Optimization of Thickness of Car Side Structure Regarding Crashworthiness in Pole Side Impact Using Kriging Method

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Abstract: In real traffic accidents, side impact of passenger cars with fixed pole may result in severe injuries to the occupants, so it is necessary to study the this collision type of pole side impact. In order to improve vehicle crashworthiness during pole side impact, a finite element model of pole side impact was developed and validated. In optimization of the thickness of side structure, Sampling points were obtained by using Latin hypercube design of experiments on thickness of key side components, and then considering computing efficiency a response surface method was employed to construct highly nonlinear crash mode to improve computing efficiency. The response surface approximate functions were optimized by multi-objective genetic algorithm and car's crashworthiness was effectively improved. The results show that the maximum side intrusion of B-pillar in driver's chest area has been reduced when the peak acceleration kept in a reasonable level. The optimization has improved occupant's living space. The methodology used in the study provided foundation for the research of on pole side impact.

Keywords: side pole impact; crashworthiness; kriging model; optimization design; multi-objective

1. Introduction

In Europe and USA, the side impact is already taken in to consideration by the compulsory safety regulation, but their goals are mainly concentrated on the car-to-car collision, rarely paying attention to car-to-pole side impact. In 2003, the number of vehicle collisions with fixed objects like trees or poles accounts for 19% of all accidents in USA, and 44% of it results in severe injuries to occupants according to the reports by National Highway Traffic Safety Administration (NHTSA) [1]. In China, the regulation about protection of the occupants in the event of a lateral collision was released on July 2006, but not concerning the pole side impact. However, the current Euro-NCAP includes a pole side crash test as an option accounting 2 points added to overall score of side impact. The pole side crash is compulsory in the new rating system issued in 2009 and the number of points is increased to 8 [2].

At present, was not too much research about pole side impact to arise people's attention on this special collision. Zhu et al. [3] used mechanics theory to analyze differences between the pole and car to car side collision regarding driver injures and deformation of the vehicle. Dong et al. [4] came to the conclusion that the sill and the lower part of the B-pillar are the key parts of the side structures in determining the passenger car crashworthiness. Mark et al. [5] developed the methodology to analyze the stiffness variation along the vehicle by repeated pole impacts based on a generalization relating energy absorption properties at different locations on the vehicle side, and applied it to experiment with the Ford structural platform.

It has been proved effective and feasible to using approximate model to carry out the optimization research for vehicle crashworthiness and safety. In Zhang's research [6], a response surface approximate model based on moving least fitting is introduced into the optimization design for car's lightweight. Sun et al. [7] successfully optimized front beam crashworthiness by applying the multi-objective particle swarm optimization algorithm. Multidisciplinary design methodology was used in one optimization study on vehicle body crashworthiness and noise, vibration and harshness (NVH) [8].

In studying case of side impact, the amount of intrusion, intrusion velocity, acceleration, and deformation pattern of the side structure are major factors influencing the safety performance in side impact accidents [9]. To reduce the intrusion and acceleration and improve crashworthiness in the pole side impact configuration in the current study, a method of optimization based on the approximate model was applied to improve crashworthiness in impact with pole. With Latin hypercube experiment design methodology, a set of testing samples for all factors' combination was created to provide data to approximate model. Then the car's pole side impact FE simulations according to Enro-NCAP have been per-

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formed sequentially to acquire the top value of side intrusion and vehicle body acceleration. From these results, the Kriging model was used fitting the sample points, so that the optimization could be done of the thickness of side components to achieve minimum intrusion and acceleration, also satisfying the restriction of upper bound of B-pillar intrusion.

2. Method and Material

2.1. Pole-side Impact model

According to the latest Euro-NCAP regulations [2], the car is propelled sideways at 29km/h into a rigid pole, 254 mm in diameter. Euro-SID dummy is used on the driver side. In the study we decided to use this configuration in the optimization process (Figure 1). The car model in LS-DYNA is composed of 389 components, 336,406 elements, and 338,058 nodes in total. Simulation time is 0.12 second. The pole is defined as rigid body, using MAT20 materials, the parameters like density and elastic modulus are referring to the property of real impactor. The CONTACT_AUTOMATIC_SURFACE_TO_SURFACE is adopted to give the contact interface between the pole and car. Both bodies are respectively defined to the master and slave surfaces. The coefficient of static and dynamic friction is set to 0.2.

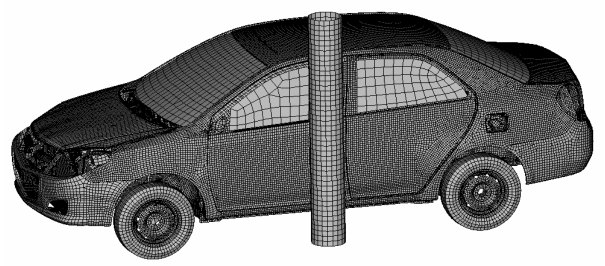


Figure 1. Pole side impact FE model

2.2. Latin Hypercube Design of Experiment

Latin hypercube methodology is an feasible tool to study the multi-factor experiments design, commonly used to generate test samples from large design space that is evenly divided into several ones so that every level of parameters can averagely fills the entire design space and be used once only. All these levels combine randomly to form a matrix made of several sampling points. This methodology has the advantage of high efficiency, well balance and accurate fitting. Figure 2 shows a demonstration of two-factor (x, y), which is composed of 9 sample points [6], based on Latin hypercube experiment design methodology.

As the variation on thickness of main components is important in energy-absorption, so in the optimization of crashworthiness in pole side impact, five components with different thickness are chosen as design variables, which are shown in Table 1. Lower and upper band values are based on engineering experience.

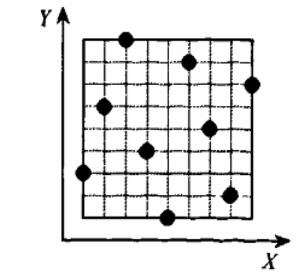


Figure 2. Sampling of Latin hypercube experiment design

Table 1. Initial value and variation for design variables

Design variable	Component's name	Initial value	Lower bound	Upper bound
t_1	Roof cross-member	0.8	0.7	1.5
t_2	Outer B–pillar	1.0	0.8	2.0
t_3	Floor cross-member	1.5	1.2	2.2
t_4	Sill reinforcement	2.0	1.5	2.2
t_5	Sill inner and outer	1.5	1.2	2.2

There are three criterions to assess car safety in pole impact: the acceleration of the car, the intrusion of B-pillar and loads to certain parts of the vehicle. In the study we used the peak lateral acceleration of B-pillar lower part on the car non-strike side filtered with SAE60 (a) and the B-pillar maximum intrusion at the level of driver's chest position (L). We used also the value of 220 mm as maximum allowed intrusion of inner B-pillar (U) in accordance to condition of "excellent" level from classification made by Insurance Institute for Highway Safety (IIHS).

A general multi-objective optimization problem is expressed as:

$$\begin{gathered} \text{Min } (L, a) \\ \text{s.t. } U \leq 220 \text{ mm} \\ 0.7 \text{ mm} \leq t_1 \leq 1.5 \text{ mm} \\ 0.8 \text{ mm} \leq t_2 \leq 2.0 \text{ mm} \\ 1.2 \text{ mm} \leq t_3 \text{ and } t_5 \leq 2.2 \text{ mm} \\ 1.5 \text{ mm} \leq t_4 \leq 2.2 \text{ mm} \end{gathered} \tag{1}$$

Considering the no-linear functional relation between the variables and targets, the kriging response surface methodology was employed to build up the approximate model.

2.3. Kriging Approximate Methodology

We selected kriging model to construct approximation of optimized problem. This model describes a response surface of curve interpolation and response approximation, and can estimate unbiased minimum variance. That makes it easier to obtain ideal fitting results when dealing with the highly non-linear problem[10].

Kriging models combine a global model plus localized departures:

$$y(x) = f(x) + z(x) \quad (2)$$

where $y(x)$is the unknown function of interest, $f(x)$ is the known approximation (usually polynomial) function, and $z(x)$ is the realization of a stochastic process with mean zero, variance σ^2, and non-zero covariance. The $f(x)$ term in (2) is similar to a polynomial response surface, providing a "global" model of the design space. In many cases $f(x)$ is taken as a constant (β) and we employ only a constant term for $f(x)$ in the car side structure thickness optimization design, as shown in following:

$$y(x) = \beta + z(x) \quad (3)$$

where β . is an unknown constant, to predict by the response value known.

While $f(x)$ globally approximates the design space, $z(x)$ creates "localized" deviations so that the kriging model interpolates the n_s sampled data points; however, non-interpolative kriging models can also be created to smooth noisy data. The covariance matrix of $z(x)$ is given by the following:

$$Cov[z(x^{(i)}), z(x^{(j)})] = \sigma^2 R[R(x^{(i)}, x^{(j)})] \quad (4)$$

In formula (4), R is the correlation matrix, and R(x^i, x^j) is the correlation function between any two of the ns sampled data points x^i and x^j, R is an ($n_s \times n_s$) symmetric matrix with ones along the diagonal. The correlation function R(x^i, x^j) is specified by the user, and a variety of correlation functions exits. In the study, we utilize the Gaussian correlation function of the following form:

$$R(x^{(i)}, x^{(j)}) = \exp\left[-\sum_{k=1}^{n_v} \theta_k \left|x_k^{(i)} - x_k^{(j)}\right|^2\right] \quad (5)$$

where n_v is the number of design variables, θ_k are the unknown correlation parameters used to fit the model, and can be replace by the scalar θ In some cases, using a single correlation parameter gives sufficiently good results, however, we use a different θ for each design variable. So the formula (5) turns into the following:

$$R(x^{(i)}, x^{(j)}) = \exp\left[-\theta \sum_{k=1}^{n_v} \left|x_k^{(i)} - x_k^{(j)}\right|^2\right] \quad (6)$$

The predicted estimates $\hat{y}(x)$ of the response $y(x)$ at untried values of x are given by:

$$\hat{y}(x) = \hat{\beta} + r^T(x) R^{-1}(y - f\hat{\beta}) \quad (7)$$

where y is a column vector with the length of n_s, that includes the sample value of the response, and f is a column vector of length n_s that is filled with ones when $f(x)$ is taken as a constant. In equation (7), $r^T(x)$ is the correlation vector of length n_s, between an untried x and the sampled data points {x^1, … , x^{n_s} }

$$r^T(x) = [R(x, x^1), R(x, x^2), \ldots, R(x, x^{n_s})]^T \quad (8)$$

The $\hat{\beta}$ in（7）can be estimated using equation (9):

$$\hat{\beta} = (f^T R^{-1} f)^{-1} f^T R^{-1} y \quad (9)$$

The estimated value of variance $\hat{\sigma}^2$ between the underlying global model $\hat{\beta}$ and y is estimated using equation (10):

$$\hat{\sigma}^2 = \frac{(y - f\hat{\beta})^T R^{-1}(y - f\hat{\beta})}{n_s} \quad (10)$$

where $f(x)$ is assumed to be the constant $\hat{\beta}$. The maximum likelihood estimates (MLE) for the parameter . in equation (8) used to fit a kriging model are obtained by make the following equation (11) maximum when $\theta_k > 0$:

$$-\frac{[n_s In(\hat{\sigma}^2) + In|R|]}{2} \quad (11)$$

where both Matrix R and $\hat{\sigma}^2$ are functions of θ While any value for the θ creates an interpolative kriging model, the "best" kriging model is found by solving the unconstrained nonlinear optimization problem given by equation (11). With θ values we can generate an interpolation model. So as soon as parameters θ are determined, the kriging model can be completely established.

3. Results

3.1. Evaluation of FE Model Validity in Side Impact

In current study we used the available finite element (FE) model of the car that was based on an existing car on Chinese market. The car model was validated with the model of movable deformable barrier (MDB) in the configuration according to the Chinese safety regulation "The protection of the occupants in the event of a lateral collision". As it is shown in Figure 3, the MDB model was moving towards the car with the speed of 50 km/h. In general, the simulation time was set to 120 ms to save computing time, although the actual one in the test may last for 200 ms. The accuracy of car model was validated by comparing time-histories of acceleration form crash test and simulation. As shown in Figure 4 the trends of acceleration curves are basically similar. The corresponding peaks of the curves were appearing almost at the same time. There is a little difference in the peak values. However, this difference is less than 5%, so the FE model of the car can be accepted in the simulations for the purpose of the study.

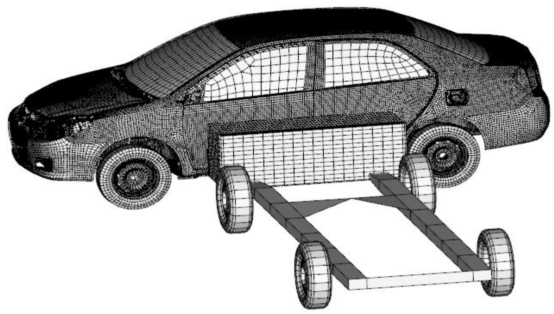
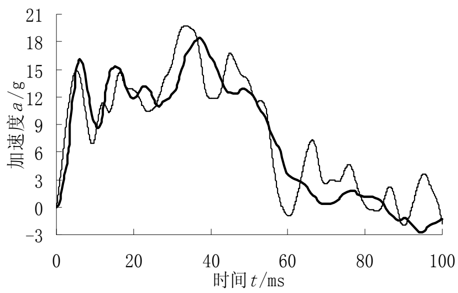


Figure 3. Side impact FE model Figure



1. simulation 2. expriment

Figure 4. Acceleration curves for simulation and experiment

3.2. Result from Experiment Design

In order to obtain sufficient design samples, a mathematical model was built with the help of Latin hypercube experimental design methodology. The five design variable are t_1, t_2, t_3, t_4 and t_5, were used in 25 simulations using LS-Dyna are completed to calculate the value of L, a, and U for each group of variabels. The results from these simulations are summarized in Table 2.

Table 2. Experimental samples designed

No.	L [mm]	a ([g]	U [mm]
1	152.8	28.27	207.5
2	196.2	24.70	247.8
3	150.2	29.81	200.5
4	182.9	25.69	232.9
5	190.9	24.19	238.6
6	162.4	27.65	209.4
7	181.6	25.97	234.9
8	202.6	23.47	252.6
9	167.1	27.35	219.9
10	171.7	26.74	224.3
11	139.3	29.60	185.4
12	217.8	21.79	267.4
13	161.5	27.94	210.8
14	196.2	23.82	248.4
15	179.3	24.54	227.0
16	232.3	20.11	282.3
17	154.8	27.19	202.5
18	214.2	22.38	265.5
19	154.9	28.67	205.9
20	164.2	26.88	212.3
21	194.8	23.96	244.0
22	158.5	28.21	208.2
23	211.4	22.55	262.9
24	180.8	22.51	231.6
25	160.3	27.79	208.9

3.3. Result from Kriging Model

Kriging model is established by using the approximate module of iSIGHT software to get corresponding values of parameters θ for three responses, as shown in Table 3.

Table 3. Response parameter θ of Kriging model

	t_1	t_2	t_3	t_4	t_5
L	0.0066	0.0355	0.1079	0.0439	0.3504
a	0.0010	5.9084	0.0010	0.1661	7.3053
U	0.0015	0.0644	0.0689	0.0299	0.8032

Repeating the modeling process in iSIGHT, the kriging models for each response were obtained. These models was used in optimization of thickness meeting the crashworthiness requirements, see Table 4.

Table 4. Optimized thickness of components in mm

Design variable	t_1	t_2	t_3	t_4	t_5
Optimum thickness	1.498	1.999	1.410	1.748	1.826

As we can see from these results, the optimized t_1 and t_2 are larger than before, while t_3 remain almost unchanged, t_4 and t_5 are slightly decreased and increase, respectively with the same degree when comparing the original values.

To check the accuracy of the predicted optimal design of thickness, the set of these values (t_1- t_5) are used as inputs into the original FE model, and the percentage error between predicted values by optimization and ones from simulations is calculated, as shown in Table 5. As we can see, the results of approximate model prediction fit perfectly ones from FE simulation, with the error less than 5%. The kriging models used in the study offer highly accurate approximations, as evidenced by small prediction errors of the optimum design.

Table 5. Comparison of target values predicted and verified

Target	Predicted optimum	Verified optimum	Error [%]
L [mm]	150.27	154.00	2.42
a [g]	26.88	26.38	1.88
U [mm]	208.66	207.80	0.42

Comparison of the results from finite element simulations of the original and optimized structure, is shown in Table 6. From these results we can see that the peak value of acceleration is greatly below 80g-the prescribed value in regulation, although a certain increase to some extent. The maximum intrusion of B-pillar on chest position has been reduced by approximately 25%, ensure that structural deformation of B-pillar is in the condition of ‘excellent’, greatly improving the crashworthiness of vehicles in pole side impact. It indicates that the match for thicknesses of the key components is reasonable.

Table 6. Improvement obtain by the optimization

Target	Former	Latter	Improvement [%]
L [mm]	205.3	154.0	24.99
a [g]	23.4	26.4	-12.60
U [mm]	254.4	207.8	18.32

4. Conclusions

The results of the current study show that applying the approximate model to the crashworthiness optimization of vehicle in pole side impact configuration is feasible and efficient. By establishing the Kriging approximation model for pole side impact instead of performing analysis only with the finite element model, it is possible to carry out the match and optimization on the thicknesses of key components combined with improvement of vehicle crashworthiness saving the production time and cost simultaneously.

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