increases with the increase of temperature according to equation (4), so the sound velocity at the lowest working temperature should be selected. When the car is running, the gas temperature in the tire is higher than normal atmospheric temperature. So the normal atmospheric temperature is taken for calculation.

For \( \rho_{cr} \), during the gas production process of gas generator, the stagnation pressure and stagnation density in the airbag increase gradually, so the initial stagnation density of gas generator should be selected. Then the critical density \( \rho_{cr} \) is determined by isentropic process and the initial stagnation density.

Isentropic process equation is
\[ \frac{P}{\rho^k} = \text{const} \]  
\[ (5) \]

The equation of critical pressure ratio is
\[ \frac{P}{P_0} = \left( \frac{2}{k+1} \right)^{\frac{k}{k-1}} \]  
\[ (6) \]

By combining the above equations, the cross-sectional area of the spoke holes and the inflation mass can be solved.

According to the parameters in Table 1 and the equations above, the cross-sectional area of the spoke holes \( A \geq 0.007 \text{ m}^2 \) and the required inflation mass \( m = 0.201 \text{ kg} \). Finally, the cross-sectional of the spoke holes were set as circular, their areas were set as 0.007 \text{ m}^2 and according to the analysis above, the performance index of the system is to be able to inflate the airbag to 250 kPa within 0.1 s.

(2) Results and analysis

For better simulation, the following assumptions were made: (a) The gas-producing powder is instantaneously and fully ignited, each side is a uniform air source. (b) The influence of folding and encapsulation of airbag on inflation process was ignored. (c) The gas emitted by gas generator and the gas in tire are instantaneously and fully mixed.

Due to the symmetry of the model, the symmetrical model was used for simulation and meshing scheme 4 was adopted. The grids at the spokes were refined. The symmetrical grid model of tire emergency inflation system is shown in Figure 9.
Figure 9. Schematic diagram of symmetrical mesh model

For better simulation, the gas production mass curve is properly simplified according to its characteristics, as shown in Figure 10.

Figure 10. Simplified gas production mass curve

The inflation mass $m=0.201$ kg, because of the symmetrical model, half of $m$ is 0.1 kg, that is, the surrounding area of gas production mass and $x$-axis is 0.1 in Figure 10. According to the inflation time $t=0.1$ s, the peak value $m_{\text{max}}$ of gas production can be determined. According to the analysis above, the pressure in the airbag is only related to the filled gas mass, and has nothing to do with the peak time $t_{\text{max}}$ of gas production.

The gas production mass curve with peak value $m_{\text{max}}=2$ kg/s and peak time $t_{\text{max}}$ of 10, 20, 30, 40 and 50 ms respectively were selected for calculation, and the $p$-$t$ curve in the airbag is shown in Figure 11.

Figure 11. Trends of pressure in airbag with time
It can be seen from Figure 11 that under different peak time of gas production, the pressure in the airbag all increases first and then decreases slowly, the peak time of gas production has little effect on the peak pressure and the pressure at the end simulation. Taking the peak time of 40 ms as an example, when $t=61.8$ ms, the pressure reaches the warning pressure $p=200$ kPa and when $t=98.7$ ms, the pressure reaches the peak pressure $p=260.27$ kPa. After that, due to the dropping temperature, the pressure decreases slightly and finally are about 250 kPa, meeting the performance index.

4. Conclusion

According to the airbag technology, a tire emergency inflation system for wheel was put forward in this paper, the pyrotechnic gas generator structure was designed and its working principle was explained. The feasibility of the system was studied through CFD simulation. The conclusions are as follows:

1. The tank model established is accurate and the model parameters are correct, the model parameters can be applied to the inflation simulation of tire emergency inflation system.

2. According to the calculation method of the cross-sectional area of the spoke whole, for the hub used in this paper, the total minimum cross-sectional is 0.007 m$^2$ and the required gas production mass is 0.201 kg.

3. The peak time of gas production has little effect on the peak pressure in the airbag, under different peak times of gas production, the final pressures are all about 250 kPa, which meet the performance index. Therefore, the function of the tire emergency inflation system put forward in this paper can be realized.

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