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ScienceDirect
Defence Technology 9 (2013) 237−241
www.elsevier.com/locate/dt

Study on Multi-objective Optimization of Airbag Landing Attenuation System for Heavy Airdrop

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Received 8 November 2013; revised 29 November 2013; accepted 6 December 2013
Available online 17 December 2013

Abstract

A finite element model of vehicle and its airbag landing attenuation system is established and verified experimentally. Two design cases are selected to constrain the airbag design for extreme landing conditions, while the height and width of airbag and the area of vent hole are chosen as design variables. The optimization is forced to compromise the design variables between the conflicting requirements of the two extremes. In order to optimize the parameters of airbag, the multi-dimensional response surfaces based on extended Latin hypercube design and radial basis function are employed instead of the complex finite element model. Pareto optimal solution sets based on response surfaces are then obtained by multi-objective genetic algorithm. The results show the optimization method presented in this paper is a practical tool for the optimization of airbag landing attenuation system for heavy airdrop.

Keywords: Airbag; Multi-objective optimization; Finite element analysis; Response surface

1. Introduction

The airbag landing attenuation system is one of the most important technologies for the landing impact attenuation for heavy airdrop. There are many landing cushion technologies, such as honeycomb and retro, which normally have complicated structures and thus are very expensive. Airbag landing attenuation system is comparatively simple, convenient, efficient and cheap. It can absorb most of landing impact energy to reduce the impact force by exhausting the inflation gas through vents.

Drop tests are credible to research airbag landing attenuation system but too expensive. The safety and time are the other two key problems. Thus it is practically impossible to optimize the parameters of airbag landing attenuation system for heavy airdrop only by experimental methods. Development of simulation technology makes the problems overcome. Several simulation models of airbag were established [1−3]. It's feasible to optimize the parameters of airbag landing attenuation system for heavy airdrop using simulation technology.

In this paper, a finite element model of vehicle with airbag landing attenuation system was established based on control volume model and finite element method. The established model was validated by drop test. Furthermore, the multi-dimensional response surfaces were employed instead of the complex finite element model. Pareto optimal solution sets based on response surfaces were then obtained by multi-objective genetic algorithm.

2. Modeling and verification

2.1. FE Model of airbags

Airbag landing attenuation system consists of eight independent and identical airbags, as shown in Fig. 1. It's connected to the bottom of vehicle. Each airbag has a main

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Peer review under responsibility of China Ordnance Society.

Production and hosting by Elsevier

2214-9147/$ - see front matter
http://dx.doi.org/10.1016/j.dt.2013.12.004

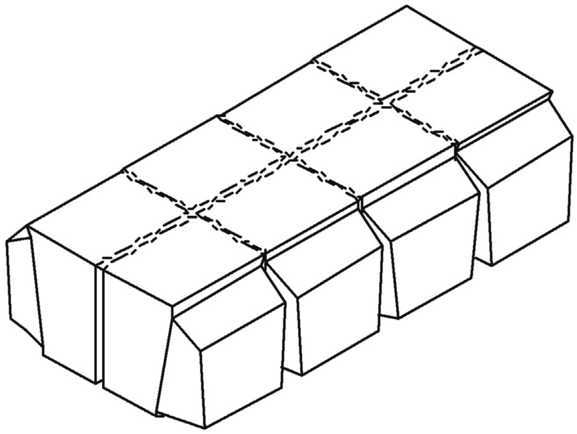

Fig. 1. Airbag landing attenuation system.

chamber and an assistant chamber connected with main chamber through communication holes. The injection holes are located in the bottom of the main chamber in order to implement air inflation when vehicle descends. When the bottoms of airbags are in contact with the ground, the injection holes are closed. The vent holes are located at the sides of airbags for exhaust. These holes are closed initially and are opened when the pressure difference between the inside and outside airbags exceeds venting pressure Fig. 1.

The model of airbag landing attenuation system can be modeled on the basis of the following assumptions [4]:

1) Perfect gas law and adiabatic condition are valid for the gas in airbag during landing process.
2) The aerodynamic resistance is negligible in the process of landing cushion.
3) The air in airbag is exhausted only through the vent holes.
4) The pressure in airbag is uniform.

The equations of the air in airbag are

$$\begin{cases} PV = mRT \\ P = (\gamma - 1)\rho E \\ \frac{\mathrm{d}E}{E} = (1-\gamma)\frac{\mathrm{d}V}{V} \end{cases} \tag{1}$$

where P is the gas pressure in airbag; V is the gas volume; m is the gas mass; T is the gas temperature; R is the gas constant; ρ is the gas density; E is the energy in airbag; and γ is the ratio of specific heat.

Airbag is regarded as expanding control volume [5]. For each time step, the gas pressure in airbag is calculated based on the thermodynamics equations. When the gas pressure acts on the elements of airbags, the shape of airbags can be then obtained. Control volume is given as

$$V = \int\int\int \mathrm{d}x\mathrm{d}y\mathrm{d}z = \oint x n_x \mathrm{d}\Gamma \approx \sum_{i=1}^{N} \overline{x}_i n_{ix} A_i \tag{2}$$

where $\overline{x}_i$ is the mean value of x coordinate values of element I; n_{ix} is the direction cosine between normal of element and x direction; and A_i is the surface area of element i.

The mass flow rate in control volume is given by the mass flow of gas injected into airbag and the mass flow of gas expulsed out of airbag.

$$\dot{m} = \dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{out}} \tag{3}$$

where $\dot{m}_{\mathrm{in}}$ is the mass flow of gas injected into airbag; and $\dot{m}_{\mathrm{out}}$ is the mass flow of gas expulsed out of airbag.

2.2. Contact model between vehicle, airbag and ground

The transformations of shape and position of airbags are very complex in the process of landing cushion. The airbags may contact with each other because of large compression deformation. Here, penalty method is adopted to describe self-contact of airbags [6]. Every side of airbags is slave surface as well as master surface. For each time step, it's checked whether the slave nodes penetrate the master surfaces first. If a slave node does not penetrate through master surface, no treatment is required. Otherwise, an interface force vector is introduced at the position between slave node and master surface. It can be modeled as a normal spring between the slave node and the master surface. The absolute magnitude of force is proportional to penetration l and master surface stiffness k_i.

$$f_s = -l k_i n_i \tag{4}$$

where f_{s} is the contact force vector between slave node and master node; and n_i is the normal unit vector in contact point of master surface S_i.

The contact between airbag landing attenuation system and vehicle is described by tied contact model. The bottom of simplified vehicle model is defined as master surface, while the top of airbag landing attenuation system is defined as slave surface. With a tied contact model, it is possible to connect rigidly the slave surface nodes with a master surface. This kinetic constraint is applied on all slave nodes. They remain at the same position on their master surfaces. The acceleration and velocity of each master node are calculated from the force and mass applied by the slave nodes.

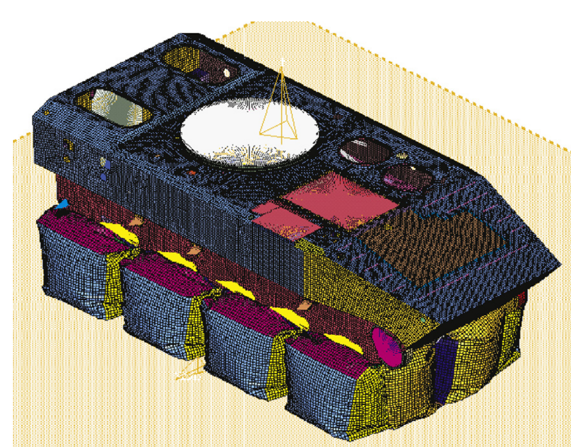

Fig. 2. Finite element model.

The ground is modeled as an infinite plane. The contact between airbags and ground is described and solved by penalty method, too. The FE model of vehicle and airbags cushion system is shown in Fig. 2.

2.3. Result verification

The FE model was established based on the simplifications and assumptions. Thus, the model should be validated by experiment because of unexpected errors. The test data is obtained from the drop test which was thoroughly discussed in Ref. [7]. The initial vertical velocity is 7.0 m/s, the initial horizontal velocity is 0 m/s, and the ground is flat. The accuracy of the model was validated by the comparison of acceleration results, as shown in Fig. 3.

As shown in Fig. 3, the curves of simulation and experiment match well with each other. The error of maximal acceleration is 8.1%. Thus, the established model can be used for further research.

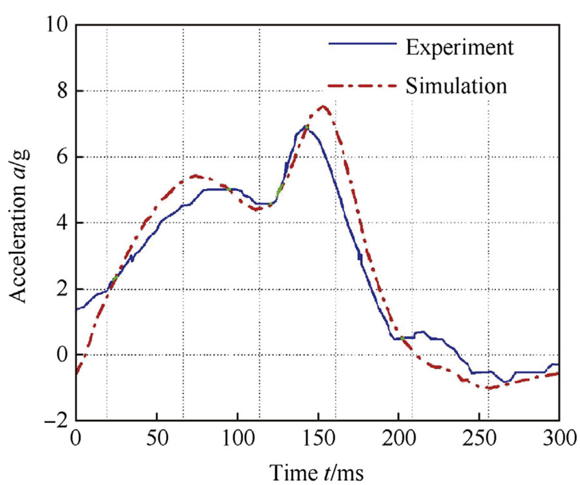

Fig. 3. Result comparison.

3. Response surfaces

3.1. Response surface method

Airbag landing attenuation system offers an attractive means of impact attenuation for heavy airdrop. Design optimization of airbag landing attenuation system relies on explicit finite element analysis because of the non-linear behavior of cushion characteristics and the difficulty of adequate airdrop test. However, the simulation of an impact typically requires tens of hours. As a result, it is difficult to use the traditional iterative approach to optimize the design based on a nonlinear model. The response surface method presents a methodology for overcoming these problems with design optimization of airbag landing attenuation system for heavy airdrop.

A response surface [8] gives the value of a key output variable in the design space as a function of design variables. In response surface modeling approach, the response surfaces are approximated from a relatively small number of FE analysis runs by using surface-fitting algorithms. The response surface method can be used to solve optimization problem with minimal computational effort.

The success of the response surface modeling approach depends on the quality of the response surface approximations. These must reproduce highly non-linear response functions over a large parameter space from only a limited number of analyzed points. The quality of the response surface approximations is determined by selecting the sampling points in the parameter space and the surface-fitting algorithm through the sample points.

3.2. Extended Latin hypercube design

The choice of the sampling points is important for generating response surface. There are different methods to select the locations of the sampling points. As one of these methods, the efficiency of Latin hypercube design was proven for wide range of applications. Latin hypercube design developed by McKay et al. [9] is an alternative approach which can yield precise estimates of output statistics with a lesser number of samples. The Latin hypercube samples are random but are guaranteed to be relatively uniformly distributed over each dimension.

In practice, Latin hypercube design can be obtained as follows. The range of each design variable is divided into n non-overlapping intervals on the basis of equal probability. One value from each interval is selected at random with respect to the probability density in the interval. The n values thus obtained for x_1 are paired in a random manner with the n values of x_2. These n pairs are combined in a random manner with the n values of x_3 to form n triplets and so on. A similar procedure is followed for x_4, ..., x_n, which exhausts all observations and results in n LHD points. In this design, the points are generated randomly. But The Latin hypercube samples can be iteratively generated to find the best one according to careful design criterion.

Extended Latin hypercube design is a Latin hypercube design with the addition of the corner points in the parameter space. This ensures that the extreme parameter combinations are included in the analyzed set and give a uniform filling of

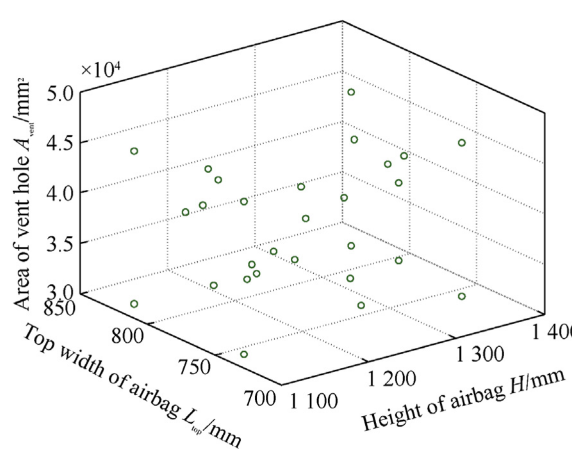

Fig. 4. Extended Latin hypercube design.

the design space. For the design optimization of airbag landing attenuation system, 3 variables were considered and 28 combinations of these parameters obtained by extended Latin hypercube design were sought as sampling points for the FE analysis runs, as shown in Fig. 4.

3.3. Response surface fitting

The response values are obtained according to the simulation of FE analysis runs. Most literature about airbag design optimization just considered vertical landing case. However, the landing environment is commonly complex. Two design cases were selected to constrain the airbag design. In Case 1, the contact area with the ground is maximized in the case of vertical impact. Relatively tall profile is required to reduce the impact force, but it makes vehicle stability worse. In Case 2, high lateral landing velocity component, pitch-down angle and upper slope landing site are added. This case tends to push the airbag design towards a larger plane area. Relatively short profile is better for stability.

28 FE analysis runs are performed for each landing case (i.e., a total of 56 runs) for the design parameter combinations. The response values listed were then extracted from the FE analyses. The response surfaces are fitted to the analysis results using radial basis function. The response surfaces at a vent area of 38,000 mm^2 are shown in Figs. 5 and 6.

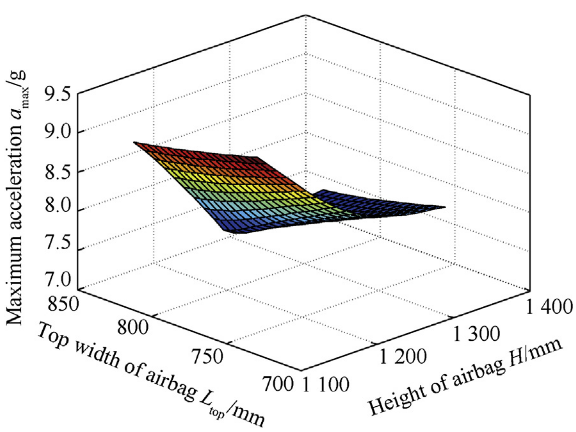

Fig. 5. Acceleration response surface.

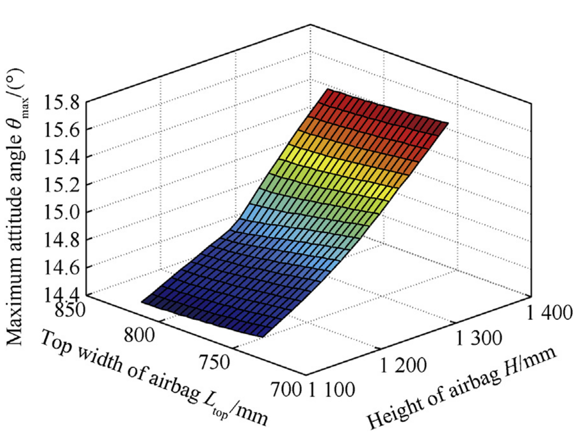

Fig. 6. Attitude angle response surface.

4. Multi-objective optimization

4.1. Optimization analysis

Here the height and width of airbag and the area of vent hole are chosen as design variables, while the objective of the optimization is to minimize the maximum acceleration and the maximum attitude angle. It's a multi-objective optimization problem. There is no unique solution to this problem. Instead, the concept of non-inferiority (also called Pareto optimality) must be used to characterize the objectives. A non-inferior solution is one in which an improvement in one objective requires a degradation of another. The mission of multi-objective optimization is to work out a set of non-inferior solutions.

Multi-objective genetic algorithm can solve the type of problem efficiently. NSGA-II (fast elitist non-dominated sorting genetic algorithm) is one of better elitist multi-objective genetic algorithms [10]. It reduces the computational complexity, assures the preservation of previously found best solutions, and makes the algorithm independent of users. Thus, considering both cushion performance and stability, a set of non-inferior solutions and the Pareto front are obtained by NSGA-II based on response surfaces, as shown in Fig. 7 and Table 1. The Pareto front PF* is defined as $PF^* = \{\vec{f}(\vec{x}) \mid \vec{x} \in P^*\}$, where P is a set of all non-inferior solutions.

The Pareto plot displays two competing objectives. The horizontal axis is the maximum acceleration, while the vertical axis is the maximum attitude angle. In Fig. 7, there are 14 points on the Pareto front. A set of Pareto solutions include the 14 points. The final design parameters can be chosen from the 14 points. The 3 non-inferior solutions in left lower part of Fig. 7 have smaller acceleration and attitude angle. For other solutions, an improvement in one objective requires a relatively large degradation of another objective. The 3 non-inferior solutions are the 1st solution, the 3rd solution and the 14th solution listed in Table 1. Compared with the other two solutions, the cushion performance of the 1st solution is obviously improved, while the stability is not worse. Thus the 1st solution is chosen as optimized solution.

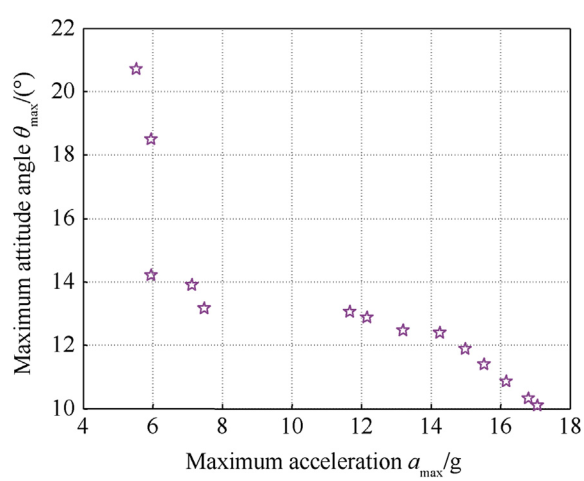

Fig. 7. Pareto front.

Table 1
A set of Pareto solutions.

No.	Area of vent hole A_{vent}/mm^2	Height of airbag H/mm	Top width of airbag L_{top}/mm	Maximum acceleration a_{max}/g	Maximum attitude angle θ_{max}/(°)
1	30,939	1357	798	5.97	14.21
2	33,805	1350	780	5.55	20.71
3	34,809	1345	785	7.13	13.90
4	42,034	1217	790	15.55	11.39
5	42,218	1202	791	17.07	10.08
6	37,608	1254	789	13.21	12.47
7	41,978	1204	789	15.00	11.87
8	41,975	1291	795	14.27	12.40
9	42,147	1203	790	16.81	10.32
10	42,091	1216	790	16.17	10.86
11	37,741	1229	788	12.17	12.86
12	37,249	1230	786	11.69	13.06
13	33,329	1339	789	5.97	18.48
14	34,631	1222	756	7.49	13.17

4.2. Comparison of airbags cushion characteristics

In order to estimate the improvement of airbags cushion performance and stability, the optimized velocity, acceleration, pressure inside airbags, residual energy and attitude angle are compared with the original results, as listed in Table 2.

As listed in Table 2, the landing velocity is decreased from 2.20 m/s to 0.73 m/s, and the maximum acceleration of airborne vehicle is decreased by 16%. The maximum pressure inside airbags is slightly increased. Because the energy absorption performance of airbags is improved, the residual energy of the system is decreased by 23%. The maximum attitude angle is decreased in Case 2. Overall, the cushion performance of airbags cushion system is obviously improved after optimization, while the stability is slightly improved. It indicates that the optimization method presented in the paper is feasible to such complex nonlinear problem.

5. Conclusions

1) A FE model of vehicle and its airbag landing attenuation system was established on the basis of volume control model in this paper. The established model was validated by drop test. The simulation results agree very well with the experimental results.
2) In order to optimize the parameters of airbags, the multi-dimensional response surfaces based on extended Latin hypercube method and radial basis function were employed instead of the complex finite element model. The method overcomes the difficulties in traditional iterative optimization method.
3) The cushion performance of airbags cushion system is obviously improved after optimization, while the stability is slightly improved. It indicates the optimization method presented in the paper is feasible to such complex nonlinear problem.

Table 2
Comparison of simulation results and original values.

Response	Original value	Optimized value	Relative variation
Landing velocity v_{land}/(m s^{-1})	2.34	0.73	69%
Maximum acceleration a_{max}/g	7.42	6.22	16%
Maximum pressure P_{max}/kPa	140.89	144.33	2%
Residual energy $E_{residual}$/kJ	48.37	37.01	23%
Maximum attitude angle θ_{max}/(°)	14.75	13.38	9%

References

[1] Wang YE, Yang CX, Peng K. Airbag cushion process simulation for cargo airdrop system. J Syst Simul 2007;19(14):3176–9 [in Chinese].
[2] Le YX. Numerical simulation and optimal design of the process of airbag landing. Changsha: Hunan University; 2010 [in Chinese].
[3] Taylor AP. Investigation of the application of airbag technology to provide a softlanding capability for military heavy airdrop. AIAA 2001-2046; 2001. pp. 284–92.
[4] Hao GX. Research on impact responses of airborne tracked equipment and parameter optimization for airbag system. Beijing: Academy of Armored Forces Engineering; 2011 [in Chinese].
[5] Wang JT, Nefske JD. A new CAL3D airbag inflation model. SAE Paper No.880654; 1988.
[6] Wang XC. Finite element method. Beijing: Tsinghua University Press; 2003 [in Chinese].
[7] Du ZQ, Shao PL. Dynamic finite element simulation of the aluminum alloy hull at landing. Acta Armamentarii 2009;30(1):1–4 [in Chinese].
[8] Box GEP, Wilson KB. On the experimental attainment of optimum conditions. J R Stat Soc 1951;13:1–45.
[9] McKay MD, Conover WJ, Beckman RJ. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics 1979;21(2):239–45.
[10] Deb K, Pratap A, Agarwal S, Meyarivan T. A fast and elitist multi-objective genetic algorithm:NSGA-II. IEEE Trans Evolut Comput 2002;6(2):182–97.