Optimization of Adaptive Restraint System for Vehicle Frontal Impact

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Abstract: In order to provide more comprehensive protection for occupant, optimization design of vehicle restraint system was conducted. The simulation model established was validated at the condition of 50 km/h full frontal crash. With this validated model we performed the design of experiments，parameter sensitivity analysis and design optimization. The following parameters were selected for optimization: Diameter of airbag ventilation hole, mass rate of gas flow, belt load level of seatbelt, length of the preload pretensioners. This optimized model was evaluated by the simulation with 50 percentile Hybrid III and reduction of WIC with 29.82% was obtained. Also, we studied the restraint efficiency with 5 percentile Hybrid III occupant dummy based on the optimized model. In case of this small dummy the gas flow rate of airbag inflator and the belt load level of the seatbelt were optimized. After optimization either 50 percentile Hybrid III occupant or 5 percentile Hybrid III occupant could be well protected.

Keywords: frontal crash; restraint system; model validation; design optimization

1. Introduction

Against the background of an always growing traffic volume on the roads and the thereby resulting aim to reduce the number of traffic fatalities continuously, in the recent years a number of research projects and field studies were performed. As a result of this, legal tests and consumer requirements have been strongly tightened. Consequently, car manufacturers and suppliers are faced with completely new challenges as to the development of adaptive occupant restraint systems. Such systems gained more and more importance.

The literature study shows that smaller sized occupants are prone to be injured more than mid sized occupants in the crash accidents[1]. The reason is that most restraint systems are designed for an average size of occupant anthropometry. Due to various sizes of occupant, it is difficult to protect them with fixed restraint system. According to the another study, the adaptive restraint system may offer improved safety of different sized occupants[2]. Adaptive systems use various vehicle sensor inputs to adjust parameters of the restraint system. Thus, the vehicle restraint performance can be “tailored” to the crash and the individual occupant situation at the time of the accident. Dependent upon the vehicle, the adaptive aspects may include any of the following in many different combinations: airbag vents, mass flow rate of airbag inflator, variable airbag opening time, seat belt force limiters, variable pretensioning force.

As the characteristics of airbag depend on inflator mainly and seat belt on load limiter[3], mass flow rate of airbag inflator and the characteristics of seat belt force limiters were selected as parameters for designing real adaptive system in the study. The current paper aim is to design an adaptive restraint system which can protect well both 50 percentile and 5 percentile occupant represented by Hybrid III. In order to optimize the performance of restraint system components without spending a lot of time, CAE should be involved[4].

2. Numerical Methods

2.1. Frontal Impact Simulation Model

The simulation model was developed based on a domestic car. It includes airbags, seat belts, steering column, steering wheel, instrument panel, knee pad, accelerator pedal, windshield, seats and dummy model. Various features used in the development of the model of restraint system, such as stiffness of seat belt and seat, characteristics of the airbag gas generator, were obtained from the experimental measurements. In order to improve computational efficiency, the airbag and seat belts, which contact with the dummy, were developed by the finite element model, and other parts were established by multi-body model. Algorithm of uniform pressure was used to calculate the deployment of the airbag. Airbag system consists of two-stage triggered gas generator. Seat belt systems include pre-tensioners and force limiters. To represent the occupant the 50 percentile and 5 percentile Hybrid III test dummies were used. The location of 5 percentile Hybrid III test dummy was about 12 cm more forward than 50 percentile Hybrid III dummy. Developed model of restraint system and location of the

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dummies are shown in Figure 1 and Figure 2. We simulated full front crash collision at the speed of 50 km/h as the requirement of C-NACP, the simulation pulse is shown in Figure 3.

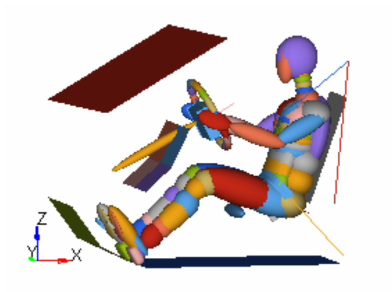

Figure 1. 50th Hybrid III percentile dummy

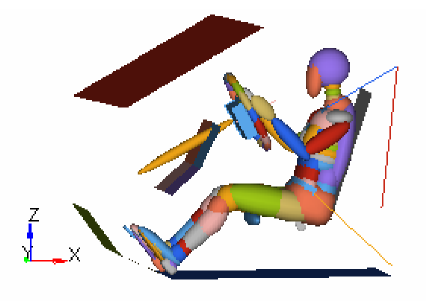

Figure 2. 5th Hybrid III percentile dummy

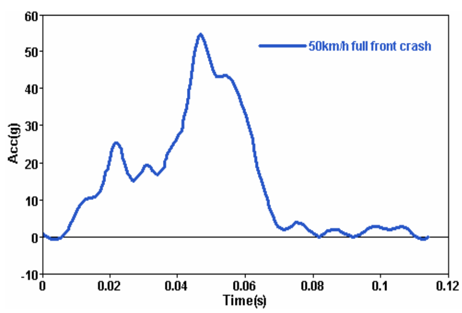

Figure 3. Crash pulse

2.2. Model Validation

In the study, the restraint system with 50 percentile Hybrid III dummy at the speed of 50 km/h was validated. The validation follows the principle "from bottom to top". It was completed by comparing the numerical simulation results with the experimental findings from the test obtained from car company. In the validation the head, chest, pelvis resultant accelerations and shoulder belt load were compared. The comparison of head and chest accelerations resultant of MADYMO model and crash test results were shown in Figure 4 and Figure 5.The results of the simulation model and experimental were in good agreement, the differences were within 15%. Therefore, the simulation model was accepted to study on optimization of the restraint system.

2.3. Occupant Injury Assessment Criteria

Effectiveness of occupant restraint system affects the protection level of the human body. Therefore, evaluation of these systems should be based on the injury criteria of human body. At present, Weighted Injury Criterion (WIC) is used in the domestic and international standards to comprehensively evaluate the performance of occupant restraint system. Lower the WIC value indicates the better protective properties of restraint system. The evaluation function is defined as follows:

$$WIC=0.6(HIC_{36}/1000)+0.35(C_{comp}/0.0762)+0.05(F_{femur}/10) \qquad (1)$$

the chest deflection in m; F_{femur} is the thigh force in kN; Denominators in the formula are the corresponding standard damage value of FMVSS208.

As the position the women is rather forward, the pressure in expanding air bags designed for males generate a high contact force especially in case of small sized women, so neck bending moment and neck tension values can be too large. In order to investigate this problem on the combined effects to head and neck, we used weighted damage value (I).

$$I = 0.5\times\frac{HIC}{1000}+0.25\times\frac{M_y}{57}+0.25\times\frac{F_z}{3300} \qquad (2)$$

where HIC is the Head Injuries Criteria, M_y is the neck bending moment in Nm, F_z is neck force in N; Denominators in the formula are the corresponding standard damage value of FMVSS208.

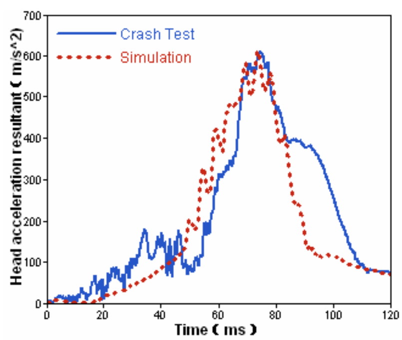

Figure 4. Head acceleration resultant

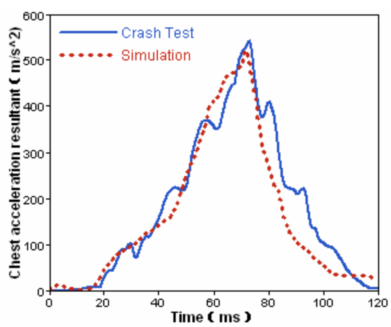

Figure 5. Chest acceleration resultant

3. Optimization Method

3.1. Parameter Sensitivity Analysis

The main influence on passengers safety in frontal impact are diameter of airbag ventilation hole, airbag ignition timing, mass rate of gas flow, seat belt webbing stiffness, size of force limiters, length of the preload pretensioners, and seat stiffness. Optimization design was conducted based on parameters summarized in Table 1.

Table 1. Levels of the Design Parameters

	Design parameter	Level 1	Level 2	Level 3
A	Diameter of airbag ventilation hole	0.7	1.0	1.3
B	Airbag ignition timing	0.01	0.015	0.02
C	Mass rate of gas flow	0.7	1.0	1.3
D	Seat belt webbing stiffness	0.7	1.0	1.3
E	Size of load limiters	0.7	1.0	1.3
F	Length of the preload pretensioners	0.7	1.0	1.3
G	Seat stiffness	0.7	1.0	1.3

Using Orthotropic Experiment Technology [5], analysis of variance was done. The Orthotropic Experiment design is shown in Table 2. The significance of the parameters is correlative with F_1 value. Larger value means greater the significant.

Table 2. Orthogonal experimental design

Test NO.	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2
3	1	3	3	3	3	3	3
4	2	1	1	2	2	3	3
5	2	2	2	3	3	1	1
6	2	3	3	1	1	2	2
7	3	1	2	1	3	2	3
8	3	2	3	2	1	3	1
9	3	3	1	3	2	1	2
10	1	1	3	3	2	2	1
11	1	2	1	1	3	3	2
12	1	3	2	2	1	1	3
13	2	1	2	3	1	3	2
14	2	2	3	1	2	1	3
15	2	3	1	2	3	2	1
16	3	1	3	2	3	1	2
17	3	2	1	3	1	2	3
18	3	3	2	1	2	3	1

In this study, F_{femur} has little influence on the value of WIC, so we only considered the variance of HIC_{36} and C_{comp}. The influence of the parameters on HIC_{36} is shown in Table 3. It shows that when comparing F_1 values the strongly significant parameters are diameter of airbag ventilation hole, mass rate of gas flow, size of load limiters and length of the preload pretensioners.

Table 3. Analysis of variance of HIC_{36}

	A	B	C	D	E	F	G
F_1	2.322	0.044	0.634	0.221	1.533	1.363	0.884

The influence of the parameters on C_{comp} is shown in Table 4. It shows that strongly significant factors are diameter of airbag ventilation hole, mass rate of gas flow, size of load limiters ,length of the preload pretensioners and seat stiffness.

Table 4. Analysis of variance of C_{comp}

	A	B	C	D	E	F	G
F_1	2.322	0.044	0.634	0.221	1.533	1.363	0.884

After considering the variance of HIC_{36} and C_{comp} ,we choose diameter of airbag ventilation hole, mass rate of gas flow, size of load limiters and length of the preload pretensioners as the design parameters.

3.2. Optimization Model

In the study we decided use the response surface regression method as the objective function to search for the optimal experimental conditions. Response surface method is an approximate model, initially used in the fitting of physical experiments, as later applied in a variety of optimization area[6]. Response surface design is a statistical method that uses reasonable experimental data in quadratic regression equation to fit the functional relationship between multiple factors and response values, searching for the optimal combination of process parameters through the analysis of the regression equation and solving multi-variable problem. This method is derived from the quadratic function model, because this function often can be a good approximation. The general expression of response surface regression model is:

$$f(x) = \beta_0 + \sum_{i=1}^{m} \beta_i x_i + \sum_{i=1}^{m} \beta_{ii} x_i^2 + \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \beta_{ij} x_i x_j \tag{3}$$

where $f(x)$ is the objective function, m is the total number of design variables, x_i is the ith design variable, and the is the unknown coefficient of each polynomial term.

In order to obtain optimization equations regression method was used. Design parameters were selected to Full Factorial Design (FFD) [5] to obtain the MADYMO simulations results of the combination of different levels of design parameters. Results from the MADYMO were used to form surrogate model. The most important statistical parameter used for evaluation of model fitness is coefficient of determination R^2. Generally speaking, the closer the values of R^2 to one, the error of mathematical model is smaller and the fit is better. Usually when R^2 is more than 0.90, the optimized model is accepted.

3.3. Non-Dominated Sorting Genetic Algorithm

Non-dominated Sorting Algorithm (NSGA-II) is based on a fast non-dominated sorting approach and a selection operator creating a mating pool by combining the parent and offspring populations and selecting the best (with respect to fitness and spread) solutions. NSGA-II, in most problems, is able to find much better spread of solutions. Initially, a random parent population is created. The population is sorted based on the non-domination. Each solution is assigned a fitness (or rank) equal to its non-domination level. Thus, minimization of fitness is assumed. At first, the usual binary tournament selection, recombination, and mutation operators are used to create an offspring population of size [7] [8].

4. Results and Discussions

4.1. Optimization of Restraint System Evaluated with 50 Percentile Hybrid III Occupant Dummy

We used FFD to obtain the MADYMO simulations results of the combination of different levels of design parameters. Results from the MADYMO were shown in Table 5. It is adopted to form surrogate model. The solution obtained from iSIGHT software by using Non-dominated Sorting Genetic Algorithm.

Table 5. Full Factorial Design of 2^4

Test No.	A	C	E	F	WIC
1	0.7	0.7	0.7	0.7	0.7924
2	0.7	0.7	0.7	1.3	0.7906
3	0.7	0.7	1.3	0.7	0.8000
4	0.7	0.7	1.3	1.3	0.7593
5	0.7	1.3	0.7	0.7	0.6975
6	0.7	1.3	0.7	1.3	0.7014
7	0.7	1.3	1.3	0.7	0.7390
8	0.7	1.3	1.3	1.3	0.7120
9	1.3	0.7	0.7	0.7	0.6309
10	1.3	0.7	0.7	1.3	0.6317
11	1.3	0.7	1.3	0.7	0.6789
12	1.3	0.7	1.3	1.3	0.6489
13	1.3	1.3	0.7	0.7	0.5017
14	1.3	1.3	0.7	1.3	0.4841
15	1.3	1.3	1.3	0.7	0.4941
16	1.3	1.3	1.3	1.3	0.4620

Using equation (3) the second-order response surface model of WIC is:

$$\begin{aligned} WIC = {} & \beta_0 + \beta_1 A + \beta_2 C + \beta_3 E + \beta_4 F + \beta_{12} AC \\ & + \beta_{13} AE + \beta_{14} AF + \beta_{23} CE + \beta_{24} CF + \beta_{34} EF \\ & + \beta_{11} A^2 + \beta_{22} C^2 + \beta_{33} E^2 + \beta_{44} F^2 \end{aligned} \tag{4}$$

According to the 16 groups design points in Table 2 we determined the value of β_x by the least square method. After calculation of β_x the equation of WIC is:

$$\begin{aligned} WIC = {} & 0.9084 - 0.2474AC + 0.0051AE - 0.0094AF \\ & - 0.0131CE - 0.0008CF - 0.0796EF - 0.0263A^2 \\ & + 0.0327C^2 + 0.0504E^2 + 0.0298F^2 \end{aligned} \tag{5}$$

From Table 5 we can calculate the R^2 of WIC that reach 0.996 also the model is reliable.

Using Equation 5 we calculated the design point when the WIC reach the minimum. It was found that at the point (A=1.3, C=1.3, E=1.13, F=1.3) the value of WIC is so low as 0.469. At this point, the WIC value from MADYMO simulation is 0.456. The relative error between the solution from response surface model and the result from simulation is less than 3%, so we can say that the convergence condition of optimization is achieved and the optimization process end. The WIC value from MADYMO simulation of optimal solution is about 30% lower than one from the simulation of the initial design that was 0.6498.

4.2. Optimization of Restraint System with 5 Percentile Hybrid III Occupant Dummy

The optimization of restraint system with 5 percentile Hybrid III occupant dummy we started with the set of parameters obtain from former optimization. The experimental design including mass rate of gas flow and the size of force limiters and the corresponding values of I calculated from MADYMO are shown in Table 6.

Table 6. Full Factorial Design of 3^2

Test No.	C	E	I
1	0.7	0.7	0.3697
2	0.7	1	0.3885
3	0.7	1.3	0.3972
4	1	0.7	0.3745
5	1	1	0.4263
6	1	1.3	0.3961
7	1.3	0.7	0.4877
8	1.3	1	0.4984
9	1.3	1.3	0.5257

Using the same methodology as in case using the 50 percentile dummy, we obtained the second-order response surface model of I:

$$\begin{aligned} I = {} & 0.5563 - 0.8435C + 0.2991E + 0.029CE \\ & + 0.5063C^2 - 0.1398E^2 \end{aligned} \tag{6}$$

From Table 6 we can calculate the determination coefficient value of I reached 0.967. Using Equation 6, the I value reach the minimum 0.3625 at the design point (C=0.813, E=0.7). At this point, the I value from MADYMO simulation is 0.3645, the relative error between the solution of response surface model and the of simulation have been small enough to meet the convergence condition. The I value from MADYMO simulation of optimal solution is about 29% lower than one from the simulation of the initial design that was 0.5106.

5. Conclusion

Simulation model of restraint system for frontal impact was developed based on multi-rigid-body theory. Optimization was conducted applying response surface method. With the methodology of design of experiments, diameter of airbag ventilation hole, mass rate of gas flow, the size of force limiters and the length of the preload pretensioners were found to be strongly influencing WIC value of 50 percentile Hybrid III dummy. The head and neck evaluation index I of 5 percentile Hybrid III dummy was reduced after optimal design of mass rate of gas flow and the level of force limiters. Optimization results show that adaptive restraint system can expand the scope of protection and improve the protective effect. The application of sensitivity analysis and response surface method to optimize restrained systems have high efficiency and reliability.

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References

[1] Iyota, T. (2003) The effect of occupant protection by controlling airbag and seatbelt, 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan.

[2] Holding, P.N., Chinn, B.P., Happian-Smith, J. (2001) An evaluation of the benefits of active restraint systems in frontal impacts through computer modeling and dynamic testing. International Technical Conference on the Enhanced Safety of Vehicles, Amsterdam, Netherlands.

[3] Shin, H. S., Yeo ,T. J., Ha, W. P. (2007) The Numerical Study for the Adaptive Restraint System. SAE World Congress, Detroit, Michigan

[4] TNO Automotive Safety Solutions.(2005) MADYMO R6.3 Applications. Netherlands: TNO Automotive Corporation, 2005: 91-102.

[5] Liu, W.Q. (2005). Experimental Design. Beijing: Publishing Company of Qinghai University.

[6] Myers, R.H., Montgomery,D.C., (2002) Response Surface Methodology：Process and Product Optimization Using Designed Experiments., John,W., New York,

[7] Kalyanmoy D., Pratap, A., Agarwal, S. (2002). A fast and elitist multi-objective genetic algorithm: NSGA-II. IEEE Trans. Evolutionary Computation, 182-197.

[8] Srinivasa, D. (1995). Multi-objective function optimization using non-dominated sorting genetical algorithms. IEEE Trans. Evolutionary computation, 154-159.