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PARAMETER OPTIMIZATION FOR REAR SEAT CUSHION ROTATION SYSTEM IN VEHICLE FRONTAL COLLISIONS

Zhongxing Li[1], Jian Shen[1], Ying Lu[1] and Hong Jiang[2]

[1]School of Automotive and Traffic Engineering
[2]School of Mechanical Engineering
Jiangsu University
No. 301, Xuefu Road, Zhenjiang 212013, P. R. China
532286137@163.com

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Abstract. *In vehicle frontal collisions, rotating the cushion can reduce injuries of rear occupants, and matching scheme of rotation parameters has a significant influence on protection performance. Based on a specific type of vehicle, a finite element model of rear occupant restraint system was constructed by using LS-DYNA, and then a cushion rotation system was proposed and added into the model. With C-NCAP rating of rear occupant as the optimization objective, optimal Latin hypercube design, Kriging model and multi-island genetic algorithm were used to optimize the rotation parameters (rotation angle, start time and end time). The result shows that compared with the model without cushion rotation system, rear occupant rating can increase by 71.26% as the cushion rotates by 25.35° from 12.56ms to 104.28ms in 50km/h frontal collisions.*
Keywords: Cushion rotation system, Parameter optimization, Kriging model

1. **Introduction.** With the rapid development of science and techniques and the continuous improvement of people's living standards, China's car ownership increases steadily and has reached to 154 million by 2014. However, the great amount of car ownership is becoming an important factor of frequent traffic accidents. In 2013, 198000 road traffic accidents occurred in China and resulted in 58000 deaths, which caused direct economic losses up to 1.03 billion yuan. Therefore, vehicle safety has aroused people's great attention. As an important part of vehicle safety, passive safety is aimed to protect occupants and minimize the occupants' injuries during accidents. Current researches of passive safety are mainly concentrated on safety belt and airbag, while the researches on seat are at an immature stage. Meanwhile, major researches focus on front occupants rather than rear occupants. Since a majority of rear occupants are out of the protection of airbag, the probability of getting a serious injury is higher compared with front occupants in vehicle frontal collisions [1].

Some researches on rear seat restraint system have been done in recent years. The importance of the seatbelt for rear seat occupants in frontal crash was highlighted in Parenteau's study [2]. They found that chest would be the most vulnerable region when occupants were restrained with 3-point seatbelt and the head would be injured without the restraint of seatbelt, which showed that head and chest were the important parts in rear occupant protection study. Gavelin et al. [3] developed a finite element model of a seat structure with integrated seatbelts evaluated to full-scale experiments, and a 50th percentile Hybrid III dummy was used as the occupant. The simulated results were consistent with the corresponding experimental responses. Therefore, simulation method could be used to research rear occupants' injuries. The cushion rotation system was first proposed by Ge [4], who constructed a multi-body model with a rotatable cushion in the driver's seat by using MADYMO. After simulation analysis by different rotation angles, the result indicated that when 25° rotation angle of seat cushion was used, head injury declined by 21.4%, chest injury dropped by 16.6%, and the leg wound was still low. Li et al. [5] focused on the rotation parameter optimization of rear seat cushion for rear occupant restraint system in different types of frontal collisions. A finite element model of rear occupant restraint system with cushion rotation system was constructed by using LS-DYNA, and rotation angle and start time were chosen as the optimization parameters. It was found that in 50km/h full frontal rigid barrier crash, the cushion rotation system provided the best occupant protection by rotating by an angle of 20° with the initial time of 20ms. The innovations of our study compared with those previous ones are as follows. First, our study builds the mathematic relationship between cushion rotation parameters and injury criteria of rear occupant and the optimal scheme is obtained by the above mathematic relationship rather than simulation attempts. Second, we take the interactive influence of cushion rotation parameters into account which is ignored in a lot of recent work. Third, we also investigate the injury criteria in different parts of the body synthetically, which is seldom seen in previous studies.

The content of this paper is organized as follows. In Section 2, a finite element model of rear occupant restraint system is constructed by using LS-DYNA, and cushion rotation system is added into the model at the same time. The optimization problem is described in Section 3. Section 4 presents a surrogate model to build the mathematical relationship between cushion rotation parameters and dummy's injury criteria, as well as setting China new car assessment program (C-NCAP) rating of rear occupant as optimization objective. Then multi-island genetic algorithm is used for finding the optimal scheme of cushion rotation system. Finally, Section 5 presents summary comment and discusses promising area for future research.

2. **Construction and Verification of Finite Element Model.** Figure 1 shows the finite element model of rear occupant restraint system based on a specific type of vehicle. Finite element modeling process includes:

1) Modeling the seat and floor according to the size and material of real vehicle;

2) Choosing the 5th percentile female Hybrid III dummy as a rear occupant, and positioning the dummy according to C-NCAP;

3) Modeling the seat belt, including the selection of three-point seat belt tracking points and the design of retractor and pretensioner [6];

4) Defining the relative motion relationships, friction coefficients and contact characteristics between different parts.

Figure 1. Finite element model of rear occupant restraint system

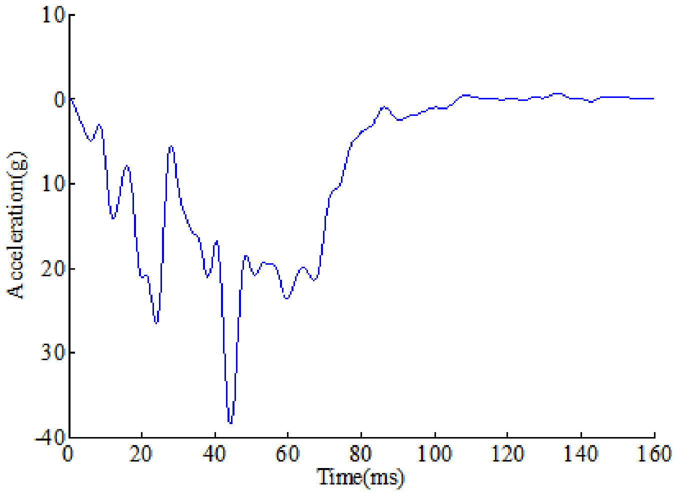


Figure 2. Vehicle acceleration along x-axis of 50km/h frontal collision

Table 1. Comparison between simulation and experiment results

Injury criteria	Simulation result	Experiment result	Error(%)
HIC_{15}	299.8	310.4	3.4
F_x	2.27kN	2.24kN	1.4
F_z	2.53kN	2.40kN	5.4
M_y	50.5Nm	49.1Nm	2.9
D_{chest}	46.8mm	46.2mm	1.3

50km/h frontal collision experiment was conducted in accordance with C-NCAP. The signal collected from the sensor that at the central tunnel in front of the electronic control unit (ECU) of the airbag is regarded as the acceleration input for the simulation model. The magnitude of the x-axis acceleration measured is shown in Figure 2.

According to C-NCAP, the major injury criteria of rear female dummy include head injury criterion (HIC_{15}), shearing force of neck (F_x), tensile force of neck (F_z), stretching moment of neck (M_y) and chest deflection (D_{chest}). To verify the accuracy of the finite element model, dummy's injury criteria between simulation and experiment are compared in Table 1.

Table 1 shows that errors of HIC_{15}, F_x, M_y and D_{chest} between simulation and experiment are within 3.5%. Besides, there is a slight larger error in terms of F_z that is only 5.4%. Consequently, the finite element model can be used as the basic model for subsequent research in that the model is able to accurately respond the major injuries of rear occupant in vehicle frontal collisions.

3. **Description of Optimization Problem.** Parameter optimization of cushion rotation system in 50km/h frontal collisions is studied. The optimization problem consisted of three parts of content: optimization parameters, constraint condition and optimization objective.

3.1. **Optimization parameters.** On the basis of rear occupant restraint system, rear seat cushion rotation system is added. Figure 3 shows the rear occupant restraint system with cushion rotation system. As soon as the collision signal is detected, controller emits an instruction to drive the cushion to rotate backward around the rotation axis. Setting cushion rotation angle (θ), start time (t_{start}) and end time (t_{end}) as optimization

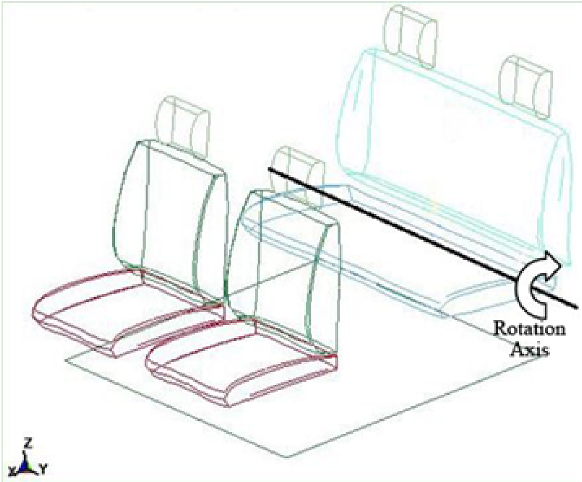


FIGURE 3. Rear occupant restraint system with cushion rotation system

parameters, optimization scheme by which the cushion rotation system provides the best protection in vehicle frontal collisions is studied.

3.2. **Constraint condition.** In order to avoid a local serious injury to the occupant due to a specific extreme injury criterion, all injury criteria should be given consideration when the cushion rotation system is designed. Thus, every injury criterion should have improvement after applying the cushion rotation system.

3.3. **Optimization objective.** To quantize the protection performance that cushion rotation system provides for the rear occupant, the main injury criteria of rear female dummy are rated according to the C-NCAP. The optimization objective is to make rear female dummy get the highest score.

4. **Parameter Optimization.** It takes long time and has low precision to search for the optimal rotation scheme through finite element simulation. Therefore, mathematical relationship between occupant injury criteria (HIC_{15}, F_x, F_z, M_y, D_{chest}) and optimization parameters (θ, t_{begin}, t_{end}) is constructed by using surrogate model. Then, score of rear seat occupant can be calculated and cushion rotation parameters are optimized based on the score. Parameter optimization process mainly includes the design of experiment, the construction of surrogate model and optimization calculation.

4.1. **Sample point selection for surrogate model.** First, sample points should be determined for constructing surrogate model associating occupant injury criteria (HIC_{15}, F_x, F_z, M_y, D_{Chest}) with optimization parameters (θ, t_{begin}, t_{end}). As a method of sample point selection, optimal Latin hypercube design (Opt LHD) can not only reduce the number of experiments, but also improve the accuracy of surrogate model constructed in nonlinear problem like vehicle collisions. Therefore, Opt LHD is used to select the sample points for the construction of surrogate model.

Initial value and design interval of cushion rotation optimal parameters are listed in Table 2. Then, the number of sample points is determined. Both efficiency and accuracy should be considered so that 64 sample points are chosen in this optimal design. The

TABLE 2. Initial values and design intervals of cushion rotation parameters

Optimization parameter	θ (°)	t_{begin} (ms)	t_{end} (ms)
Initial value	20	20	110
Design interval	$[10, 30]$	$[10, 30]$	$[100, 120]$

design interval of every parameter is divided into 64 small intervals in Opt LHD in which parameter values are randomly selected. 64 values of every parameter are generated from different intervals, and the sample points of Opt LHD are obtained by matching.

4.2. **Construction and verification of surrogate model.** Kriging model is an unbiased estimation model whose estimation variance is minimum and can provide an exact interpolation which is good at solving nonlinear problem. Therefore, mathematical relationship between occupant injury criteria and rotation parameters is constructed through Kriging model. 64 sample points are selected by the Opt LHD and HIC_{15}, F_x, F_z, M_y, D_{chest} are obtained through finite element simulation. Eventually, the Kriging model is constructed based on simulation data.

To verify the accuracy of Kriging model, 8 sample points are randomly selected in design space. Table 3 shows the calculation error of dummy's injury criteria between surrogate model and simulation analysis.

Table 3. Errors of dummy's injury criteria between surrogate model and simulation analysis

Injury criterion	1	2	3	4	5	6	7	8
HIC_{15}	2.49%	1.11%	4.81%	1.00%	0.79%	3.05%	5.06%	4.07%
F_x	1.19%	3.09%	0.40%	2.18%	0.69%	3.55%	1.05%	3.53%
F_z	2.50%	3.48%	3.68%	1.25%	2.54%	2.54%	5.18%	2.63%
M_y	3.31%	8.08%	3.46%	9.85%	2.13%	2.23%	9.61%	6.17%
D_{chest}	0.66%	2.36%	0.68%	3.52%	1.71%	5.63%	5.61%	1.85%

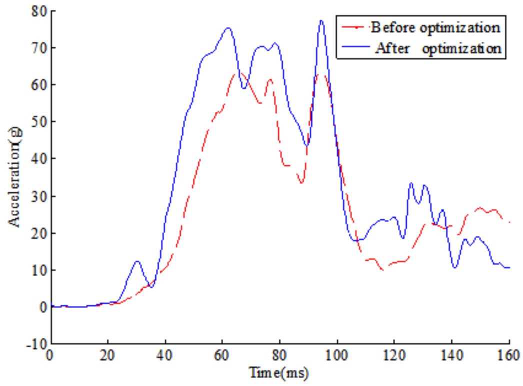
As can be known from Table 3, the error of HIC_{15}, F_x, F_z, D_{chest} is within 6.0%. The result shows that the Kriging model is able to replace the simulation calculation for the above four injury criteria. Besides, M_y is slightly large and no more than 10.0%. However, M_y is only regarded as constraint condition rather than rating item. So the error is still within the permission range. Therefore, the subsequent work for parameter optimization will be conducted on the basis of the Kriging model.

4.3. **Parameter optimization and result analysis.** The accuracy and calculation efficiency of the parameter optimization depend on the selection of optimization algorithm. Multi-island genetic algorithm (MIGA) is good at multimodal search and has better global solving capability and computing efficiency. So MIGA is used to resolve the parameter optimization problem for cushion rotation system.

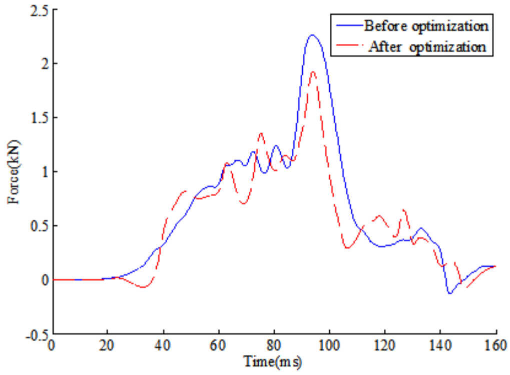
Result is obtained after 1000 times of iterative computation. On the premise of not deteriorating each injury criterion, rear seat female dummy gets the highest score by rotating the cushion 25.35° from 12.56ms to 104.28ms.

As shown in Figure 4, the dummy's injury criteria are compared between the model with the optimal cushion rotation scheme and the model without cushion rotation system. Figure 4 shows that dummy's injury criteria decrease dramatically through the rational allocation of the design variables of cushion rotation system.

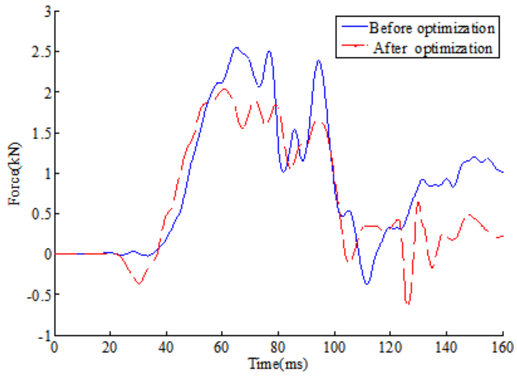
5. **Conclusions.** Mathematical relationship between cushion rotation parameters and occupant injury criteria is constructed through finite element simulation, experimental design and Kriging model. Then multi-island genetic algorithm is used to optimize parameters of cushion rotation system based on the Kriging model. The result shows that rear occupant rating can increase by 71.26% when cushion rotates by 25.35° from 12.56ms to 104.28ms compared with the model without cushion rotation system. This research lays a theoretical foundation to promote cushion rotation system.



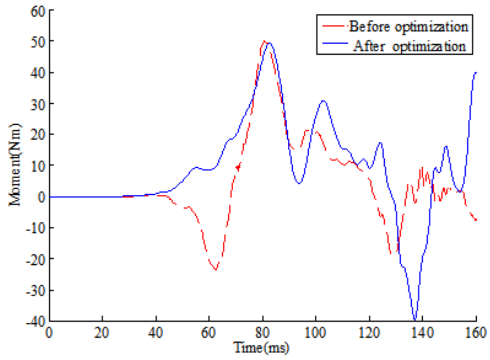
(a) Head acceleration



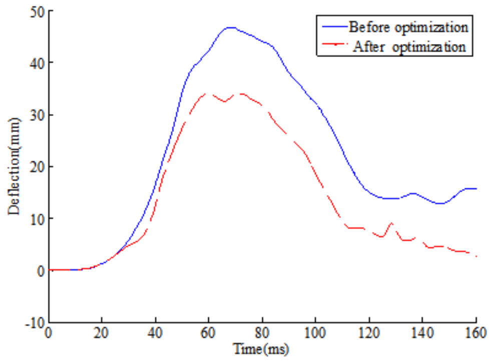
(b) Shearing force of neck



(c) Tensile force of neck



(d) Stretching moment of neck



(e) Chest deflection

FIGURE 4. Comparison of dummy's injury criteria before and after the optimization

There are several possibilities for furthering our research on this topic area. First, one could further improve the simulation model of rear occupant restraint system which is simplified in this paper. Second, one could optimize the cushion rotation parameters on other types of cars like minibuses, passenger cars and trucks because our research is only aimed at sedan. A third extension would be to design the apparatus to rotate the cushion which can promote the practical application of cushion rotation system.

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