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Reliability Analysis of Pressure Vessel Interval Based on Intelligent Search Algorithm

Shuicai QIU*, Lingyan ZHANG

Abstract: Pressure vessels are mostly made of high-strength steel, metal and some alloys, and the probability statistics of their uncertain parameters are difficult to obtain or can not be obtained at all. At this time, the interval reliability method will be a more reasonable method. Firstly, the interval reliability analysis model of this type of pressure vessel is established, and the calculation expressions of mean value, standard deviation and deviation of fiber stress are derived by using the interval factor method. The interval reliability design of this type of pressure vessel is realized by using the interval reliability calculation method, and the influence of the fluctuation of structural uncertainty parameters on the design size of the vessel thickness is investigated. Examples show that the design results of interval reliability meet the safety requirements, but the accuracy is not as high as that of probabilistic reliability method. Secondly, the approximate model of the stress constraint function is constructed according to the trained BP neural network and the stress intensity evaluation criteria, and then the objective function, the approximate model of the stress constraint function and the value range of the design variables are combined to form a complete optimization mathematical model. The optimized mathematical model is optimized by the cuckoo search algorithm, and the minimum design variable value of the objective function is obtained. Finally, the two independently evolved subpopulations are fused with each other through fixed algebra to strengthen the information exchange between different individuals. Combined with the advantages of intelligent search algorithm, it has a good optimization effect in the optimal design of pressure vessel.

Keywords: cuckoo search algorithm; intelligent search; interval reliability analysis; pressure vessel

1 INTRODUCTION

Compared with traditional metal pressure vessels, composite pressure vessels have the characteristics of corrosion resistance, light weight and strong designability, so they have been widely used in the aerospace field [1]. So far, many researches have been carried out on the structural design and strength check of such vessels at home and abroad, such as the structural optimization design of such vessels in literature [2], and the influence of temperature and winding Angle on the burst pressure of such vessels in literature [3] based on the finite element method. However, the uncertainties of structural parameters and loads are not considered in the above work.

In fact, there are many uncertainties in the manufacture and service of composite pressure vessels, such as the error of geometric parameters such as fiber winding Angle and cylinder radius, the uncertainty of physical parameters and fiber strength caused by the uncertainty of the matrix and fiber components of the material itself, and the volatility of the internal pressure of the container. In order to solve the uncertainty problem of composite pressure vessels, probabilistic reliability methods are adopted in some literatures. For example, in literature [4], probabilistic reliability analysis of vessel structures is carried out by Monte Carlo method and response surface method, considering the randomness of design variables. Literature [5] carried out reliability life prediction for containers with random parameters. In short, the structural analysis and design of composite pressure vessels are still mostly based on deterministic methods. Although probabilistic reliability methods have been applied, Monte Carlo method is often used, which has low computational efficiency and fails to consider the uncertainty when the probabilistic and statistical characteristics of structural parameters cannot be obtained.

Reliability methods for uncertainty problems [6] include probabilistic reliability methods and interval reliability methods. The key of probabilistic reliability analysis is to determine the probability distribution function of each uncertain parameter, which requires sufficient statistical information. However, for the problem of small sample and poor information, the probability statistics of uncertain parameters are difficult or impossible to obtain. At this time, interval reliability method will be a more reasonable choice, because this method only focuses on the value interval of uncertain parameters, and does not need the probability statistics of uncertain parameters, so it is used as a supplement to probability method. In the interval reliability analysis, the upper and lower bounds of the structural response interval are actually its maximum and minimum values, so the interval problem can be transformed into an optimization problem. Literature [7] proposed the interval parameter programming method to solve the optimization problem of interval parameter structure. Reference [8] studies the reliability optimization problem of interval parameter structure based on convex model. Literature [9] uses interval analysis method and particle swarm optimization method to study the structural dynamic response of vehicle-bridge coupling system with interval parameters.

Based on the interval factor method, the probabilistic reliability analysis of the composite cylindrical pressure vessel structure is carried out. The expressions of mean and standard deviation of fiber stress are derived, and the influence of variation coefficient of random variable on the thickness of the vessel is analyzed. Then, using the interval reliability method and the improved Particle Swarm Optimization (PSO) interval algorithm, the interval reliability analysis of the structure was carried out to examine the influence of the variation of interval parameter deviation on the thickness of the container. An optimal design method of pressure vessel based on adaptive cuckoo is proposed, which belongs to the improvement and application field of intelligent optimization algorithm. On the one hand, the search step size of cuckoo birds can be adjusted according to the gap between the current nest and the optimal nest environment fitness value, and the egg discovery probability is calculated according to the standard deviation of the individual fitness value, thus improving the search efficiency of the population. The first part is the introduction, the second part is related work, and the third part is reliability analysis and design of pressure vessel interval based on interval factor method, the fourth part is reliability optimization of pressure vessel interval based on adaptive search cuckoo algorithm, the fifth part is experimental verification, and the sixth part is conclusion.

2 RELATED WORK

At present, most domestic researches on the structure optimization of pressure vessels are based on the finite element analysis theory, and the relevant structures of pressure vessels are optimized on various finite element software. For example, literature [10] takes low-temperature storage tank as the optimization object, first analyzes the influence of various parameters on the critical buckling load by using finite element analysis software, and constructs an optimization model. Finally, in order to realize the lightweight of the storage tank, the structure optimization is carried out by using related plug-ins in Ansys WorkBench. The final optimization results show that the mass of the storage tank is reduced by about 33% under the premise of satisfying the structural strength. In literature [11], the stress distribution of the container structure with large openings outside the specified range of GB15.0 was obtained through ANSYS.

Although it is feasible to use finite element software to optimize the structure of pressure vessels, the finite element analysis process is generally complicated, so designers need to be proficient in this type of software, and the optimization process calculation needs time. In order to find a more efficient pressure vessel structure optimization method, a few researchers in China are using bionic algorithm to optimize the structure of pressure vessel related structures. In literature [12], based on the "analysis method for the design of cylindrical radial nozzle opening reinforcement design" in GB150-2011 Pressure Vessel, an optimization model for cylindrical nozzle opening was constructed under the guidance of design criteria, and genetic algorithm was adopted for global optimization, and the optimal wall thickness of cylindrical nozzle opening meeting the design constraints was finally obtained. Literature [13] et al. proposed a differential evolution pollination algorithm with time-varying factors to accelerate the convergence rate of the pollination algorithm in the optimization process. Finally, the overall structure of the pressure vessel was optimized to reduce the production cost of the vessel, that is, lightweight. Although the research of applying intelligent algorithms to pressure vessel structure optimization has begun in China, the progress of pressure vessel industry is relatively slow compared with other engineering fields.

There are also some researches on the optimization of pressure vessel mechanism abroad. In literature [14], differential evolution and particle swarm optimization methods were used to optimize the geometry and wall thickness of the internal pressure toroidal shell container to obtain the minimum weight toroidal shell under constrained conditions. By comparing the geometrical parameters of the annular shell before and after optimization, the material saving is up to about 32%, and it is found that differential optimization is better than PSO in most cases when solving such problems. In literature [15], simulated annealing algorithm was used to optimize the meridional profile shape of the vessel head under internal pressure, so as to achieve the design goal of minimizing the depth and capacity of the constant thickness closure under geometric and strength constraints. In literature [16], global sensitivity analysis and acoustic search algorithm were used to optimize shell-and-tube heat exchangers. In order to simplify the optimization problem, the gradient method based on the meta-heuristic algorithm is used to optimize the influential geometric parameters. Through an optimization example, the optimization results of the HSA algorithm ((Harmony SearchAlgorithm)) are compared with those of the genetic algorithm. It is found that the HSA algorithm can converge to the optimal solution with higher accuracy.

At present, domestic and foreign researchers have conducted a lot of research on the reliability design of composite materials [17-19]. Literature [20] combined failure criterion and structural reliability model to study reliability optimization and the influence of microscopic material parameters on the reliability of composite materials. Reference [21] studies the strength distribution of unidirectional fiber composites and considers the probability statistics of design parameters. Literature [22] considered the probability distribution of material properties and compared fiber-wound composites with metal materials, and found that the dispersion degree of property distribution of the former was greater than that of the latter. Numerous theoretical and experimental studies have been carried out in literature [23] on the influence of the volume ratio of fiber to resin base on the strength dispersion of unidirectional fiber composites. On the basis of the research of unidirectional fiber composites, scholars have done a lot of research on the reliability of composite laminates. References [24, 25] studied the reliability of composite laminates under random static load in plane. The above studies mainly focus on probability-based reliability analysis of simple structures such as unidirectional fiber composites and composite laminates. However, there are few relevant studies on reliability analysis at present, and most of them are based on deterministic methods. For example, optimization design is carried out in literature [26, 27], but the randomness of material parameters is not considered. Literature [28] studied the influence of temperature and winding Angle on blasting pressure based on finite element method, but did not consider the randomness of temperature and winding Angle. However, it has been observed in many experiments that due to the randomness of the design variables, the bursting pressure is also decentralized [29, 30]. Therefore, literature [31] pointed out for the first time that the use of probability and statistics to analyze the random distribution of material parameters is a necessary condition for structural design. In order to solve these problems, probabilistic reliability method is widely used, which regards structural parameters as random variables, first obtains their probability distribution, and then analyzes their structural reliability.

3 RELIABILITY ANALYSIS AND DESIGN OF PRESSURE VESSEL INTERVAL BASED ON INTERVAL FACTOR METHOD

3.1 Interval Factor Reliability Design

Structural parameters R, t, a and load are considered as interval variables in the interval reliability design of pressure vessel structure. According to the interval operation rules, fiber stress S is also an interval variable, and assuming fiber strength is also an interval variable, then the interval reliability index Z of the structure without strength failure is obtained by using the interference theory of stress and strength and following the definition of probabilistic reliability index:

$$Z = \frac{\sigma_b^c - S^c}{\sigma_b^R + S^R} \tag{1}$$

When $Z > 1$, the structure is reliable, and the larger the Z value, the safer the structure. The expression of fiber stress S derived by interval factor method is as follows:

$$S = \frac{2PR}{3t} + \frac{1-K_a}{2K_a}\frac{P}{t} \tag{2}$$

According to the interval operation rules, the upper and lower bounds of fiber stress $\overline{S}$ can be derived as follows:

$$\overline{S} = \frac{P^C R^C}{t^C}\frac{1-K_a}{K_a}\frac{1+R_l^R}{1-t_l^R} \tag{3}$$

Taking the composite pressure vessel made of glass fiber epoxy resin system as the research object, the numerical characteristic values of each random parameter of 8 pressure vessels were obtained by measuring the randomness of geometric and physical parameters, as shown in Tab. 1.

Table 1 Measurement results of pressure vessel

Random variable	R / km	t	a	δ	Pb
Mean value	75.2	1.96	25.3	2562	41.6
Standard deviation	0.35	0.03	0.34	107	2.09
Coefficient of variation	0.42	1.22	1.35	4.32	5.12

In probabilistic reliability design, the coefficient of variation of each random parameter of the structure may fluctuate. To this end, the influence of variation coefficients of the four random parameters R, a, and P on the design results of t when the reliability of the pressure vessel structure Pr = 0.9999 999 was examined respectively, as shown in Tab. 2.

Table 2 Reliability design results corresponding to different coefficient of variation of each random parameter

	Coefficient of variation				
	2	4	6	8	10
Influence of R	2. 718 5	2. 768 8	2. 872 7	3. 019 1	3. 151
The influence of a	2. 674 3	2. 58 4 5	2. 674 9	2. 665 4	2. 686 2
Influence of δ	2. 449 8	2. 649 3	2. 923 3	3. 327 2	3. 876 0
Pb effect	2. 531 6	2. 626 3	2. 735 3	2. 892 5	3. 052 1

It can be seen from Tab. 2 that the variation coefficient of each random parameter increases, resulting in the design result increasing. However, the randomness of each parameter has different influences on the design results, in order of the influence degree from large to small. $\sigma > R > p > a$. Therefore, in the structural design of composite pressure vessels, the coefficient of variation (that is, the dispersion of values) that has a large influence on the parameters should be controlled.

In the interval reliability design, since the variation of interval parameter deviation rate will have an impact on the design result, as before, when the interval reliability index Z of the pressure vessel structure is 1, the influence of the variation of four interval parameter deviation rates R, a, and P on the design result of the mean thickness C is investigated respectively, as shown in Tab. 2. And Fig. 1 is made according to the data in Tab. 2.

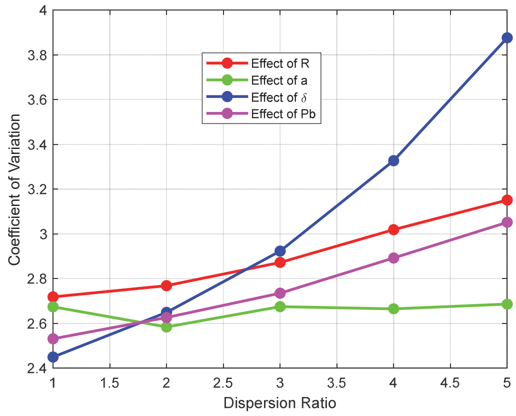

Figure 1 Changes of the mean thickness when the deviation rate of different variables changes

It can be intuitively seen from Fig. 1 that the increase of deviation rate of interval parameters leads to the increase of design result, and the order of influence of deviation rate of different parameters on design result is completely consistent with the result of probabilistic reliability. In addition, comparing the reliability design results corresponding to the same parameters in Tab. 2 and Tab. 1, it can be seen that the dispersion degree of the results of the interval reliability design is small, which indicates that the interval reliability design allows large uncertainty of parameters.

3.2 Interval Reliability Analysis of Pressure Vessel Based on Interval Finite Element Algorithm

In the structure of pressure vessel, there are a lot of uncertain factors. For example, the material and size of the structure and the load (such as temperature, pressure, etc.) it is subjected to. It is often difficult to determine the value of these variables, and in the actual operation of the pressure vessel, its load is also changed in a range.

For linear elasticity problem of finite element with fixed value, the governing equation is:

$$[K]\{\sigma\} = \{F\} \tag{4}$$

where $[K]$ is stiffness matrix; $[F]$ - load vector. $[K]$ depends on the properties and shape of the material, $\{F\}$ depends on the form of the load. For the pressure vessel structure, assuming that there are N random variables, the relationship between the response function of the pressure vessel and the random variables x_1, x_2, x_3 is as follows:

$$\alpha = f(x_1, x_2, x_3 ...) \tag{5}$$

Because higher-order nonlinear time-varying weight factors can obtain faster convergence speed, the inertial weight factor of the algorithm will decrease linearly with the increase of the number of iterations. The formula is as follows:

$$w(l+1) = w_{\max} - (w_{\max} - w_{\min})\frac{l}{l_{\max}} \quad (6)$$

The algorithm flow chart is shown in Fig. 2.

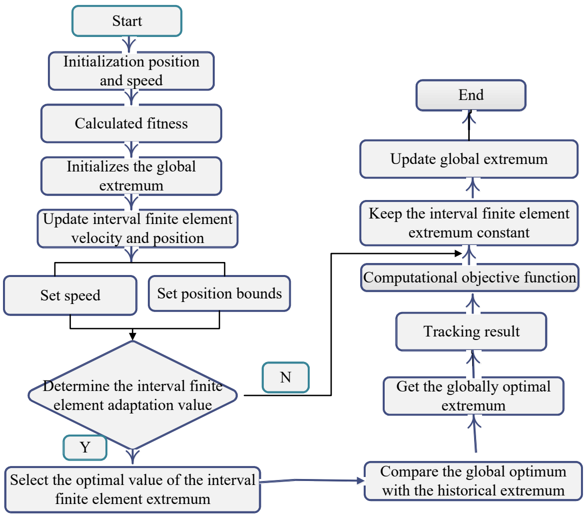

Figure 2 Flow chart of interval finite element optimization algorithm

The three-dimensional finite element calculation model of a spherical pressure vessel is shown in Fig. 3. The inside diameter, wall thickness, internal pressure and yield strength of the pressure vessel are all random variables, as shown in Tab. 3.

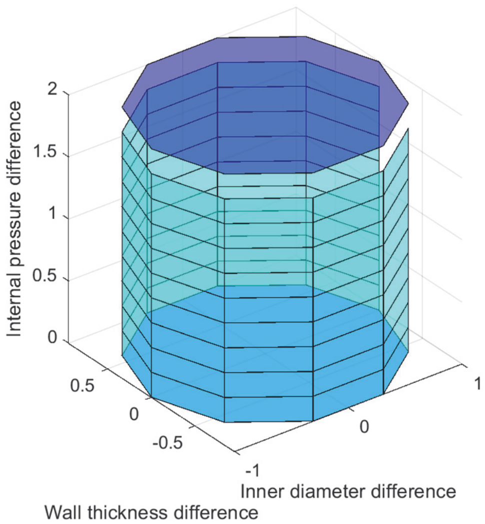

Figure 3 Finite element model of pressure vessel

Table 3 Uncertainty parameters of pressure vessel structure

Variable	D /mm	t /mm	P / MPa	R / MPa
Mean value	1000	70	28	175
variance	5	0. 38	4	15
Distribution type	Normal distribution	Normal distribution	Normal distribution	Normal distribution

According to the combination of the interval value of the given variable, the combined value is calculated by the finite element software, and the interval value of the stress of the pressure vessel structure is obtained. In order to consider the reliability of the structure under different k values, Tab. 4 lists the stress interval and reliability of the pressure vessel when k values are 1, 1.5, 2, and 2.5. It can be seen that the greater the value of k, the greater the range of the interval. When $k = 1$, the non-probabilistic reliability of the structure is 1.619, and the pressure vessel is safe. When $k = 1.5, 2, 2.5$, the non-probabilistic reliability is less than 1, and the structure is between failure and safety. According to the definition of non-probabilistic reliability, the pressure vessel is not reliable at this time and therefore cannot be used. It can be seen that the pressure vessel is reliable when the variation interval of the variable is strictly controlled, that is, within a variance interval. But this is often impossible in practical engineering.

Table 4 Range estimation of pressure vessel structural stress

k	Pressure solution / m	Pressure solves the upper bound / m	Reliability
1	125.5	144.9	1.619
1.5	97.8	154.8	0.954
2	88.3	164.8	0.711
2.5	81.1	174.6	0.562

4 RELIABILITY OPTIMIZATION OF PRESSURE VESSEL INTERVAL BASED ON ADAPTIVE SEARCH CUCKOO ALGORITHM

4.1 Optimization Analysis of Pressure Vessel Based on Adaptive Cuckoo Algorithm

The Cuckoo algorithm uses the way of Levy-flight to update the information of the individual, so that the cuckoo constantly explores the region where the optimal value may exist. After several iterations of selection, the individual can finally determine the global optimal solution of the function. The fireworks algorithm generates a large number of Mars in all directions of space through the explosion point, while comparing the adaptation values of all Mars, reserving the best explosion point position, and constantly improving the optimal value of each generation population. By mixing cuckoo and fireworks algorithms, using two evolutionary environments in the same population, and then mixing evolutionary selection after a certain period of time, not only ensures the independence of each algorithm, but also facilitates the complementary advantages between different population evolutionary methods.

This paper adopts the adaptive Cuckoo algorithm and adaptively adjusts the parameters of the algorithm. The solution includes the following steps:

(1) Through the mathematical modeling of the pressure vessel, each variable affecting the structural performance of the pressure vessel and its variation range is determined, and the objective function of the optimization of the pressure vessel structure is established. The optimal design of pressure vessel is to obtain the best vessel performance at the lowest cost by adjusting various structural parameters. The following functional model is established based on the functional relationship between pressure vessel parameters and performance:

$$\min f(x) = 0.624x_1x_2x_3 + 1.78x_2x_4 + 19.84x_1x_3 \quad (7)$$

$$\begin{aligned} g_1(x) &= -x_1 + 0.019x_3 \\ g_2(x) &= -x_2 + 0.00954x_3 \\ g_3(x) &= -x_3^2 - \frac{1}{3}\pi x_3^2 \\ g_4(x) &= x_4 - 24 \end{aligned} \tag{8}$$

x_1 represents the thickness of the inner wall of the container, x_2 represents the thickness of the circular head of the container, x_3 is the inner diameter of the circular head, x_4 is the length of the cylindrical part of the container. In the above formula, $f(x)$ is the desired objective function;

(2) Set the initialization parameters and population of Cuckoo algorithm. Initialization parameters: In Cuckoo algorithm, search step a, cuckoo egg discovery probability Pa. In the fireworks algorithm, Radius of the explosion point R_i, number of sparks at the explosion point; i, number of layers at the explosion point W. According to the objective function dimension obtained in industrial production D, the size of the population N_p, the maximum number of iterations of an individual GMAX, set the current iteration number $t = 0$, and the first individual of the population in the t generation can be represented as:

$$X_i^t = (x_{i,1}^t, x_{i,2}^t .....x_{i,D}^t) \tag{9}$$

The feasible search domain of the population is $[X_{\min}, X_{\max}]$, and each dimension of the individual must be limited within the specified range.

Population initialization:

$$X_i^0 = X_{\min} + \text{rand}(1, N_p)(X_{\max} - X_{\min}) \tag{10}$$

rand(1, N_p) generates N_p uniform random numbers between (0, 1) when the algorithm is run;

(3) The population of the algorithm is divided into two subpopulations: $N_1 = N_p/2$, $N_z = N_p/2$; N_1 and N_2 were placed in two completely separate evolutionary environments (E_1, E_2).

(4) In the evolutionary environment E_1, the population follows the basic flow of cuckoo algorithm:

The location of the nest of the contemporary cuckoo is Y_i, and the individual searches the nest of the next generation by Levi's formula, thus realizing the random search of space. The fit values of alternative nests were calculated, the fit values were compared, and the individuals with the top fit values in the two populations were selected to form a new cuckoo nest.

Each bird's nest generates uniformly distributed random numbers. If the probability of cuckoo eggs being found by the original bird's nest owner is less than, it indicates that the original host has already found cuckoo eggs. Therefore, cuckoo birds need to randomly find new nests and eliminate the disadvantaged nests by comparing the sizes of the two adaptation values. If it is greater than that, the cuckoo's nest does not change. Finally, the location of the cuckoo's nest was updated, generating a new generation of nest locations.

(5) Information exchange between subpopulations. In the process of population evolution, subpopulations N_1 and N_2 are merged into a population N every 10 generations, a single evolutionary environment is set as E, the adaptation values of cuckoo individuals are sorted, and the current best individuals are recorded;

(6) Termination of inspection: Determine whether the algorithm meets the termination condition, the algorithm ends, and the optimal value is output.

The flow chart is as follows in Fig. 4.

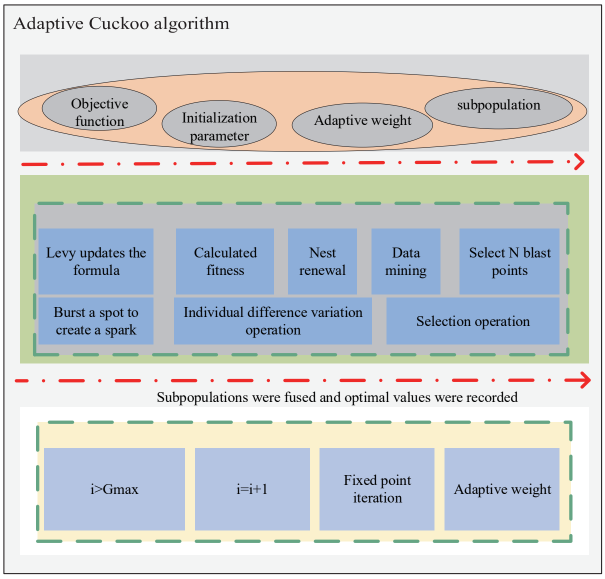

Figure 4 Pressure vessel optimization algorithm based on adaptive Cuckoo algorithm

The symbol variables in this article are shown in Tab. 5.

Table 5 Symbol variables

Symbol	Meaning
Z	interval reliability index
σ	probabilistic reliability index
S	fiber stress
P, R	Structural parameters
[K]	Stiffness matrix
[F]	Load vector
w	inertial weight factor
$f(x)$	desired objective function

There are many abbreviations, as shown in Tab. 6.

Table 6 Abbreviations

Abbreviations	Full name
PSO	Particle Swarm Optimization
ANSYS	Analysis Software
HSA	Harmony Search Algorithm

4.2 Interval Reliability Analysis of Adaptive Search Cuckoo Algorithm

In the optimization problem, it is necessary to establish an accurate mathematical model first, and then adopt the appropriate optimization algorithm to meet the constraints of conditions, obtain the extreme value of the objective function, and establish the optimal design scheme. ANSYS (Analysis Software) structure optimization design process is based on a large number of adaptive search cuckoo algorithms to complete a series of optimization iterative processes until all constraints are satisfied to get the final optimization result.

Still using the model established before, the loading part has changed. The static analysis before showed that the applied load does not change with time, but now the applied load changes linearly with time. Therefore, a function is set, with time as the independent variable and the dependent variable as the load, and the following function is obtained:

$$P = 50000 * Time(0 \prec Time \prec 1) \tag{12}$$

This function is applied to a composite pressure vessel as a pressure load. Set the time interval of the load step to 0.01 seconds and the end time to 1 second to solve. It can be seen from the results that setting such a time interval is accurate enough, and then the results need to be queried in the time history post-processor. Since the time history post-processor can only query the functional relationship between a specific node and time, the node with the largest displacement needs to be obtained in the general post-processor. It is necessary to use the query result option. Through this method, the maximum node number is 852. Then, in the post-time history processor, check the relationship between the ring displacement in the *Y* direction of the node number 852 and the time, as shown in Fig. 5.

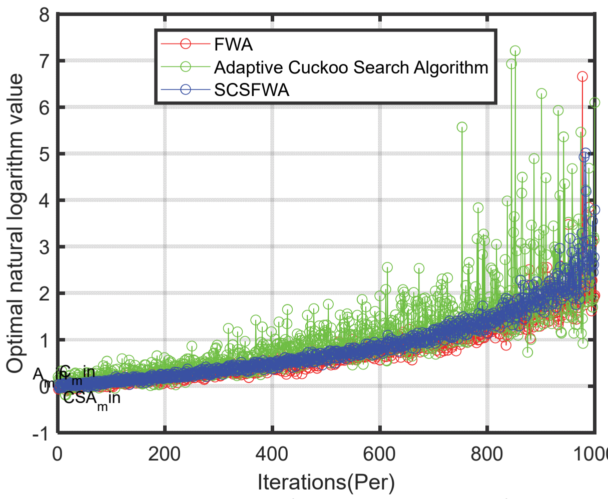

Figure 5 Maximum *Y* - circumferential displacement time function

The sensitivity analysis of the output results can help to find the quantity that has a large impact on the results, so as to obtain the optimal design variables. If the influence level of the input variable on the output variable is below 2.5%, it can be classified as a factor with little influence, and if the influence level is above 2.5%, it can be classified as a factor with significant influence. It can be seen from Fig. 6 that material thickness and internal pressure are the main factors affecting deformation. The thickness is negatively related to the amount of deformation, and the internal pressure is positively related to the amount of deformation. In addition, the longitudinal tensile elastic modulus and plane shear modulus are also the main factors affecting the deformation, and they are negatively correlated with the deformation amount. The effects of transverse elastic modulus, interlayer elastic modulus and shear modulus in the other two planes on the failure probability can be ignored.

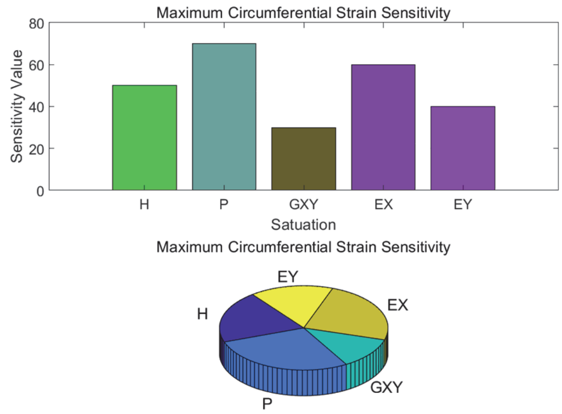

Figure 6 Maximum circumferential strain sensitivity

The mathematical model for optimal design of pressure vessel interval reliability *US* is as follows:

$$\text{Subject, to, } US \in [US_{\min}, US_{\max}] \tag{13}$$

In this paper, the intelligent search algorithm adopts the difference variation method instead of the Gaussian method in the basic algorithm, which simplifies the evolution process and increases the purpose of individual selection, and increases the probability of finding a better individual. The cuckoo algorithm is used to solve the optimal design problem of pressure vessel. The hybrid algorithm keeps the diversity of population in the process of evolution, and the search individual can adaptively adjust its search focus according to the distribution law of the optimal value in the feasible region. By comparing the basic Cuckoo algorithm with other algorithms, the container design cost is reduced and the container parameters with higher precision are obtained.

5 SIMULATION VERIFICATION

In order to illustrate the iteration of the intelligent search algorithm, when the deviation rate of the interval variable takes different values, the intelligent search algorithm can converge within 100 iterations. In the interval reliability design, the variation of interval parameter deviation will affect the design result. The influence of the variation of parameter deviation rate in *R*, *a*, *Rb* and *P* intervals on the design result of thickness *t* is investigated, as shown in Fig. 7.

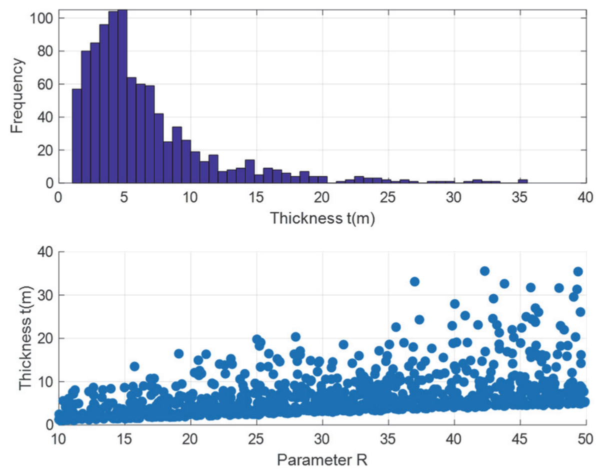

Figure 7 Thickness variation range when deviation rate of different parameters changes

It can be seen from Fig. 7 that the interval limit of *t* increases with the increase of the interval parameter deviation rate. Compared with the results in the figure, it is basically consistent with the probabilistic reliability design results according to the influence degree of each parameter on the thickness. It shows that the interval reliability design allows large uncertainty of parameters. When the deviation rate of all variables increases, the value range of *t* increases. Therefore, properly increasing the dispersion of fiber strength can improve the lower limit of design thickness and improve reliability.

There are several parameters in cuckoo search algorithm, besides the two key parameters of population size n and discovery probability pa, there are also step scale factor a and Levy index entry. Set the population size n = 30 unchanged, the discovery probability of cuckoo search algorithm is pa, and accordingly is 0.05, 0.25, 0.5, and the maximum iteration number of algorithm is 100. The iterative curves of the optimization process of the cuckoo search algorithm with three discovery probabilities are shown in Fig. 8 below.

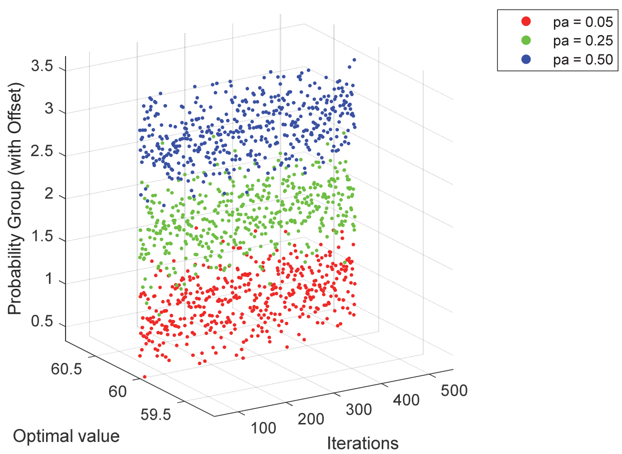

Figure 8 Fitness evolution curve of Cuckoo algorithm iteration process with different discovery probabilities

The three cuckoo search algorithms with no discovery probability are cycled 30 times in MATLAB for optimization, and their average values are calculated for comparative analysis, and the table is drawn as shown in Tab. 7.

Table 7 Optimization results of Cuckoo algorithm with different discovery probabilities

Discovery probability	*Re*	*Ret*	*h*	*V*	Number of iterations with the most solutions
0.05	8	13.0723	316	1 .8374	38
0.25	8	13.0741	314.9889	1 .8374	41
0.50	8	13.0726	314.9740	1 .8374	63

Based on the influence of cuckoo parameters on the convergence speed and convergence effect, the cuckoo search algorithm was used to optimize the optimization model to obtain the optimal structural geometry model size. After rounding, finite element analysis was carried out to verify that the optimized structure met the stress intensity criterion. According to the mathematical model of this optimization function, its two-dimensional grid image is given, as shown in Fig. 9. It shows that the optimization method in this paper has a good effect on the optimization of the structure.

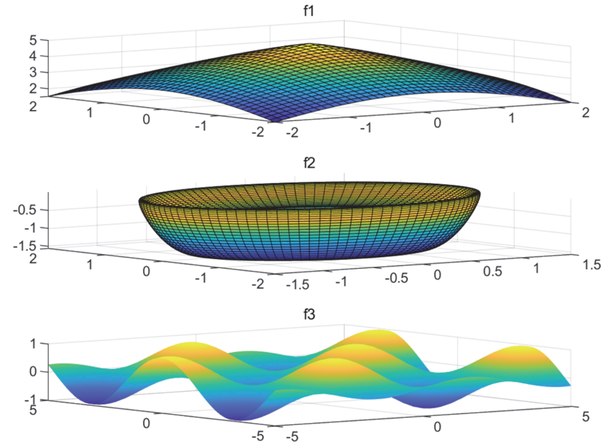

Figure 9 Two-dimensional grid diagram of optimization function

The model was simulated, the population size was set to 30, the evolutionary algebra was set to 1000, the transformation target method was used to process constraints, the model was optimized, and finally the optimal frontier of the corresponding intelligent search algorithm was obtained. The spatial distribution among the targets is shown in Fig. 10.

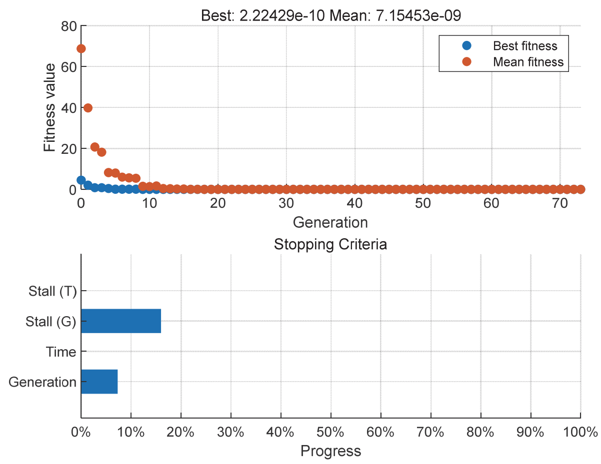

Figure 10 Non-dominated solution set of intelligent search algorithm

The maximum and minimum values of individual independent variables and targets in the optimal front of the intelligent search algorithm are shown in Tab. 8.

When each target takes the minimum value, the values of other targets and independent variables are shown in Tab. 9.

Table 8 Maximum and minimum values of independent variables and targets

Parameter	*L*	*h*	*L*	*R*	*U*	*S*	*C*
Minimum value	252	0.6	11	0.1186	328.6	6.26	28.21
Maximum value	502	0.616	12.109	0.1776	617.2	12.6	59.53

Table 9 Values of targets and independent variables when the minimum values of each target are taken

Parameter	*L*	*h*	*L*	*R*	*U*	*S*	*C*
R	500	0.6	10.0972	0.1186	328.6	12.26	59.53
U	502	0.6	10.0819	0.1196	328.6	12.6	59.53
S	252	0.6	11.7842	0.1767	597.6	6.26	28.21
C	251	0.6	11 .9657	0.1783	618.1	6.26	27.21

According to the maximum and minimum values of the individual independent variable and the target in the optimal frontier of the intelligent search algorithm, as shown in Tab. 6, the maximum and minimum values of the non-dominated solution of the intelligent search algorithm obtained by the two constraint methods are basically the same on the objective function, and the difference is small. From the distribution of the optimal solution set of the intelligent search algorithm in the target space obtained by the two methods, they are basically the same. As can be seen from Fig. 10, the solution set of the intelligent search algorithm obtained by the multi-objective optimization method presents a strip or strip distribution, which is close to the front end of the intelligent search algorithm of the model itself. This shows that the method proposed in this paper is feasible, and its performance is not much different from that of penalty function method, and it is suitable for constrained multi-objective optimization problems. As can be seen from Tab. 7, each target basically obtains the minimum value at the end point, *R* and *Ut* obtain the minimum value when the ground network area is maximum, and then *S* and *F* obtain the maximum value, *R* and *Ut* obtain the maximum value when the ground network area is minimum, and then *S* obtains the minimum value. It can be seen from the relevant formula that S is only related to the length and width of the ground network, and the width and fixed in this paper, so *S* is only related to the length of the ground network, and the two have a linear relationship. Although it is related to the length *L* and width of the ground network, the length of the vertical grounding pole and the number of horizontal and vertical grounding pole conductors, the vertical grounding pole is only a supplement to the horizontal grounding pole, and the number of horizontal grounding pole conductors is ultimately determined by the length *L* and width of the ground network. *R* and *Ut* are related to the three parameters, and the length of the ground network is also the most influential. Therefore, the maximum and minimum values of the pressure vessel interval reliability non-dominated solution of the intelligent search algorithm are obtained at the end points of the parameters.

In the interval reliability design, since the variation of interval parameter deviation rate will have an impact on the design result, the influence of the variation of four interval parameter deviation rates *R*, *a*, *Rb* and *P* on the design result of thickness *t* was investigated respectively, as shown in Fig. 11 to Fig. 13.

It can be seen from Fig. 11 to Fig. 13 that the interval limit of thickness t increases with the increase of interval parameter deviation rate, in which a has the greatest influence on *t*. Therefore, as shown in Fig. 12, when the deviation rate of all variables is the same, the trend of thickness variation range is consistent with that when the deviation rate changes separately, which further indicates that a has the greatest influence on *t*. The results in Fig. 11 to Fig. 13 are compared. According to the influence degree of each parameter on the thickness, the order is $a > R$, which is basically consistent with the probabilistic reliability design results. At the same time, comparing the results of thickness mean values, it can also be seen that the dispersion degree of the results of the interval reliability design is small, which indicates that the interval reliability design allows large uncertainty of parameters.

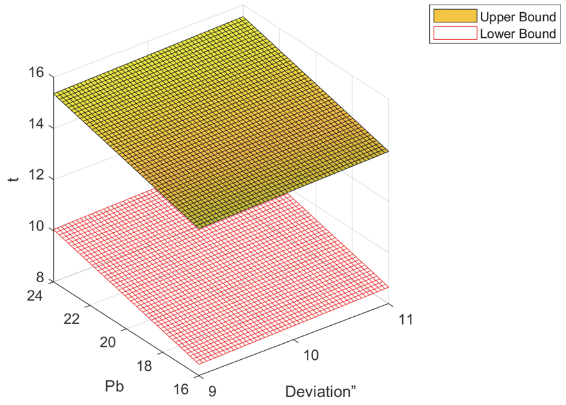

Figure 11 Thickness variation range when *Pb* dispersion changes

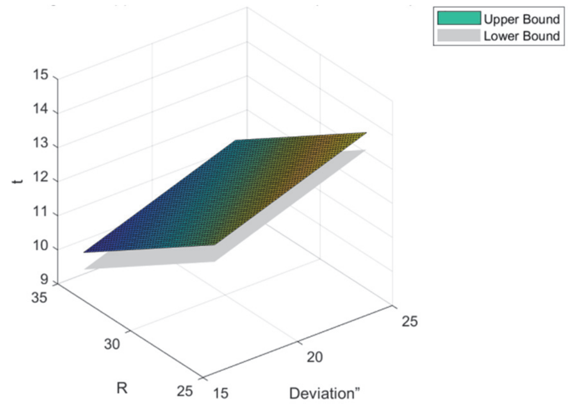

Figure 12 Thickness variation range when *R* deviation rate changes

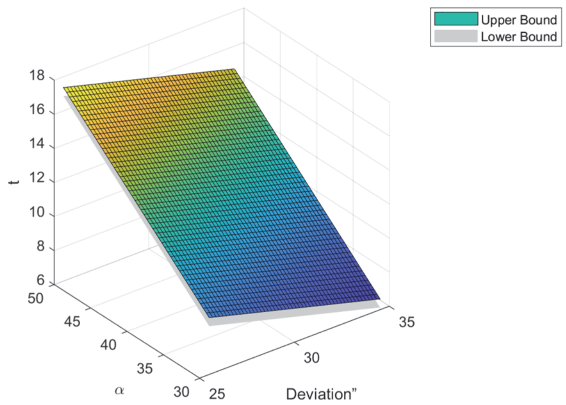

Figure 13 Thickness variation range when deviation rate changes

However, there are some differences in the application scope of intelligent search algorithm, and not one method can solve all the problems about the reliability analysis and design of pressure vessel interval. In some special cases, when the random distribution of design parameters is known, probabilistic reliability should first be used for analysis and design, which is the most accurate and commonly used method. However, in most cases, the pressure vessel cannot conduct a large number of sample tests, so it is mostly a small sample problem. However, the interval range of the design parameters can generally be obtained, so the method proposed in this paper must be adopted, namely, the interval reliability method based on the interval factor method and the interval reliability analysis method based on the intelligent search Cuckoo algorithm. For these two methods, there are some differences, interval factor method needs more complicated formula derivation, based on the improved intelligent search cuckoo algorithm interval reliability method can be implemented by computer programming, relatively simple and easy, but sometimes for large finite element problems may also be very time-consuming. In summary, when the probability statistics of design parameters are known, the probabilistic reliability method should first be used for analysis and design, and the other two interval reliability methods can be used as a necessary supplement to the probabilistic reliability method. The specific operation is to convert the parameters of normal distribution into interval parameters. The normal parameters can be transformed into normal parameters by the method of equivalent normalization, and then the parameters of normal distribution can be transformed into interval parameters according to the criterion. When the probability statistics of design parameters cannot be obtained, the interval range of design parameters can be obtained in most cases, so the interval reliability method of intelligent search algorithm can be used as a reference for the reliability design of pressure vessels.

6 CONCLUSION

The design results of probability and interval reliability methods (i.e., average thickness) are closer to the experimental results, and both are significantly better than the traditional deterministic analysis methods, indicating that the reliability method makes the design results more accurate and reasonable. In the interval reliability design, the deviation rate of interval variables arranged according to the degree of influence is completely consistent with the probabilistic reliability design. The comparison of the corresponding design results when the same parameter value fluctuates between probability and interval reliability design shows that the dispersion degree of interval reliability design results is small, that is, interval reliability design can tolerate greater uncertainty. With the mean of design thickness as the comparison standard, the probabilistic reliability design result obtained by the random factor method is closer to the actual value than that obtained by the interval factor method, indicating that the probabilistic reliability method has higher accuracy. However, in terms of computational complexity, the calculation formula of random factor method is long and the derivation process is also complicated. Compared with interval algorithm, it is easier, it does not need algebraic synthesis method or moment method, and saves the process of derivation, and the calculation formula is more concise. In this paper, an interval reliability model of pressure vessel based on intelligent search algorithm is proposed, which saves the complicated formula derivation of interval reliability model based on interval factor method, and is more convenient for computer programming, and effectively improves the computational efficiency of interval reliability analysis and design. In the probabilistic reliability analysis, this paper assumes that each variable follows a normal distribution. In fact, if possible, it is better to conduct a large number of sample statistics to obtain the real probability model of the samples and the general law of probability and interval reliability. However, the research is not detailed enough. The next step in research on interval reliability analysis of pressure vessels based on intelligent search algorithms will focus on algorithm optimization and integration, refinement of interval reliability models, experimental validation and data analysis, multidisciplinary fusion, and intelligent design and optimization. The aim is to further enhance the accuracy and efficiency of the analysis, and to promote the intelligent development of pressure vessel design and manufacturing technologies.

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Contact information:

Shuicai QIU
(Corresponding author)
Department of Mechanical and Material Engineering,
Changzhou University Huaide College,
Jingjiang, 214500, China
E-mail: qiushuicai_czuh@163.com

Lingyan ZHANG
Department of Mechanical and Material Engineering,
Changzhou University Huaide College,
Jingjiang, 214500, China