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Study on cushioning characteristics of soft landing airbag with elastic fabric

Jinpeng Wen*, Bin Li and Zhichun Yang
School of Aeronautics, Northwestern Polytechnical University, No.127 Youyi Xilu Xi'an Shaan Xi, 710072, China

Abstract. Based on the energy conservation principle and thermodynamic equations, an analytical model of soft landing considering the elasticity of airbag fabric was presented. The analytical model was verified by comparing the results with those results from a similar simulation using ls-dyna and our design-oriented model is solved with less calculation time than the finite element method. Then this analytical model was used to investigate the deceleration characteristics of a horizontal cylinder airbags. A series of simulations were conducted to find out the influence of fabric elasticity, initial airbag pressure, and vent size on attenuating properties.

Keywords: Cushioning, airbag, venting orifice, elastic fabric, payload

1. Introduction

Airbag cushioning system provides an attractive means for soft landing and heavy airdrop delivery. The system can not only limit landing loads but augment the stability, protect the payloads. As one kind of the most important airbag cushioning systems, vented airbags have been used almost exclusively from 1960s to the present day, for payloads ranging from a few kilograms to a few tonnes. And they have also been used in man-rated safety critical systems, such as the F-111 crew escape capsule [1].

In order to meet multiform requirements, varied airbags have been designed and manufactured. As an important step of airbag design, accurate modelling of the proposed configuration is carried out and simulated to determine whether the model's performance meets requirements. However, the finite element simulations will cost tens of hours for a typical case that an impact of a few tenths of a second duration occurs to the airbag attenuation process. In order to simplify the simulating procedure, and speed up the evaluation of cushioning characteristics of airbag systems, this paper develops an analytical model of soft landing airbag considering the elasticity of airbag fabric. The analytical model is solved by a Matlab program, and just tens of minutes are needed for a simulation of airbag attenuation process, but the simulation results keep well consistent with finite element analysis.

2. Energy equation for airbag

Vented airbags provide a dead-beat (no rebound) solution to landing objects. And on current vented airbag soft landing systems these are all one-shot valves, so that once opened they stay open. Figure 1 describes the process of the vented airbag landing.

*Corresponding author. E-mail: job_wen@mail.nwpu.edu.cn.

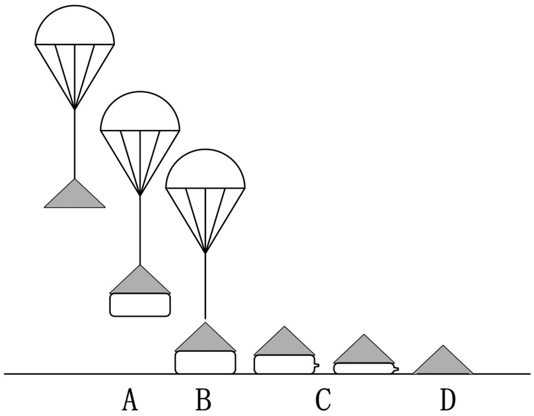

Fig. 1. Vented airbag landing.

A Airbags are deployed before impact.
B Adiabatic compression stage. The airbag contacts the ground, and begins to be compressed.
C Gas bleed stage. When the dynamic response of payload achieves a predetermined threshold acceleration value or the inner pressure of airbag approaches to the pre-set threshold, vented orifices are opened, and the inner gas is extruded out of the airbag, airbag system continues attenuating the impact energy.
D The payload lands.

To simplify this physical prototype, some assumptions firstly were introduced:

– The thickness of airbag fabric is small, and stress distribution in cross section of fabric is uniform.
– The payload is descending vertically, and the airbag deforms symmetrically.
– Compression of gas inside airbag occurs adiabatically, and temperature distribution in airbag is uniform throughout the airbag.
– The vented orifice area of the airbag is constant.

The airbag attenuation system is composed of the payload, the airbag fabric, and the air inside the airbag. Based on above assumptions, the energy conservation equation of airbag attenuation system can be defined as:

$$\Delta Q_t + \Delta W + \Delta Q_l = \Delta E \quad (1)$$

The left 3 terms show the energy interaction between the airbag and the environment. ΔQ_t expresses the heat transfer by conduction or radiation through the surface of the airbag. At this point, ΔQ_t is assumed zero because of the infinitesimal duration of attenuation progress. ΔW is the external force work. For this system, only externally applied work is done by the atmospheric pressure on the system upper surface. ΔQ_l is the internal energy of the gas flowing out of airbag.

The system energy change ΔE includes change in airbag gas internal energy ΔU and change in payload kinetic ΔE_k and potential energy ΔE_p, and change in airbag fabric stretch potential energy ΔE_f. Hence the energy equation for the system becomes

$$\Delta W + \Delta Q_l = \Delta U + \Delta E_k + \Delta E_p + \Delta E_f \quad (2)$$

The physical expandedness of every term in the Eq. (2) is shown as follow:

1. The atmospheric pressure work ΔW:

The external force work is defined as positive if the force is the same direction as the displacement. In this study, only the vertical motion of airbag system is taken into account, so the vertical work done by the atmospheric pressure on the top of the airbag is shown below.

$$\Delta W = \int -P_a A\dot{z}dt \tag{3}$$

Where, P_a is the atmospheric pressure, A is the contact area of payload with the top of the airbag, and $\dot{z}$ is vertical speed of the payload.

2. The dissipative energy by the gas flowing out of the airbag ΔQ_l can be expressed as:

$$\Delta Q_l = c_p \int \dot{m} T dt \tag{4}$$

Where, $\dot{m}$ is mass flow rate of gas into $(+)$ or out $(-)$ of the airbag, c_p is constant pressure heat capacity of gas per change in temperature, and T is temperature of the gas in the airbag.

3. The change in internal energy ΔU of inner gas:

ΔU is a function of temperature T and the gas mass inside the airbag m.

$$\Delta U = \int_{T_0}^{T} c_v m(t) dT = c_v \left[m(t)T - m_0 T_0\right] \tag{5}$$

Where, c_v is constant volume heat capacity of gas per change in temperature. The subscript 0 is the initial moment.

4. The change in system kinetic energy ΔE_k:

The mass of airbag fabric self is less than 1% of the payload mass, so the change in system kinetic energy only considers the contribution of the payload mass

$$\Delta E_k = M(\dot{z}^2 - \dot{z}_0^2)/2 \tag{6}$$

Where M is the mass of the payload.

5. The change in payload potential energy ΔE_p:

$$\Delta E_p = Mg(z - z_0) \tag{7}$$

Where z is height of the payload above the ground.

6. The change in fabric stretch energy ΔE_f:

The change in fabric stretch energy of the system ΔE_f is the work done by the fabric as it stretches in response to airbag pressure. This energy is predominantly stretching of the airbag in the axial and circumferential direction.

$$\Delta E_f = \iiint\limits_{V_{fabric}} \frac{1}{2}\sigma_{ij}\varepsilon_{ij} dV_{fabric} \tag{8}$$

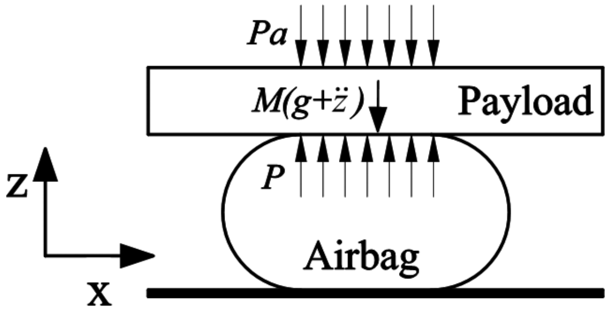

Fig. 2. The force balance of the payload.

As shown in Fig. 2, if we separate the payload to perform a force balance analysis, then the force balance equation of the payload can be written as:

$$M\ddot{z} = (P - P_a)\,A - Mg \tag{9}$$

Where P is the pressure of the gas in the airbag.

3. Basic equations of the stage B – Adiabatic compression stage

Based on the analysis in Section 2, airbags are compressed adiabatically when the attenuation system contacts ground. There is no gas bleed from the airbag, so $\Delta Q_l = 0$, and the mass of the inner gas is constant, hence $m(t) = m_0$. So the inner gas is satisfied with following thermal dynamic equation in the soft landing stage B.

$$RT = PV/m_0 \tag{10}$$

Where, R is the gas constant, V is the volume of the airbag which is a function of variables z. Combining Eqs (2), (9) and (10), and using numerical integral method to solve those equations, then we can calculate the $z(t)$, $P(t)$, $T(t)$ at any time step.

4. Basic equations of the stage C – Gas bleed stage

When the payload reaches a predetermined acceleration magnitude or the pressure in the airbag reaches the reassigned threshold, the soft landing is into stage C, the vented orifices are opened, and the inner gas is forced out of the airbags so that the impact energy is released. The mass flow rate through the orifice can be described by the one dimensional isentropic flow equation [2].

$$\dot{m} = -KA_{bag}\frac{P}{R\sqrt{T}}\left(\frac{P_t}{P}\right)^{\frac{1}{r}}\sqrt{2g_c\left(\frac{rR}{r-1}\right)\left(1-(\frac{P_t}{P})^{\frac{r-1}{r}}\right)} \tag{11}$$

Where, K and A_{bag} are the vent orifice coefficient and area, and the mass flow rate of gas into the airbag is defined as positive. The pressure in the flow nozzle throat of the airbag P_t is given by:

$$\begin{cases} P_t = P_a & When\ P_a > 0.528P \\ P_t = P\Big/\left(\frac{r+1}{2}\right)^{\frac{r}{r-1}} & When\ P_a < 0.528P \end{cases} \tag{12}$$

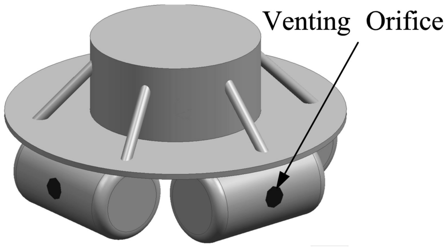

Fig. 3a. Soft landing system with horizontal cylinder airbags.

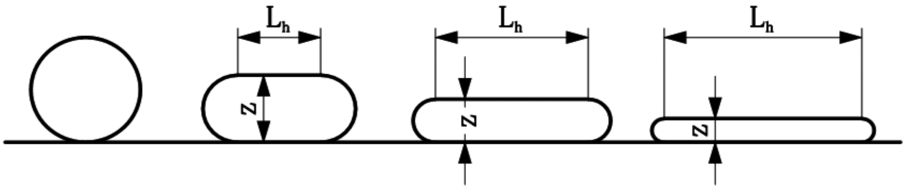

Fig. 3b. The deformation of the cross section of the airbag during the impact attenuation.

Here, γ is the ratio of the specific heats, $\gamma = 1.4$ for air. And g_c is the gravitational conversion constant.

As the mass of the gas flows out of the airbag, the thermal dynamic equation in the stage C is:

$$RT = PV/m(t) \tag{13}$$

By substituting Eq. (11) into Eq. (4), we can combine Eqs (2), (9) and (13) to solve the airbag attenuating dynamic behavior.

5. Model of the horizontal cylinder airbags

Horizontal Cylinder Airbags have been widely applied in soft landing system. Figure 3a shows the physical model of a soft landing system with 4 horizontal cylinder airbags. Every horizontal cylinder airbag has a venting orifice, which will open when the dynamic response of payload achieves a predetermined threshold acceleration value. A special characteristic of this type airbag is that the contact area of airbag with the payload and the ground increases with the decreasing of airbag height, and the cross section of the airbag is also variable. We assume that the bottom surface of the payload is flat and large enough, there is no invagination in the cushioning process. If we take single airbag to analyze, and assume the airbag deforms symmetrically as shown in Fig. 3b, the volume of airbag can be expressed as [3]:

$$V = \left[\pi z^2/4 + \pi z\,(D - z)/2\right] L_t = \pi z L_t\,(2D - z)/4 \tag{14}$$

$$A = L_t L_h, L_h = \pi\,(D - z)/2 \tag{15}$$

Where D and L_t are the diameter and the axial length of the horizontal cylinder airbag respectively, and L_h is shown as Fig. 3b.

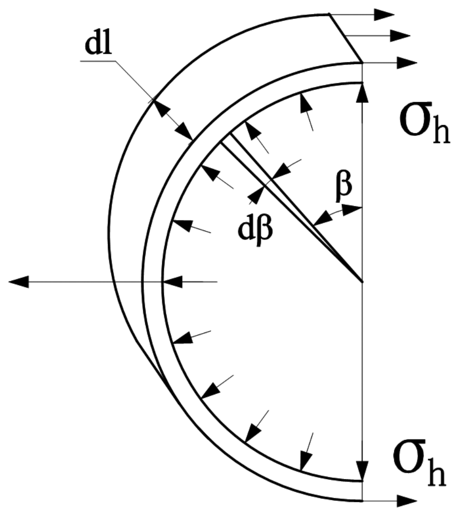

Fig. 4. The stress of the cross section of the airbag.

The thickness of airbag fabric is very small, and the fabric cannot bear the compressive and bending loads, only axial and circumferential tensile stresses exist in fabric. For isotropic linear fabric material, the relationship between the tensile strain and tensile stress can be expressed as:

$$\varepsilon_t = (\sigma_t - \mu\sigma_h)/E, \varepsilon_h = (\sigma_h - \mu\sigma_t)/E \tag{16}$$

Take a part of the horizontal cylinder airbag fabric to make an equilibrium analysis of all forces (see Fig. 4). The force acted on the arc fabric $d\beta$ is: $(P - P_a)\,\frac{z}{2}d\beta dl$. So the equilibrium equation of these forces in horizontal direction is:

$$2\sigma_h h_0 dl = \int\limits_s (P - P_a)\,\frac{z}{2}d\beta dl\sin\beta = (P - P_a)\,zdl \tag{17}$$

Where h_0 is the thickness of the airbag fabric. From Eq. (17),

$$\sigma_h = (P - P_a)\,z/2h_0 \tag{18}$$

The equilibrium equation of these fabric forces in axial direction is:

$$\sigma_t = (P - P_a)\left(\pi z^2/4 + \pi z\,(D - z)/2\right)/\pi D h_0 = z\,(P - P_a)\,(2D - z)/4Dh_0 \tag{19}$$

Substituting Eq. (16) into Eq. (8), we then obtain the following equation:

$$\Delta E_f = \frac{1}{2E}\iiint\limits_{V_{fabric}} \left(\sigma_h^2 + \sigma_t^2 - 2\mu\sigma_h\sigma_t\right) dV_{fabric} \tag{20}$$

Substituting Eqs (18) and (19) into Eq. (20), and expanding the integral equation, then Eq. (20) can be converted as:

$$\Delta E_f = \frac{\pi\,(P - P_a)^2\,z^2}{32h_0ED^2}\left(DL_t + Dz - z^2/2\right)\cdot\left(8D^2 + z^2 - 4Dz - 8\mu D^2 + 4\mu Dz\right) \tag{21}$$

So the Energy Eq. (2) in its fully expanded forms becomes:

$$\begin{aligned} c_p \int \dot{m} T dt - P_a \int A \dot{z} dt &= c_v \left(mT - m_0 T_0 \right) + M \left(\dot{z}^2 - \dot{z}_0^2 \right)/2 + Mg \left(z - z_0 \right) \\ &+ \frac{\pi \left(P - P_a \right)^2 z^2}{32 h_0 E D^2} \left(D L_t + Dz - z^2/2 \right) \cdot \left(8D^2 + z^2 - 4Dz - 8\mu D^2 + 4\mu Dz \right) \end{aligned} \tag{22}$$

Since $z_0 = D$ to a horizontal cylinder airbag, Differentiating Eq. (22), and simplifying:

$$\begin{aligned} & c_p \dot{m} T = M \dot{z} \left(\ddot{z} + g \right) + c_v \dot{m} T + c_v m \dot{T} + \dot{z} P_a A + \frac{\left(P - P_a \right) \pi z^2}{16 D^2 E h_0} \dot{P} \left(D L_t + Dz - z^2/2 \right) \\ & \cdot \left(8D^2 + z^2 - 4Dz - 8\mu D^2 + 4\mu Dz \right) + \frac{\left(P - P_a \right)^2 \pi z \dot{z}}{32 D^2 E h_0} [-3z^4 + 5z^3 D(3 - 2\mu) \\ & + 4z^2 D(L_t + 8D\mu - 8D) + 12 z D^2 \left(\mu - 1 \right) \left(L_t - 2D \right) - 16 L_t D^3 (\mu - 1)] \end{aligned} \tag{23}$$

The ideal gas law is used to express T and $\dot{T}$ in terms of P, V, m, $\dot{P}, \dot{m}$.

$$R\dot{T} = \frac{d\left(\frac{PV}{m} \right)}{dt} = \frac{m \frac{d(PV)}{dt} - \dot{m} PV}{m^2} = \frac{m \left(\dot{P} V + P \dot{V} \right) - \dot{m} PV}{m^2} \tag{24}$$

Both sides of the Eq.(24) are multiplied by $c_v m/R$,

$$c_v m \dot{T} = \frac{c_v}{R} \left(\dot{P} V + P \dot{V} \right) - \frac{c_v \dot{m} PV}{Rm} \tag{25}$$

Combining Eqs (23) and (25) to eliminate $\dot{T}$, substituting ($c_p = c_v + R$), and simplifying:

$$\begin{aligned} R \dot{m} T = & M \dot{z} \left(\ddot{z} + g \right) + \frac{c_v}{R} \left(\dot{P} V + P \dot{V} \right) - \frac{c_v \dot{m} PV}{Rm} + \dot{z} P_a A + \frac{\left(P - P_a \right) \pi z^2}{16 D^2 E h_0} \dot{P} \left(D L_t + Dz - z^2/2 \right) \\ & \cdot \left(8D^2 + z^2 - 4Dz - 8\mu D^2 + 4\mu Dz \right) + \frac{\left(P - P_a \right)^2 \pi z \dot{z}}{32 D^2 E h_0} [-3z^4 + 5z^3 D(3 - 2\mu) \\ & + 4z^2 D(L_t + 8D\mu - 8D) + 12 z D^2 \left(\mu - 1 \right) \left(L_t - 2D \right) - 16 L_t D^3 (\mu - 1)] \end{aligned} \tag{26}$$

Grouping the $\dot{P}$ to the left side produces

$$\begin{aligned} \dot{P} = & \{ -M \dot{z} \left(\ddot{z} + g \right) - \frac{c_v}{R} P \dot{V} + \frac{\left(c_v + R \right) \dot{m} PV}{Rm} - \dot{z} P_a A - \frac{\left(P - P_a \right)^2 \pi z \dot{z}}{32 D^2 E \delta} [-3z^4 + 5z^3 D(3 - 2\mu) \\ & + 4z^2 D(L_t + 8D\mu - 8D) + 12 z D^2 \left(\mu - 1 \right) \left(L_t - 2D \right) - 16 L_t D^3 (\mu - 1)] \} / \\ & \left[\frac{c_v V}{R} + \frac{\left(P - P_a \right) \pi z^2}{16 D^2 E \delta} \left(D L_t + Dz - z^2/2 \right) \cdot \left(8D^2 + z^2 - 4Dz - 8\mu D^2 + 4\mu Dz \right) \right] \end{aligned} \tag{27}$$

A specific Matlab program using four order Runge-Kutta method is used to solve these equations.

Table 1
Basic parameters of landing system

Requirement	symbol	Value	Units
Payload weight	M	135	kg
Payload vertical speed	$\dot{z}$	-6	m/s
Z axis load limit	–	15	g
Z axis velocity limit	–	1.5	m/s
Ambient pressure	P_a	1.0E05	Pa
Initial Temperature	T_0	293	K
Vent orifice coefficient	K	0.7	–
Airbag diameter	D	0.45	m
Airbag axial length	L_t	0.75	m
Airbag fabric thickness	h_0	0.25	mm
Airbag fabric elasticity	E	0.2	GPa

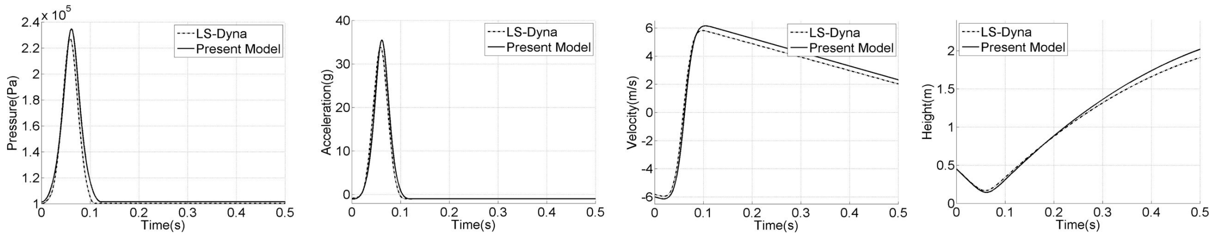

Fig. 5. Time history comparison of the airbag between the present model and LS-DYNA3D model.

6. Model validation

For the purpose of verifying the analytical model proposed in Section 5, a numerical example of a horizontal cylinder airbag system impacting on a rigid ground without vent orifice is used to simulate. And the results were compared with those results producted by the explicit nonlinear finite element program Ls-Dyna. In all the simulations we define the initial contact time as the beginning of the simulation, and some basic parameters of the numerical example are listed in Table 1.

Figure 5 shows the comparison of the time history curves between two simulations, two methods show a good agreement. The above results show that the proposed analytical method is reliable.

7. Results and discussion on vented airbag attenuating system

The influence of the airbag parameters such as airbag fabric elasticity, initial airbag pressure, and vent size on attenuating behaviour is worth investigating. Here, the airbag proposed in Section 6 will be made a vent orifice, and initial area $A_{bag} = 0.012\text{m}^2$. The vented orifice is opened when the acceleration value of payload achieves $10g$. Figures 6 to 8 shows the analysis results.

7.1. Effect of fabric elasticity

The airbag has the same parameters as Table 1, but different fabric elastic modulus will be considered. In the first case, inelastic fabric is taken into account, and set the change of fabric stretch energy ΔE_f is zero. In the subsequent cases, fabric elastic modulus values are set as 2GPa, 0.2GPa, 0.05GPa, 0.02GPa, respectively.

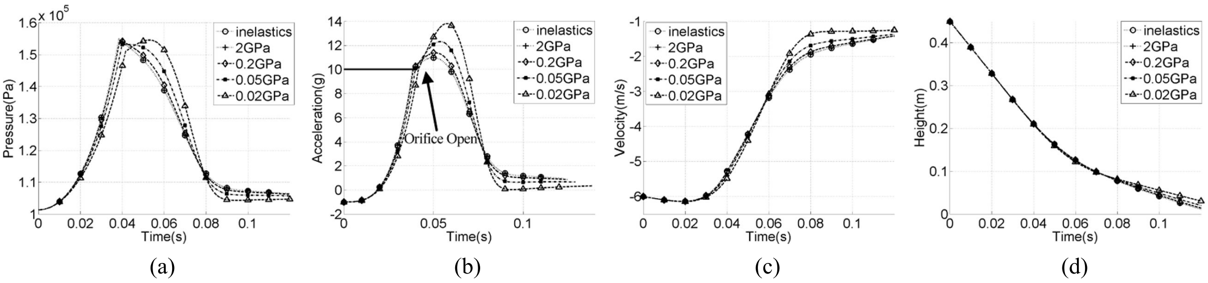

Fig. 6. Effect of fabric elasticity on cushioning characteristics.

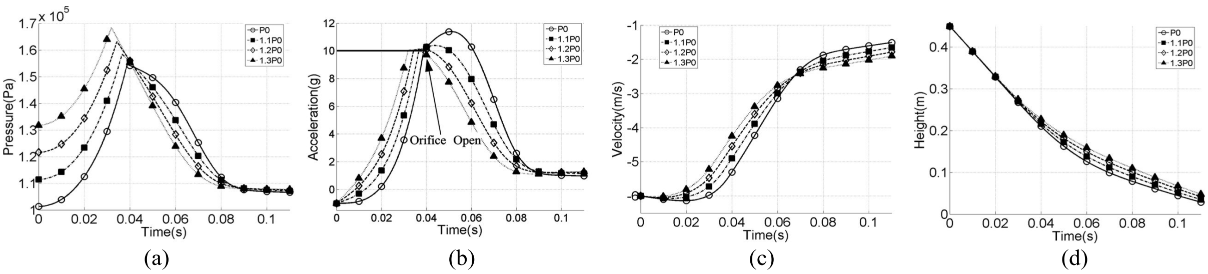

Fig. 7. Effect of initial airbag pressure on cushioning characteristics.

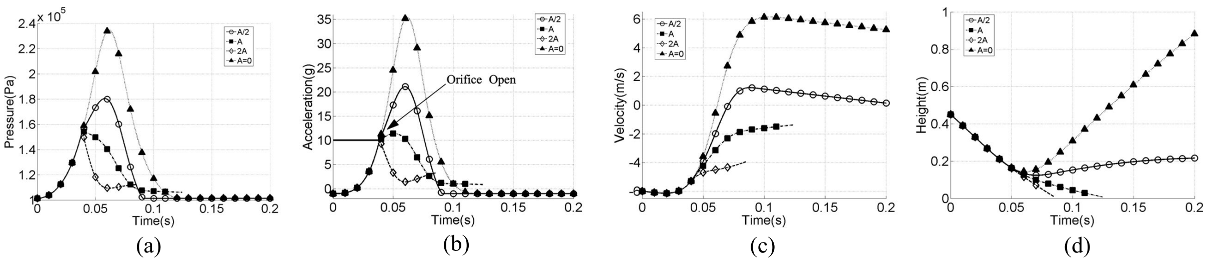

Fig. 8. Effect of venting orifice area on cushioning characteristics.

From Fig. 6, it was found that the time histories for the fabric with inelastic, 2GPa and 0.2GPa elasticity followed the same trend, and when the elasticity values were less than 0.2GPa, the affect of the fabric elasticity would be obvious. The peak values of pressure for all cases in Fig. 6a were identical, but for the 0.02 GPa elastic modulus case, occurring of peak pressure was relatively postponed compared to the other elasticity values. On the other hand, the peak acceleration of the payload for 0.02GPa elastic modulus case was relatively higher due to postponed peak pressure corresponding larger contact area.

As previously discussed, when we estimate the peak acceleration with soft material, it is necessary to consider the affect of the fabric elasticity in the process of the airbag design.

7.2. *Effect of initial airbag pressure*

To study the effect of initial airbag pressure on the cushioning characteristics, a parametric study was carried out with airbags having initial airbag pressure $P_0 = 101325$Pa, 1.1P_0, 1.2P_0, 1.3P_0. The effect of initial bag pressure on cushioning characteristics was shown in Fig. 7.

The initial airbag pressure has little effect on the final pressure and accelerations, but peak acceleration is approximately inversely proportional to the initial airbag pressure. At same time, it is found that the final velocity increases as the value of initial pressure increases, it means that the residual impact energy at the end of the impact is large. The residual velocity will produce the second rigid impact. A feasible method to avoid the second rigid impact is to use the combinations of vented and non-vented airbag.

7.3. Effect of venting orifice area

Four cases were considered for studying the effect of venting area on cushioning characteristics, and the area of vent holes is zero, $A_{bag} = 0.012m^2$, $A_{bag}/2$, and $2A_{bag}$, respectively. Figure 8 shows that four cases open their venting orifice at approximate 40 milliseconds, and the peak acceleration is the highest for the airbag model without vent hole. It is obvious that if an airbag has no vent hole then the internal pressure and the acceleration will increase quickly, and the airbag will rebound again and again. Such an arrangement would result in a disastrous landing for heavy airdrops. Figure 8 also shows that the airbag with the vent hole of area $A_{bag}/2$ can be brought to rebound with the maximum acceleration being 21g. For the case with the vent hole of $2A_{bag}$, the residual velocity is -4m/s, and only part of impact energy has been dissipated at the end of the impact because the vent hole is too large. As a matter of fact, it is necessary to optimal the area of the vent hole so as to improve the cushioning capability of the system.

8. Conclusion

Based on the energy conservation principle and thermodynamic equations, an analytical model of soft landing airbag considering the elasticity of airbag fabric was presented. The analytical model was verified by comparing with the Ls-Dyna simulation results. Then the analytical method is used to perform a parametric study of soft landing airbag with a vent hole. The airbag parameters considered include fabric elasticity, initial airbag pressure and venting orifice area. From the analysis results, the following conclusions can be drawn:

- The fabric elasticity had considerable effect on the cushioning characteristics. It is beneficial to select a fabric with higher elasticity module to decrease deceleration of the payload.
- A high initial pressure resulted in low peak acceleration, but the residual velocity has a small increase.
- An increase in vent area resulted in reduced acceleration for the payload
- The initial inflation pressure and the size of venting orifice of airbag are key parameters that affect the cushioning characteristics and should be optimized.

Acknowledgments

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References

[1] D. Northey and C. Morgan, Improved Inflatable Landing Systems for Low Cost Planetary Landers, *Acta Astronautica* **59** (2006), 726–733.

[2] J.T. Wang, An Analytical Model for an Airbag with a hybrid Inflator, AMD-Vol.30, Crashworthiness and Occupant Protection in Transportation Systems, ASME 1995.
[3] J.B. Esgar and W.C. Morgan, Analytical Study of Soft Landings on Gas-Filled Bags, Technical Report R-75, Lewis Research Center, Cleveland, Ohio.