

Reliability Analysis of Vehicle Frontal Collision Based on Differential Evolution Algorithm

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Abstract

Based on the differential evolution algorithm, this paper analyzes the reliability of a vehicle frontal collision model, builds the uncertainty mathematical model by introducing the parameter correlation, and transforms the constrained model into the unconstrained model by using the augmented Lagrangian multiplier method. Then the proposed algorithm is applied to the reliability analysis of the vehicle frontal collision. It is found from the results of numerical simulations that the proposed differential evolution algorithm can solve the reliability optimization problem with parameter correlation, and it also has high calculation efficiency and good convergence for the calculation of the limit state equation with high nonlinear degree. These results verify the feasibility of the proposed algorithm in solving more complex reliability optimization problems.

Keywords

Differential evolution algorithm; Correlation; Reliability analysis; Augmented Lagrangian multiplier method.

1. Introduction

In real life, due to the increasing number of cars, there are lots of traffic accidents caused by mutual collision increase. However, in traffic accidents, due to the large rigidity and strong impact of vehicles, frontal collision is a kind of accident form that causes the most casualties [1]. Due to a series of uncertain factors, such as material properties, the manufacturing accuracy, the splicing error, etc., the design variables and parameters of automobile will also produce a large number of uncertain factors, which will lead to certain deviation in the process of automobile reliability analysis. In order to analyze the indexes and the performances of automobile structure accurately, people need to take lots of effective methods to evaluate and predict. Because of the uncertainty and correlation of sample parameters, the traditional reliability analysis method is difficult to solve the reliability problem of vehicle structure in practical engineering. At this time, the search of new algorithm is particularly important. In recent years, many scholars have done a lot of research on the reliability calculation of automobile structure [2-3]. Wang et al. and others proposed a reliability calculation method based on sequential quadratic programming to solve the problem that traditional methods are difficult to solve the limit state function with highly nonlinear structures [4]. Du et al. Used ANSYS / LS-DYNA software to simulate the vehicle collision device, and verified the strength and effectiveness of the device [5]. Hu et al. aimed at a large number of uncertain factors in vehicle collision, adopted the uniform design method in Latin hypercube sampling to sample in the uncertain range of design variables, and optimized the structural strength of vehicle in

collision model [6]. In the calculation of structural reliability, the addition of intelligent algorithm can improve the calculation efficiency and save much time compared with the traditional algorithm.

Based on this, this paper proposes a new reliability analysis method based on differential evolution algorithm, and studies the reliability analysis of actual structure by introducing the correlation of parameters to construct uncertain model. The proposed method can solve the problem of reliability index with high nonlinear limit state equation under the influence of parameter correlation to a certain extent, and the stability and effectiveness of the present method are verified by an example of vehicle collision.

2. The Establishment of Reliability Index and the Introduction of Algorithm

2.1. Introduction of Differential Evolution Algorithm

Differential evolution algorithm (DE) is a simple and effective global search algorithm, and has the advantages of simple principle and less controlled parameters. It has been widely used in many fields such as artificial intelligence and pattern recognition. The implementation of differential evolution algorithm is as follows:

(1) Initialization of the population

$$\{x_i(0) \mid x_i(0) = [x_{i1}, x_{i2}, x_{i3}, \dots, x_{iD}], i = 1, 2, \dots, NP\} \quad (1)$$

$$\left\{ \begin{array}{l} x_{ij} = a_j + rand \times (b_j - a_j) \\ i = 1, 2, \dots, NP, j = 1, 2, \dots, D \end{array} \right\} \quad (2)$$

In formulas (1) and (2), NP stands for population size, $X_i(0)$ stands for the i -th individual, x_{ij} is its j -th component.

(2) Mutation operation

Mutation operation is to randomly select two different individuals from the population, scale their difference vectors and perform vector operation with other individuals to be changed, so as to generate new individuals.

$$V_i(g+1) = X_{r1}(g) + F(X_{r2}(g) - X_{r3}(g)) \quad (3)$$

Where r_1, r_2 and r_3 are random integers, distributed between $[1, NP]$, F is the scale factor, g represents the evolutionary algebra.

(3) Crossover operation

Cross operation between individuals on the g generation population $\{X_i(g), i = 1, 2, \dots, NP\}$ and its variation intermediate population $\{V_i(g+1), i = 1, 2, \dots, NP\}$ are given as follows.

$$u_{ij}(g+1) = \begin{cases} v_{ij}(g+1), & \text{if } rand \leq CR \\ & \text{or } j = j_{rand} \\ x_{ig}(g), & \text{otherwise} \end{cases} \quad (4)$$

(4) Selection operation

The differential evolution algorithm adopts the greedy strategy to select new individuals to enter the population according to the value of objective function.

$$X_i(g+1) = \begin{cases} U_i(g+1), & \text{if } f(U_i(g+1)) \leq f(X_i(g)) \\ X_i(g), & \text{otherwise} \end{cases} \quad (5)$$

The flow chart of differential evolution algorithm is shown in Figure 1.

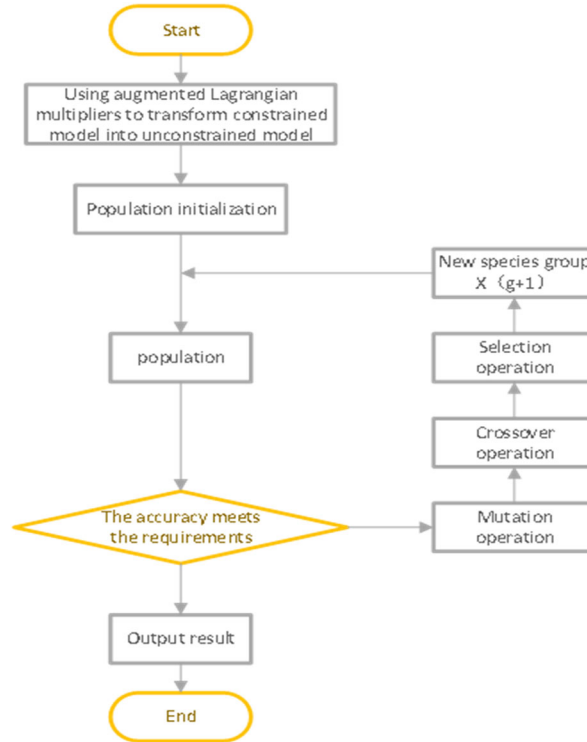


Figure 1. The flow chart of the proposed algorithm

2.2. The Establishment of Parameter Correlation and Reliability Index

The limit state equation of practical engineering structure is expressed as $Z = g(X_1, X_2, \dots, X_n) = 0$. $X_1, X_2, \dots, X_n$ is an independent random variable with arbitrary distribution. The R-F method is used to normalize the equivalent of non-normal variables, the derive mean value μ'_{xi} , standard deviation σ'_{xi} , and its reliability index β are respectively given as.

$$\sigma'_{xi} = \phi \left\{ \Phi^{-1} \left[F_{xi}(xi^*) \right] \right\} / f_{xi}(X_i^*) \quad (6)$$

$$\mu'_{xi} = X_i^* - \Phi^{-1} \left[F_{xi}(xi^*) \right] \sigma'_{xi} \quad (7)$$

$$\beta = \left(\sum \left[(X_i^* - \mu'_{xi}) / \sigma'_{xi} \right]^2 \right)^{1/2} \quad (8)$$

The initial design point is unknown. If the minimum reliability index value β is required, β should be regarded as the function of point $P(X_1, X_2, \dots, X_n)$ on the surface of the limit state equation, and the design point P and the minimum reliability index β can be obtained by derivation. The mathematical model of reliability index is established as follows.

$$\begin{aligned} \text{Min} \beta^2 &= \sum_{i=1}^n \left[\left(X_i^* - \mu'_{xi} \right) / \sigma'_{xi} \right]^2 \\ \text{s.t. } Z &= g \left(X_1^*, X_2^*, \dots, X_n^* \right) = 0 \end{aligned} \quad (9)$$

Most of the existing reliability calculation methods assume that the random variables are independent of each other, but in the actual engineering structure, the variables often have significant correlation. Due to the effect of the correlation, the calculation of reliability index will appear significant deviation. So the research of correlation is particularly important [7]. In this paper, the random variables X_i and X_j are used to describe the correlation degree, and the correlation coefficient $\rho_{X_i X_j}$ is given as.

$$\rho_{X_i X_j} = \frac{E[(X_i - \mu_{X_i})(X_j - \mu_{X_j})]}{\sigma_{X_i} \sigma_{X_j}} = \frac{E(X_i X_j) - \mu_{X_i} \mu_{X_j}}{\sigma_{X_i} \sigma_{X_j}} \quad (20)$$

Suppose that the limit state function is expressed as a linear function of the normal random variable $X_1, \dots, X_n$, namely,

$$Z = a_0 + a_1 X_1 + \dots + a_n X_n \quad (31)$$

Then the mathematical model of reliability index is obtained as.

$$\beta = \frac{a_0 + a_1 \mu_{X_1} + \dots + a_n \mu_{X_n}}{\sqrt{\sum_{i=1}^n \sum_{j=1}^n a_i \sigma_{X_i} \rho_{X_i X_j} \sigma_{X_j} a_j}} \quad (42)$$

3. An Example of Reliability Calculation of Automobile Frontal Collision

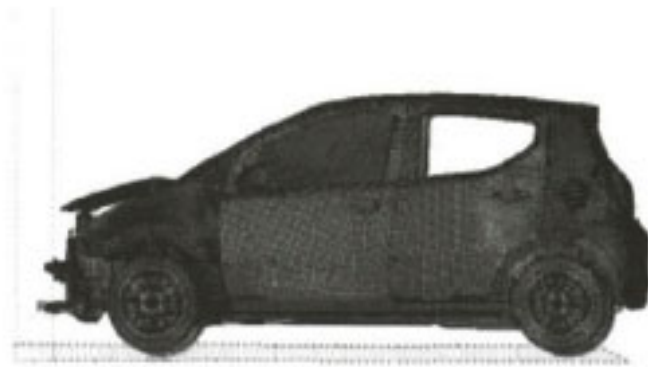


Figure 2. The finite element model of automobile frontal collision

Considering the engineering example of document [8], the reliability analysis of vehicle collision is carried out. In vehicle collision, the front area of vehicle is the main deformation area which is greatly affected. In this paper, d_1 is the thickness of the front impact beam; d_2 is the thickness of the inner plate of the energy absorption plate; d_3 is the thickness of the outer plate of the energy absorption plate; d_4 is the thickness of the inner plate of the front longitudinal beam; d_5 is the thickness of the outer plate of the front longitudinal beam; P_1 is the

elastic modulus of the front impact beam are design variables; the energy E absorbed by the energy absorption box is the safety index. The finite element model of vehicle collision is shown in Figure 2, the specific information is shown in Table 1, the limit state equation of the model is given as follows.

$$g = E(d_1, d_2, d_3, d_4, d_5, P) \quad (53)$$

Table 1. The mean and label difference of the parameters

Variable	Mean value	Standard deviation
The front impact beam d_1	0.7	0.07
The thickness of the inner plate of the energy absorption plate d_2	1.6	0.12
The thickness of the outer plate of the energy absorption plate d_3	1.6	0.12
The thickness of the inner plate of the front longitudinal beam d_4 ,	1.5	0.1
The thickness of the outer plate of the front longitudinal beam d_5	1.6	0.12
The elastic modulus P of the front impact beam	210	20

The reliability index value of the example in this paper is calculated by differential evolution algorithm. The calculation results are shown in Table 2 and the iterative process is shown in Figure 3.

Table 2. The computational results

Reliability index	Failure probability	Iteration times
3.3434	4.1379e-04	35

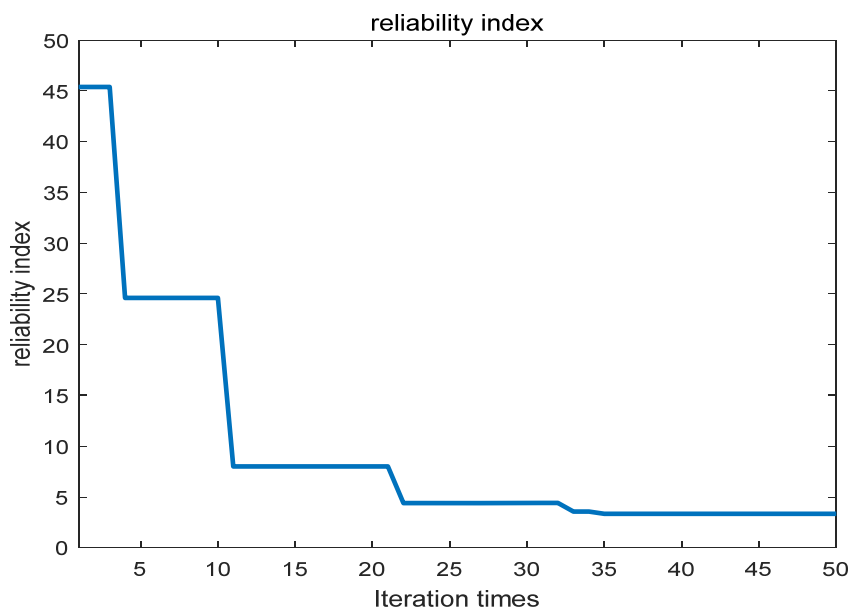


Figure 3. Iterative process of differential evolution algorithm

The reliability index β is 3.34, and the failure probability P_f is $4.1379\text{e-}04$. The stable value of the algorithm is obtained in step 35. Compared with the calculation result $\beta = 3$ in [8], they are basically the same, and this verifies the feasibility and stability of the differential evolution algorithm for the reliability index calculation.

If the correlation of parameters in the vehicle structure is considered, it is considered that the thickness of the inner plate and the outer plate of the energy absorbing plate of the vehicle are correlated, and the correlation coefficient $\rho_{d_2d_3} = 0.8$, the influence of the correlation of parameters on the reliability index is calculated and analyzed, and the iteration diagram is shown in Figure 4.

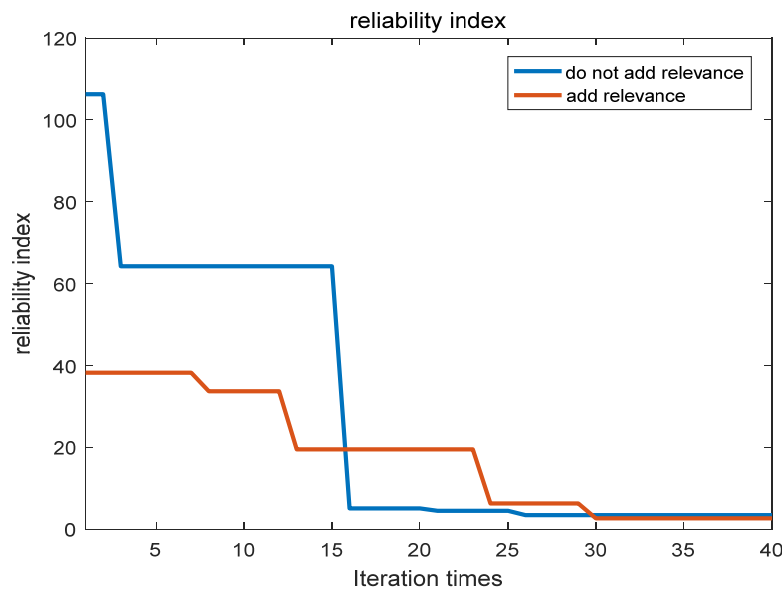


Figure 4. The comparison considering the parameter correlation

The reliability index β is 3.3434 without correlation and 3.3217 with correlation. In this case, the reliability index is reduced and the reliability of the structure is reduced. The algorithm gets stable results in 26 steps without adding correlation, and gets stable results in 30 steps when adding correlation. These results verify the effectiveness of differential evolution algorithm in solving the reliability of car frontal collision.

4. Conclusion

In this paper, we use the differential evolution algorithm to calculate the reliability index of a car frontal collision case. The analysis results show that the parameter correlation will affect the results in the calculation of reliability index, and will lead to the decrease of reliability index in this case. The proposed method can be used to solve the problem of reliability analysis of structural function equation with certain nonlinear degree and reliability model with parameter correlation. In practical engineering design, the present method has certain guiding significance for the prediction of structural reliability.

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