Multi-objective Optimization of Child Restraint System for Vehicle Side Impact

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Abstract: To minimize head and thorax injuries of child passengers in side impact, multi-objective optimization design of vehicle child restraint system (CRS) was conducted. The mathematical model of child seat, side airbag and child was developed and its validity was verified. Based on the validated model we performed the optimization containing design of experiments, parameter sensitivity analysis, full factorial design (FFD) and optimization using non-dominated sorting genetic algorithm (NSGA-II). The results indicated that location of top tether in X-direction, stiffness coefficient of lower anchorage and materials permeability of side airbag have significant influence on child passengers head and thorax protection. After optimization the three parameters could achieve reasonable configuration, meanwhile, child passengers head and thorax accelerations were controlled on low level.

Key words: Child passengers, CRS, NSGA-II, Multi-objective optimization

1 Introduction

Global accident statistics showed that side impacts account for approximately 30% of all impacts and 35% of the total fatalities (German In Depth Accident Study - GIDAS, National Automotive Sampling System - NASS & BMW accident databases)[1]. Langvider et al. [2] found that when velocity of striking vehicle is up to 50 km/h, younger children (0-3 years) showed a relatively high injury risk. He also found that intrusion of door of struck vehicle is the cause of relatively high risk of serious or fatal injuries to child passengers.

Newgard et al. (2005) found that child occupants seated on the near-side or middle-seat in a lateral crash had a higher probability of serious thorax-abdominal injury compared to far-side occupants. The severity of the injury is correlated to the relative velocity between the child occupant and the vehicle structure (Bendjellal et al, 2006) [3]. Child restraint system (CRS) when used correctly have been proven to be an effective method to mitigate injury and death for children in motor vehicle crashes (Arbogast et al., 2004) [4]. CRSs are attached to car seat using various anchorage devices. According to FMVSS 213 regulations, a CRS is tested for both with and without top tether conditions. Inside a vehicle, the use of a top tether strap is mandatory in conjunction with both lower anchorage and tethers for children (LATCH) and lap seat belt.

Occupant restraint system includes all the device protecting passengers in vehicle accidents. Usually, based on the vehicle occupant restraint system the CRS in form of a child seat is added to reduce injuries of children. The entire restraint system includes a number of subsystems, have complex input signal and multi-objective output signal. Child injury values, including such parameters as HIC value, head and chest 3 ms value, chest deflection, neck deformation, are influenced not only by the acceleration, deformation and collision force but also by the way how the CRS is applied.

There are experimental and mathematical methods to study CRS. Experimental method is very good to validate the dynamic response of protection systems in collision, but the cost is high. It is also difficult to ensure repeatability of experiments. Mathematical method can simulate the collision process and also evaluate effect of protection systems using mathematical models of all elements involved in crash that has good repeatability. Also the precise simulations results using accurate mathematical models are closer to these from real collisions. Therefore mathematical simulations are an effective analysis method at the vehicle design process.

Based on findings from literature review, in current study aimed on optimization of CRS a multi-objective optimization of CRS was carried out by using Non-dominated Sorting Genetic Algorithm. A CRS side impact simulation model was developed by applying multi-body dynamics software MADYMO, design parameters were chosen using experimental design (DOE) technology and the regression of surrogate model was performed.

2 Methodology

2.1 Numerical Methods

2.1.1 Model Development

The simulation model was developed (Fig.1). It includes the rear seat, rear door, child seat model, side airbag model and Hybrid III 3-year-old child dummy model. The vehicle seat composes of 2 hyper-ellipsoids and is defined as a rigid body. They represent seat cushion, and seat back. The configuration of the child seat was developed based on some brand product. It is adapted to child whose age is from 0 to 3 years old. The Hybrid III 3-year-old child dummy and side airbag from the MADYMO database were used. The 5-points belt integrated in the child seat is of hybrid type, and is composed with rigid-body and FE part. While the LATCH and top tether belts for CRS are modeled as rigid.

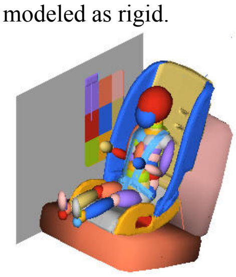

Fig.1. Simulation model

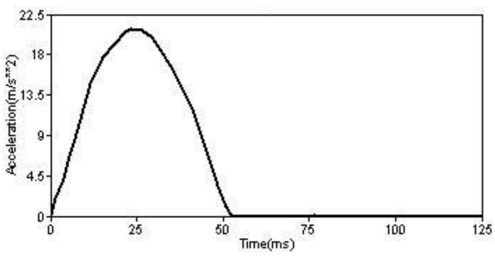

Fig.2. Simulation pulse

2.1.2 Children injury assessment criteria

Usually in side collisions the research on injuries to various body regions is focused on head, neck, thorax, abdomen and pelvis. However it was found that for a three year old child the injury to head and thorax are overrepresented [5]. Therefore, child head and thorax resultant acceleration were chosen for optimization objectives.

2.1.3 Model Validation

Simulation model validation was completed by comparing the numerical simulation results with the experimental findings from the side impact tests conducted by NTHSA at research center in 2001[6]. The acceleration pulse used in the tests is illustrated in Fig.2. In the validation the lateral head and chest acceleration were compared.

The experimental and numerical results are illustrated in Fig.3 and Fig.4. The numerical model over predicted the head and thorax Y-acceleration from experimental tests by less than 15%, therefore, it was accepted to study about optimization of the CRS.

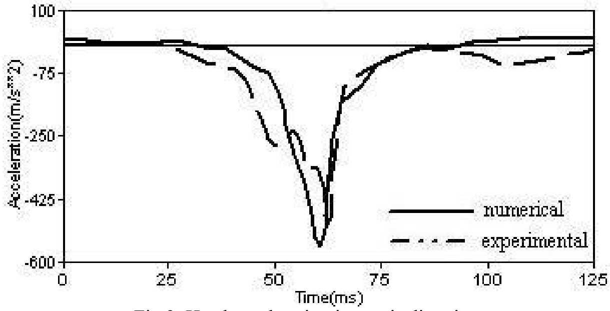

Fig.3. Head acceleration in *y*-axis direction

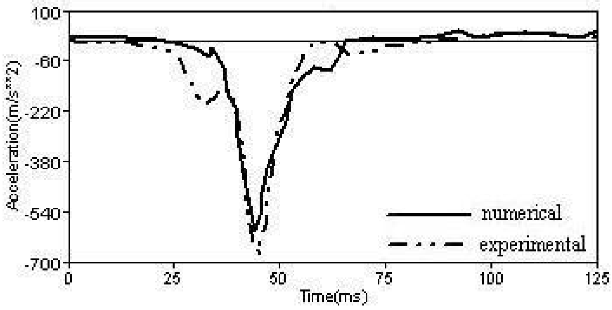

Fig.4. Thorax acceleration in *y*-axis direction

2.2 Optimization Methods

2.2.1 Analysis of Parameters Sensitivity

The main influence on child passengers safety have side airbag (1), child seat installation method (2), the interaction between child seat and car seat (3), and also child seat design parameters. The last parameter was extensively researched by other authors [7] and is not included in our optimization. Using Orthotropic Experiment Technology [8], analysis of variance and the most sensitive factors were chosen. 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
DP1	Mass flow rate function (1)	0.8	1.0	1.2
DP2	Constant factor for permeability of the material (1)	0.02	0.04	0.06
DP3	Trigger time (1) [sec]	0.005	0.01	0.015
DP4	Airbag volume (1) [L]	0.8	1.0	1.2
DP5	Location of top tether in X-direction (2) [m]	-0.25	-0.35	-0.45
DP6	Stiffness coefficient of lower anchorage (2)	0.5	1.0	1.5
DP7	Friction coefficient between child seat and vehicle seat (3)	0.2	0.5	0.7

The Orthotropic Experiment design is shown in Table 2. The significance of the parameters is correlative with P value. Usually two levels of significance are used: $P \leq 0.01$ indicates the factor that is strongly significant, $0.01 \leq P \leq 0.05$ indicates the factor is significant. In the study all the parameters with level of $P \leq 0.05$ are selected to further optimization.

Table 2 Orthogonal experimental design

Test NO.	DP 1	DP 2	DP 3	DP 4	DP 5	DP 6	DP 7
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

2.2.2 Multi-objective optimization model

Many search and optimization problems in science and engineering involve constraints and multi-objectives and can be treated as multi-objective optimization problems. Such optimization model is defined as follows:

$$\text{V-min} \quad f(x) = [f_1(x), f_1(x), f_1(x), \cdots, fn(x)] \quad n = 1, 2, \cdots, M$$

$$\text{s. t.} \quad g_j(x) \leqslant 0 \qquad j = 1, 2, \cdots, J$$

$$h_k(x) = 0 \qquad k = 1, 2, \cdots, K$$

$$x_i^{(L)} \leqslant x_i \leqslant x_i^{(H)} \qquad i = 1, 2, \cdots, I$$

Where, V-min represents vector minimization of all subsystem functions fn(x) of the objective function vector group f(x). Multi-objective optimization procedure can be divided into two steps.

The first step is to obtain Pareto-optimal solution. It is very difficult to search if the design variable is more than one, as the design space is multi-dimensional. The second step refers to choosing the appropriate trade-off solution from the Pareto optimal solution, which requires the participation of decision makers [9].

In order to obtain optimization equations regression method was used. Design parameters were selected to Full Factorial Design (FFD) [8] to obtain the MADYMO simulations results of the combination of different levels of design parameters. Results from the MADYMO were adopted to form surrogate model. The surrogate model validity is expressed with coefficient R^2. Usually when R^2 is more than 90%, the optimized model is accepted.

When the optimization function was obtained the minima were determined by Non- dominated Sorting Genetic Algorithm.

2.2.3 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 and better convergence near the true Pareto-optimal front compared to Pareto-archived evolution strategy. 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 [10] [11]. NSGA-II algorithm procedure used in the study is shown in Fig.5. Multi-objective optimization solution is a Pareto solution set, rather than simply a solution. The best solution choosing at low level depends on designer's objective.

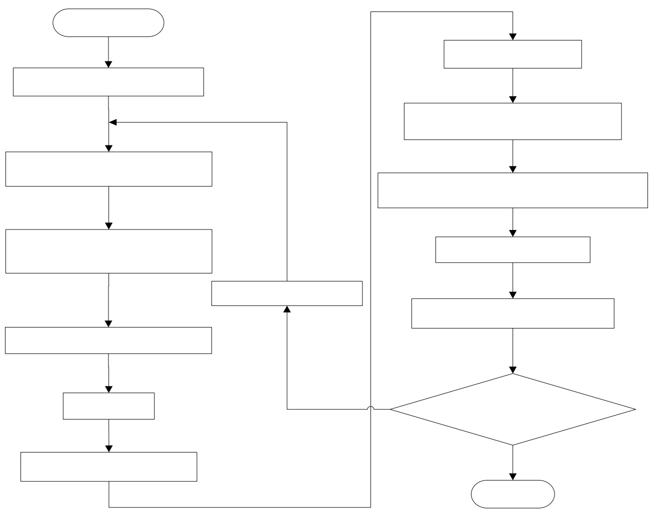

Fig.5. NSGA-II procedure

3 Results and Discussions

3.1 Influence of design parameters on injury related parameters

The influence of the parameters on the head resultant acceleration is shown in Table 3.

Table 3 Analysis of variance of the peak value of head acceleration

	DP 1	DP 2	DP 3	DP 4	DP 5	DP 6	DP 7
SS	35994	95235	18577	13680	47792	54261	15027
df	2	2	2	2	2	2	2
MS	17997	47618	9288	6840	23896	27131	7513
F	5.10	13.48	2.63	1.94	6.77	7.68	2.13
P value	0.108	0.032	0.218	0.288	0.077	0.066	0.265

It shows that when comparing P values the strongly significant factors are materials permeability parameter of side airbag, stiffness coefficient of lower anchorage, and location of top tether in X-direction. The influence of the parameters on the thorax resultant acceleration is shown in Table 4. It shows that strongly significant factors are stiffness coefficient of lower anchorage, materials permeability parameter of side airbag and location of top tether in X-direction.

Table 4 Analysis of variance of the peak value of thorax acceleration

	DP 1	DP 2	DP 3	DP 4	DP 5	DP 6	DP 7
SS	31586	28453	12827	5839	329359	163799	10497
df	2	2	2	2	2	2	2
MS	15793	14227	6414	2919	164679	81900	5248
F	1.15	1.04	0.47	0.21	11.99	5.96	0.38
P value	0.425	0.0855	0.666	0.819	0.037	0.06	0.711

3.2 Multi-objective optimization based on NSGA-II

Based on the parameters analysis, the following design parameters has been selected to Full Factorial design (FFD): materials permeability parameter of side airbag (x_1), location of top tether in X-direction (x_2) and stiffness coefficient of lower anchorage (x_3). Surrogate models were obtained by stepwise regression method and are shown as follows where H_{3ms} and T_{3ms} are head and thorax resultant acceleration 3 ms value, respectively:

H_{3ms}=-414-52.6 x_1+1610.3 x_2+479 x_3-223.3 x_1x_2+23.7 x_1x_3-181.7 x_2x_3+43.1 x_1^2-528.4 x_2^2-88.2 x_3^2

T_{3ms}=-3474.9+398x_1+6941x_2+844x_3-394.4x_1x_2-114.3x_1x_3-231.1x_2x_3-9.1x_1^2-2966x_2^2-129.1x_3^2

The determination coefficient R^2 of the regression equation of H_{3ms} is 91.3%. And the R^2 of the regression equation of T_{3ms} is 93.4%. So the two regression equations are credible.

Optimization resolving the head and thorax resultant acceleration regression equations was finished using Non-dominated sorting algorithm. The optimization model was defined as follows:

$$\mathrm{Min}H_{3ms} = f_1(x_1, x_2, x_3)$$
$$\mathrm{Min}T_{3ms} = f_2(x_1, x_2, x_3)$$
$$\text{Subject to} \quad 0.2 \le x_1 \le 0.6, \quad -0.45 \le x_2 \le -0.25, \quad 0.5 \le x_3 \le 1.5$$

Optimized values of the regression equations were obtained and Pareto-optimal front is shown in Fig.6.

In the multi objective problems, child occupant head and thorax acceleration are both supposed to be minimized. Pareto-optimal front solution showed that the two objectives were paradoxical. As head injury was the main factor causing child passengers death or serious injury, the solution to minimize head acceleration was chosen to be the best one. In this condition, materials permeability parameter of side airbag equals 0.06, location of top tether in X-direction equals -0.25m, stiffness coefficient of lower anchorage equals 0.5, peak value of head acceleration is about 410 m/s^2 and peak value of thorax acceleration is about 315 m/s^2.

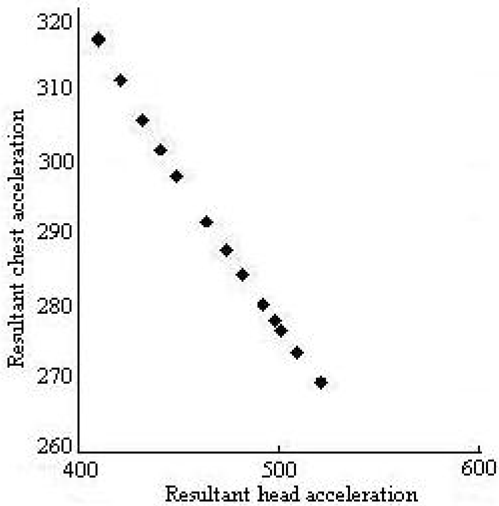

Fig.6. Pareto-optimal front

When we proved the regression equation credibility and used selected values for design parameters in the MADYMO simulation, we obtained from this simulation the value of head acceleration equaling 391.67 m/s^2 with the relative error of 4.5%.The value of thorax acceleration was 306.87 m/s^2 and the relative error was 2.9%. These values from MADYMO simulation correspond well to results of regression model. We can say that regression is credible.

4 Conclusions

Simulation model of child restraint system for side impact was developed based on multi-rigid-body theory. Multi-objective optimization was conducted applying NSGA-II considering complex input signal and multi-objective output of restraint system. Based on the experimental design, materials permeability parameter of side airbag, stiffness coefficient of lower anchorage and location of top tether in X-direction were found to be strong significant influencing child occupant head and thorax safety.

The approach of mathematical simulations combined with NSGA-II procedure is a very usable in design of CRS.

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