# THE SIMULATION OF ONE SIDE OF TETRAHEDRON AIRBAGS IMPACT ATTENUATION SYSTEM

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## ABSTRACT

This paper simulated the characteristic of one of four sides of a tetrahedral lander with airbags impact attenuation system, and got the effect of attenuation characteristic with the diameter of the gas orifices between the airbags. According to the given condition, the better diameter of the gas orifices was selected, and some improved design was brought forward, which the design of the closed airbags could base on.

## 1. INTRODUCTION

Airbag for the landing attenuation is a branch of the aircraft recovery systems which are often used in the aerospace and planetary probe. Mars Pathfinder mission, Mars exploration rover (MER) mission [1] and Mars express program [2] successfully using airbags had proved that airbag system was a simple and dependable attenuation in the terminal phase of EDL.

As a passive attenuation used in landing, airbag is mainly made up of fabric with all kinds of shape according to design requirement. The airbag operation process is as follow. At the beginning, the airproof airbag is inflated to the working pressure which is expected. In the attenuation phase, along with the airbag is compressed, the internal pressure of the airbag raise. At the same time, the energy is absorbed step by step, and the lander is cushion decelerated. According to whether exhaust or not, airbags are classified as exhaust ones or closed ones. When the internal pressure raise to the expected value, the orifices of exhaust airbags are open and exhaust, the energy is released, and the rebound is restrained [3]. In the operation process, closed airbags are not exhaust, and bounce time after time to dissipate the impact energy. Exhaust airbags are widely used in the landing attenuation on the earth. However, closed airbags are mainly used in the planetary probe.

This paper simulated the characteristic of the landing attenuation airbags in the obverse impact, and got the attenuation characteristic of the airbags.

## 2. MODELING

### 2.1 Airbag design

The airbag model of this paper is regular tetrahedron structure, as shown in Fig.1. Six ball airbags make up of an airbag face in the regular triangle shape. Each airbag face connects others with gas orifices, and the whole airbag is closed. The weight of the model is 90kg, the diameter of ball airbags is 1m, and the volume of all airbags is 10.12m$^3$.

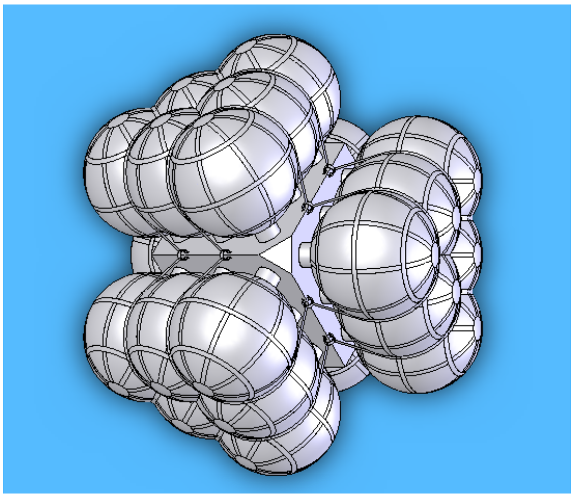

Fig 1 Landing Attenuation Airbag (sketch map)

The landing velocity of attenuation airbags in the vertical direction is 17.2m/s, which is based on the calculation of this paper. This paper optimizes the model by varying some parameters to get the variety of the overload, the internal pressure, the bounce velocity, and so on.

### 2.2 Assumption

In making the simulation, the following assumptions were made:

I The simulation neglects the aerodynamic drag force, and the model is only decelerated by the airbag.

II The impact between the model and the smooth ground is supposed to face impact.

There are three conditions of the impact between the regular tetrahedron airbag and the ground. It depends on which part of the airbag impacts on the ground, a face, an edge between the two faces, or an apex point of tetrahedron airbags. The last two conditions are unstable, and the impact time is short. In this situation, the deformation of the airbag is little, and the dissipation of the energy is also on the small side, and the distribution of stress is not uniform. Thus in the airbag recovery the attitude control equip mental ways is used to insure the face impact happens. This paper simulates the impact process between the model and the smooth ground.

III Except the impact face, the volume of the other face airbags is supposed to be invariable.

In the impact process, impact face of the airbag exchanges gas with the other faces by the internal gas orifices. When the impact face is deformed by extrusion, the gas flows into the other faces by the gas orifices, which induces the other faces inflation and deformation to some degree. The elongation of the flexible skin of the airbag is low, and relative to the extrusion one, the inflation deformation can be neglected.

IV The deformation of the airbags completely is supposed to result from the extrusion in the vertical direction.

In fact there is velocity in the horizontal direction and the roughness of the ground, the impact process is very complicate. As a matter of convenience, the velocity in horizontal direction is neglected, and the deformation of the airbags completely is supposed to result from the extrusion in the vertical direction. The other factors which effect the deformation are neglected, such like friction and the roughness of the ground.

V In the attenuation process, the gas compressibility is adiabatic and constant entropy in the airbag and the gas is ideal.

### 2.3 Equations

According to the above assumption, for a descending in the vertical direction on an airbags face as illustrated in Fig.2 (Fig.2 only shows the impact face), the following force balance of the model can be written:

$$m \times a + m \times g + Pa \times A = P \times A \qquad (1)$$

Where:

m = the mass of the model, kg;
a = the acceleration of the model, m/s$^2$;
g = local acceleration of gravity, m/s$^2$;
Pa = the air pressure, pa;
A = the area of an airbags face, m$^2$;
P = the internal pressure, pa.

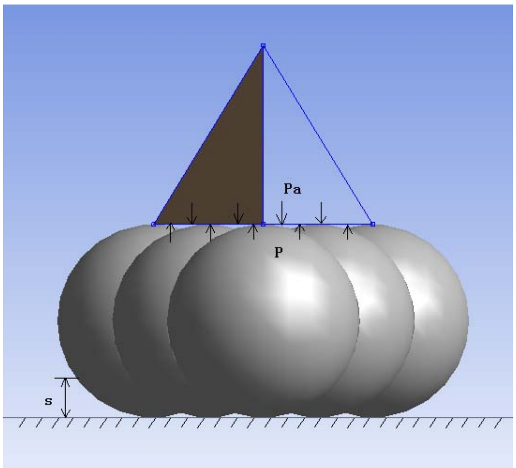

Fig.2 Force Diagram of the Model

The relationships between the parameters are as follow:

$$a = \frac{P-Pa}{m} \times A - g \qquad (2)$$

The velocity of the model:

$$\mathrm{u} = \mathrm{u}_0 + \int \mathrm{a} \cdot \mathrm{dt} \qquad (3)$$

Where:

$u_0$ = the landing velocity in the vertical direction, m/s.

The compress distance:

$$s = \int \mathrm{u} \cdot \mathrm{dt} \qquad (4)$$

The volume of the airbag:

$$\mathrm{V} = \mathrm{f(s)} \qquad (5)$$

The volume of the airbag varies by the compress distance. The compress makes the airbag ellipsoid, as shown in Fig.3.Because there are not equation that directly describes the change of the airbag, the volume of the airbag in arbitrary compress distance can be got by the linear interpolation based on some calculated volumes in known compress distances. The Fig.4 shows the volumes at different compress distances.

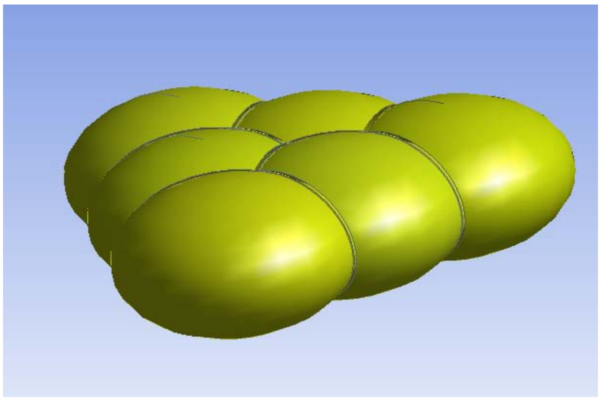

Fig.3 Deformation of the Airbag in Compression

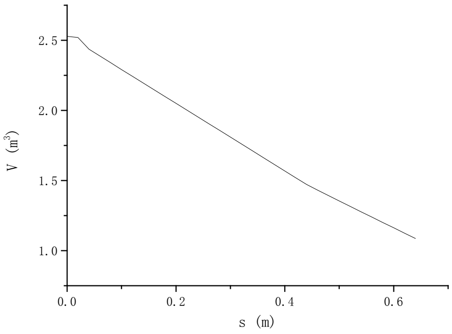

Fig.4 Volumes of the Airbag at different compress distances

The gas mass of the impact face:

$$m = m_0 - \int Q_m \cdot dt \qquad (6)$$

Where:

$m_0$ = the gas mass of the impact face at the beginning, kg;
$Q_m$ = the mass flux passing gas orifices, kg/s;

The pressure of the impact face:

$$P = C \times \frac{m}{V} \qquad (7)$$

Where:

C = constant;
The pressure of the other faces:

$$Pot = P_0 + \frac{C \times \int Q_m \cdot dt}{3 \times V_0} \qquad (8)$$

Where：

$P_0$ = the pressure of one face before the impact, Pa;
$V_0$ = the volume of one face before the impact, $m^3$;

The mass flux passing gas orifices:

$$Q_m = \frac{P \times S}{C} \times \left(\frac{Pot}{P}\right)^{\frac{1}{k}} \times \sqrt{\frac{2\times k}{k-1} \times c \times \left[1 - \left(\frac{Pot}{P}\right)^{\frac{k-1}{k}}\right]} \qquad (9)$$

Where:

S = the area of gas orifice, $m^2$;
k = adiabatic consent.

With time iteration, the whole attenuation process can be divided into many parts which are in the same length of time. In every part, the characteristic of the model can be calculated, and the calculative flow is shown in Fig.5. The iteration stops at the moment of the airbag coming back to the initial shape and bouncing.

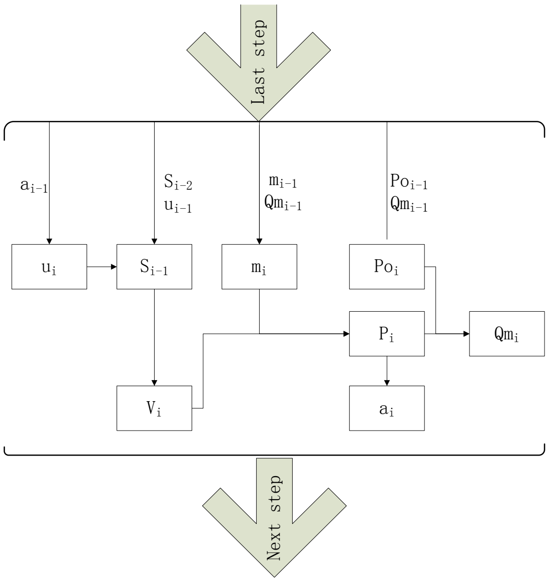

Fig.5 Flow Chart of Iteration Process

## 3. RESULTS AND ANALYSIS

### 3.1 Test verification

By the simulation of the model which is mentioned in 2.1, this paper has got some important parameters, such like the change of the internal pressure and the acceleration, which were compared with the delivery test. The model in the delivery test is the same as the simulated one, and the environment of the test is similar. The time domain curve of regular tetrahedron airbag in the delivery test is shown in Fig.6. The test landing velocity in the vertical direction is 17.2m/s. The diameter of gas orifices is 0.1m and the differential pressure between internal and external airbag at the beginning is 500Pa. The maximum overload is 44.47g's in the test. And the time domain curve of the simulation in the same situation is also shown in Fig.6 with the maximum overload 46.34g's. The both are broadly similar in characteristics.

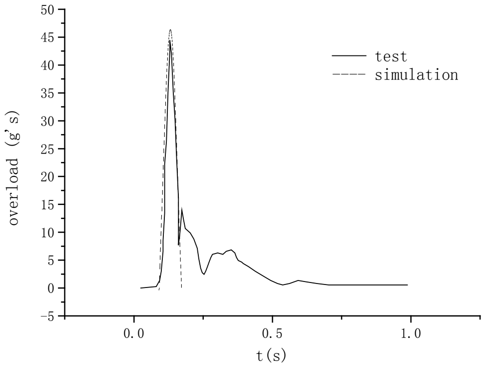

Fig.6 Time Domain Curve of the Simulation and Test

## 3.2 Results and analysis

Under the conditions that the landing velocity is 17.2m/s, and the difference pressure between internal and external of the airbag at the beginning is 500Pa, the changes of internal pressure and overload of the model which is mentioned in 2.1 with different gas orifices are shown in Figure 7 and 8in the attenuation process. In Fig.7 and 8, the peak value of the internal pressure and the maximum overload in the attenuation process reduce with the diameter of gas orifices increasing. It is because that the bigger gas orifices of the impact face in compressing phase(the whole attenuation process is divided into two parts, the compressing phase and inflation phase)make the higher mass flux, the lower extent of internal pressure increase which reduce the overload. The higher mass flux of the impact face in the compressing phase also offers the bigger room for the inflation phase and decreases the overload of the inflation phase which reduces the rebound velocity. At the same time, the lower overload defers the whole attenuation process. It is worth noticed that the long attenuation time make the change of internal pressure and acceleration slow and low. It is beneficial to both the airbags and recovery.

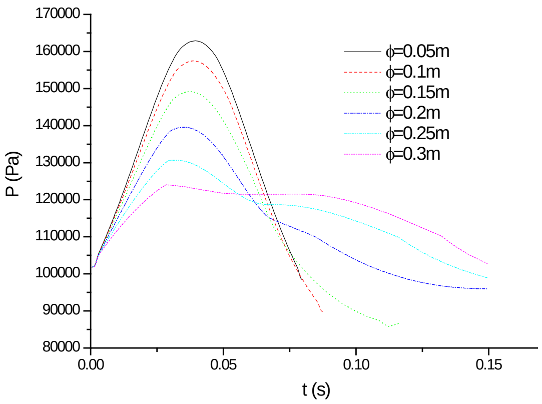

Fig.7 Time Domain Line of Airbag Internal Pressure with Different Diameter of Air Orifice

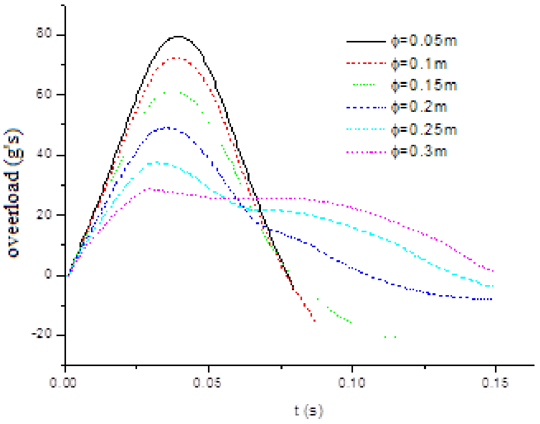

Fig.8 Time Domain line of Airbag Overload with Different Diameter of Air Orifice

On the other hand, the acceleration becomes a negative one in the end of the attenuation process in Fig.7 and Fig.8.It means that the rebound velocity of the model is decreasing at this moment. It is easy to get from the velocity cure. It is because that the volume of the impact face is faster than the gas mass in recovery, viz., the gas that flow back to the impact face from other faces is less than the inflation volume. It makes the decrease of the internal pressure. As far as the internal pressure is reduced to enough, a negative acceleration of the model appears which is of benefit to the low rebound velocity, height and times of the model. Accordingly, the small gas orifices limit the gas flowing back to the impact face, and reduce the rebound velocity, height and times of the model.

According to two above facts, the cure of the rebound velocity at different diameters of gas orifices is shown in Fig.9.When the diameter of gas orifices comes to 0.2m, the model rebounds at minimum of 4.55m/s. In the opinion of momentum, the minimum rebound velocity is inevitable. The overload of the model decreases with the diameter of gas orifices increase, but the effect period increases. Accordingly there is a right diameter that brings a minimum momentum in the attenuation process and a minimum rebound velocity.

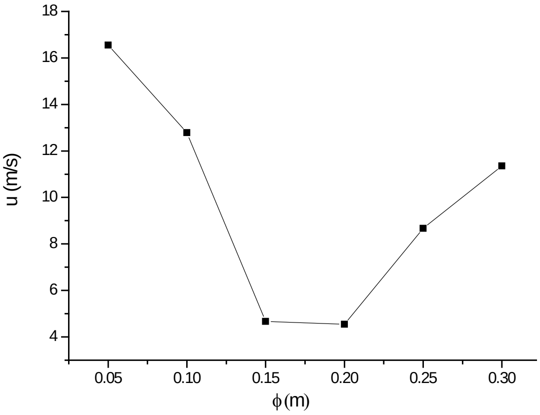

Fig.9 Rebound Velocities at Different Diameter of Gas Orifices

The maximum compress ratios of the airbag at different diameter of gas orifices are shown in Figure 10. It indicates that compress distance comes to 43%~71% of the diameter of the airbag. The airbag satisfies the attenuation requirement.

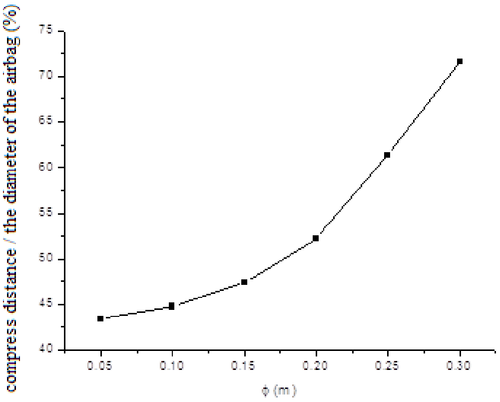

Fig.10 Maximum Compress Ratios at Different Diameter of Gas Orifices

When the diameter of gas orifices comes to 0.2m,main parameters of the attenuation is shown in Table 1 at various initial differential pressure between internal and external of the airbag. In the opinion of standard deviation, the initial differential pressure has a little effect on the attenuation characteristic.

Table.1 Main Parameters of the Attenuation at Various Initial Differential Pressures

| Initial differential pressure （Pa） | Maximum internal pressure （Pa） | Maximum overload （g's） | Maximum compress ratio （%） | Rebound velocity （m/s） |
|---|---|---|---|---|
| 300 | 139515 | 48.88 | 52.31 | 4.52 |
| 400 | 139542 | 48.91 | 52.26 | 4.53 |
| 500 | 139570 | 48.95 | 52.21 | 4.54 |
| 600 | 139597 | 48.99 | 52.17 | 4.55 |
| 700 | 139625 | 48.98 | 52.11 | 4.56 |
| 800 | 139653 | 49.06 | 52.05 | 4.56 |
| 900 | 139680 | 49.09 | 52.00 | 4.57 |
| 1000 | 139708 | 49.12 | 51.95 | 4.57 |
| 1100 | 139736 | 49.17 | 51.90 | 4.58 |
| 1200 | 139763 | 49.20 | 51.85 | 4.58 |
| standard deviation | 2.63 | 0.096 | 0.012 | 0.04 |

### 3.3 Design optimization

According to above analysis, the proper diameter of gas orifices will improve the attenuation characteristic of airbag. When the diameter of gas orifices comes to 0.2m, the airbag which is mentioned in 2.1 performs best in the attenuation process. In addition, according to two above function of the diameter of gas orifices, gas orifices could be designed to exhaust easily and flow back difficultly. The design will reduce the overload in the compress phase and the rebound velocity in the inflation phase, and the airbag will perform better.

As Equation 2 shows, the smaller area of airbags face will reduce the overload. The maximum overloads are shown in Fig.11 at different areas of an airbags face. The decrease of area will reduce the maximum overload, but increase the rebound velocity as shown in Fig.12. Therefore the proper area of airbags face can be got by balancing the maximum overload and the rebound velocity.

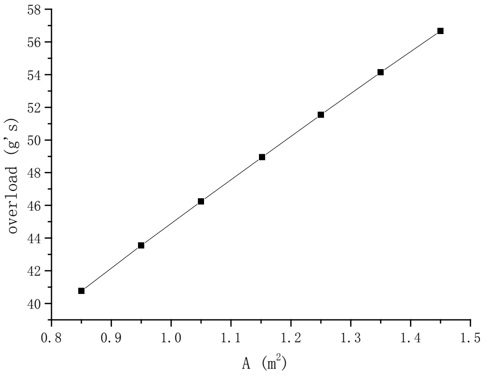

Fig.11 Maximum Overload at Different Areas of Airbags Face

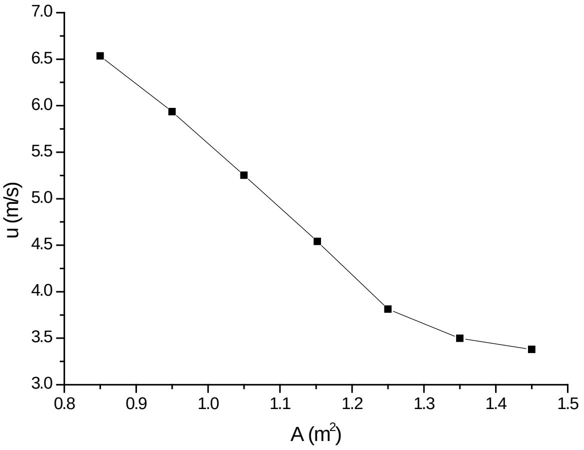

Fig.12 Rebound Velocity at Different areas of Airbags Face

## 4. CONCLUSIONS

This paper simulated the face impact of landing attenuation airbag, analyzed the results, and optimized the design of landing attenuation airbag. The conclusions are as follow:

I the increasing diameter of gas orifices would reduce the maximum overload, defer the attenuation process, and smooth the change of internal pressure and acceleration.

II the proper diameter of gas orifices would reduce the rebound velocity and increase the dissipative energy in the attenuation process.

III the initial differential pressure has a little effect on the attenuation characteristic.

IV the decrease of area would reduce the maximum overload, but increase the rebound velocity.

The simulation of this paper introduced some assumptions that would restrict above conclusions. The farther research will be independence from some assumptions, and focus on edge impact and point impact.

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