Fuzzy Optimization Method of Mechanical Engineering under the Background of Mechatronics

Ansong Qin, Zhiyuan Yan, Jun WANG, Xiaojun Huang, Linjun Jian

3rd Construction Co., Ltd of China Construction 5th Engineering Bureau, Changsha, Hunan 410116, China

970419866@qq.com

Keywords: Electromechanical integration, Mechanical engineering, Fuzzy optimization

Abstract: At first, the application of mechatronics was widely used in automobile field, and then, with the gradual maturity of technology, it was popularized and applied in the field of construction machinery. The fuzziness method is applied to deal with various fuzziness phenomena and influencing factors objectively existing in the field of mechanical engineering, which makes the engineering design, manufacturing and production management more realistic, reasonable and scientific. In this paper, the structural optimization model of mechanical engineering is established by combining fuzzy mathematics theory with finite element method. In the optimization process, an improved horizontal cut set method is used to consider the influence of fuzzy constraints. By defining membership functions, the problem is transformed into a clear ordinary optimization problem and solved by the improved algorithm, so as to improve the accuracy and reliability of the solution.

1. Introduction

With the development of the times and the improvement of productivity, the traditional construction machinery gradually transits to the electromechanical integration era. In this context, the application of construction machinery will be crucial. The reason why mechatronics technology has developed rapidly is precisely because of its own advantages [1].

Mechanical optimization design is a kind of design which gives priority to design parameters (design variables) and makes one or several design indexes (objective functions) of a certain mechanical design obtain the optimal value under various specified constraints. Mathematically, this kind of problem can be expressed as: finding the minimum value of the multivariate objective function under the constraints of some equality or inequality [2]. As long as one or more fuzzy factors are included in design variables, objective functions and constraints, it becomes a fuzzy optimization problem.

2. Application Characteristics of Mechatronics

From the current development characteristics of mechatronics, it is mainly reflected in the level of strong production capacity. Under the application of mechatronics equipment of construction machinery and the automatic processing of information, automatic control can be realized, and the functions of high-precision control and high-sensitivity detection can be effectively exerted.

Under the application of mechatronics equipment, as long as the control system can be started, the automation level of production can also be improved, and the application value can be maximized [3]. Due to the application of integrated technology, the performance of mechanical equipment has been improved, and its functions are relatively complete, which makes the functions of monitoring and alarm give full play, and the function of automatic protection can also be effectively improved. In this way, the application safety of mechanical equipment can be effectively guaranteed.

The characteristics of mechatronics mechanical equipment are also reflected in the wide application range. In this process, due to the application of composite technology, the composite

  DOI: 10.25236/iccem.2021.004

function of mechanical equipment itself is also more prominent, so that the application range can be expanded.

3. Fuzzy Sets and the Probability of Fuzzy Events

Modern design is a scientific, rational, dynamic and computerized process. On the basis of comprehensive consideration of various influencing factors, it uses the latest contemporary technical means and methods to extract the most reasonable data, so that the design scheme can achieve the best [5]. As an important part of modern design method, the importance of fuzzy design has been gradually recognized by people. With the application of fuzzy optimization design, fuzzy reliability design, fuzzy control technology and fuzzy expert system, modern design theory and method have developed to a new stage.

Vagueness is common in mechanical engineering. For example, the purpose of mechanical design is to make the designed products have good performance, high efficiency, long service life, safety and reliability, and convenient use and maintenance. Here, the concepts of “good and bad”, “high and low”, “long and short”, “safety and danger”, “convenience and trouble” are vague.

Because fuzzy set theory can solve a lot of fuzzy problems in engineering, it has developed rapidly and has become a branch of applied mathematics. Ordinary sets study either-or phenomena, which can be characterized by characteristic functions. For any subset A in the universe U, the mapping of formula (1) is called the characteristic function of set A.

$$X_A : U \to \{0,1\}$$
$$u \to X_A(u) = \begin{cases} 1, & u \in A \\ 0, & u \notin A \end{cases} \quad (1)$$

Whether any element in the domain belongs to the set A is clear. However, the boundaries of some subsets in the universe are not obvious, and there is no explicit extension, that is, whether the element u belongs to this subset can not be answered clearly, but only the degree to which it belongs to this subset, which is called membership degree, and the corresponding function is called membership function.

Fuzzy subset $\tilde{A}$ refers to the assignment of a number $\mu_{\tilde{A}}(u) \in [0,1]$ to any $u \in U$ in the universe U, which is called $\mu_{\tilde{A}}$ as the membership degree of u to $\tilde{A}$, and formula (2) as the membership function of $\tilde{A}$.

$$\mu_{\tilde{A}} : U \to \{0,1\}$$
$$u \to \mu_{\tilde{A}} \quad (2)$$

There is an essential difference between fuzziness and randomness. Reliability design mainly considers the randomness of design variables, and is based on probability statistics. However, there are many fuzzy problems involved in reliability design, which need to be dealt with by fuzzy set theory. One of the main applications in reliability design is the calculation of fuzzy event probability.

On the universe U, if the fuzzy subset $\tilde{A}$ is a random variable, then $\tilde{A}$ is called a fuzzy event. The probability of fuzzy events is defined as:

$$P(\tilde{A}) = \int_U \mu_{\tilde{A}}(x) f(x) dx = E[\mu_{\tilde{A}}(x)] \quad (3)$$

If the universe U is a finite set, the above formula can be written as:

$$P(\tilde{A}) = \sum_{i=1}^{n} \mu_{\tilde{A}}(x_i) P(x_i) \quad (4)$$

4. Fuzzy Optimization of Engineering Structure

In engineering design, people always consider various design schemes, then analyze and compare them, and finally choose the most satisfactory one. This satisfactory scheme is also the optimized scheme.

However, due to the general fuzziness of things caused by the intermediary transition process between things, the quantitative research from physical field to rational field will inevitably encounter a large number of fuzzy concepts, the complexity of research objects will inevitably involve various fuzzy factors, and the research of information technology and artificial intelligence will inevitably consider the identification and processing of fuzzy information, which will inevitably lead to the optimization design problem involving various fuzzy factors [5]. How to reflect the objective fuzziness in the optimization design of engineering structure is exactly the problem to be solved by fuzzy optimization.

4.1 Bi-Objective Fuzzy Optimization Model

Because the problem of multi-objective fuzzy optimization is not well solved in theory, it is always difficult to deal with multi-objective fuzzy optimization in engineering. If there are only two objectives in the fuzzy optimization design of the structure, we will extend the method of dealing with single objective fuzzy optimization appropriately, and we can also approximate the fuzzy optimization of two targets.

The solution of single objective fuzzy optimization design is to transform fuzzy optimization into ordinary optimization [6]. The result of optimization is a series of fuzzy optimization points in the design space. How can we make further optimization from the series of optimization points and find out the most satisfactory solution to the problem? If it is a bi-objective problem, we can carry out the second step of optimization.

Set up bi-objective fuzzy programming and find design variables:

$$\left.\begin{array}{c} X \in R^n \\ \min\{F_1(X), F_2(X)\} \\ s.t.\ \tilde{g}_u(X) \tilde{\subset} \tilde{G}_u \qquad u = 1,2,\cdots,m \end{array}\right\} \quad (5)$$

Obviously, this is a bi-objective programming problem with generalized fuzzy constraints.

The model (5) contains two objective functions $F_1(X), F_2(X)$. If the importance of the two objective functions is different, the main one can be selected first, assuming $F_I(X)$. In the first optimization step, only this main objective is grasped, and the following single-objective fuzzy programming problem is solved:

Seek design variables:

$$\left.\begin{array}{c} X \in R^n \\ \min F_I(X) \\ s.t.\ \tilde{g}_u(X) \tilde{\subset} \tilde{G} \qquad u = 1,2,\cdots,m \end{array}\right\} \quad (6)$$

4.2 Two-Level Fuzzy Optimization Method

Because some solutions are transformed from fuzzy programming to a series of ordinary deterministic programming, they are solved by general structural optimization methods. In the design space, a series of fuzzy optimization points $X^*(\lambda_s)(s = 1,2,\cdots S)$ can be obtained, which satisfy all constraints at the constraint level of λ_s, and are the solutions of formula (6).

Series $X^*(\lambda_s)(s = 1,2,\cdots S)$ of fuzzy optimization points is a function with λ as the independent variable. when considering the second objective function $F_2(X)$, we can select the point that minimizes $F_2(X_S^*)$ from the above S optimizations. therefore, let's say:

$$\phi_2(\lambda_s) = F_2(X_S^*) \quad (7)$$

We can write the mathematical model of the second step optimization:
Seek design variables:

$$\left.\begin{array}{c}\lambda^{**} \\ \min \phi_2(\lambda) \\ s.t.\ \lambda \tilde{\geq} \lambda^{*}\end{array}\right\} \quad (8)$$

Obviously, here is a very simple extremum problem with one variable, and λ^* is the optimal constraint level in the first step of optimization.

In order to ensure the reliability of the project optimization scheme, the optimal constraint level of the second step optimization should not be lower than the constraint level of the first step, namely $\lambda^{**} \geq \lambda^*$. Of course, this is only a conservative modification, and λ^{**} should be around λ^*.

After solving the programming of formula (8) and getting λ^{**}, the most satisfactory solution $X^*(\lambda^{**})$ of the fuzzy programming problem of formula (5) is also obtained.

5. Application of Fuzzy Optimization in Mechanical Engineering

In fact, there are a lot of uncertain information in the early stage of engineering structure design, such as the allowable displacement of the frame has a transitional stage from allowable to totally unacceptable, etc. [7]. Therefore, this section combines the relevant theories of fuzzy mathematics with the finite element method, and according to the complexity of the actual project, selects appropriate fuzzy parameters, and makes some discussions on the structural fuzzy finite element optimization design of the outer frame of a three-axis turntable.

5.1 Establishment of Finite Element Model

The central idea of finite element is to divide the solution domain into elements, and the establishment of its model includes two parts, namely, the establishment of the model and the division of the model elements. The frame system of three-axis turntable mainly includes shaft, frame and bearing. In this paper, the method of entity modeling is adopted to set up each part, and all variables related to optimization are established in parametric form. The load part of the outer frame shafting is simplified as equivalent mass, which is applied to the corresponding position of the outer frame.

According to the structural characteristics, the shell element with six degrees of freedom is used to mesh the frame and shaft in finite element, and the connecting bearing between each component is simplified as a spring boundary element with only stiffness and no mass, which is added to the corresponding node position of the bearing according to its equivalent stiffness. Finally, the load and boundary conditions are introduced to establish the finite element model.

5.2 Selection of Fuzzy Membership Function

Membership function is the most basic concept in fuzzy mathematics. $\mu_G(g)$ curve of membership function mainly represents the available domain of fuzzy boundary, and its function shape will have a great influence on fuzzy optimal solution. According to the nature of constraints and design requirements, the following linear functions are adopted for the fuzzy subset of $\mu_f(X)$ with frequency constraints:

$$\mu_f(X)=\begin{cases}1, & f \geq [f] \\ 1-\dfrac{[f]-f}{d_f}, & [f]-d_f < f < [f] \\ 0, & f \leq [f]-d_f\end{cases} \quad (9)$$

Where, $[f]$ is the minimum allowable value of the first-order natural frequency, which is taken as 73Hz; according to the index requirements; d_f is the allowable deviation of frequency constraint, which is determined to be 2.5Hz by amplification coefficient method.

The following linear function is used for the fuzzy subset of displacement constraint $\mu_{|d|}(X)$:

$$\mu_{|d|}(X)=\begin{cases}1, & |d|\le[d]\\ 1-\dfrac{|d|-[d]}{d_d}, & [d]<|d|<[d]+d_d\\ 0, & |d|\ge[d]+d_d\end{cases} \tag{10}$$

Where $[d]$ is the maximum allowable deformation value of the node, and $1.3\times10^{-4}\text{m}$ is taken according to the structural characteristics; d_d is the allowable deviation of deformation value, which is determined as $1\times10^{-5}\text{m}$ by amplification coefficient method.

5.3 Horizontal Cut Set Method

The core problem of fuzzy optimization is the transformation from fuzzy to non-fuzzy. There are many methods that can be used. Based on the actual characteristics of the model, this paper adopts an improved horizontal cut-set transformation method.

Because the nature of constraints is often different in engineering optimization, in order to make the optimization results more in line with engineering practice, this paper adopts an improved horizontal cut-off set method, that is, according to the nature of constraints, different design levels α_i are selected, and the formula of horizontal cut-off set is transformed as follows:

$$g_i^1(\alpha_i)\tilde{\le} g_i(x)\tilde{\le} g_i^u(\alpha_i) \tag{11}$$

From the above, the mathematical model of fuzzy optimization can be transformed into the mathematical model of ordinary optimization, as shown below:

Seek

$$X=[c \quad b \quad \delta]^T \tag{12}$$

Make

$$w(x)\to \min,\ x\in R \tag{13}$$

And satisfy

$$\begin{gathered} f\ge[f]+d_f(1-\alpha_1)\\ |d|\le[d]+d_d(1-\alpha_2)\end{gathered} \tag{14}$$

Where, $\alpha_i\in[0,1]$; The value of α_i adopts the two-level fuzzy comprehensive evaluation method, and $\alpha_1=0.8,\alpha_2=0.7$ is taken according to the fuzzy factors such as design level, importance and service conditions.

5.4 Algorithm Result

As shown in Figure 1, the whole frame is analyzed by finite element program, and the first-order natural frequency and maximum displacement distribution of nodes are obtained. The design is transformed into fuzzy optimization, the design variables of each part are modified, and the penalty function method is used to solve the problem. The objective function and constraint function form a new function in a certain way, and a constraint problem is transformed into a series of unconstrained optimization problems until the optimal solution is obtained.

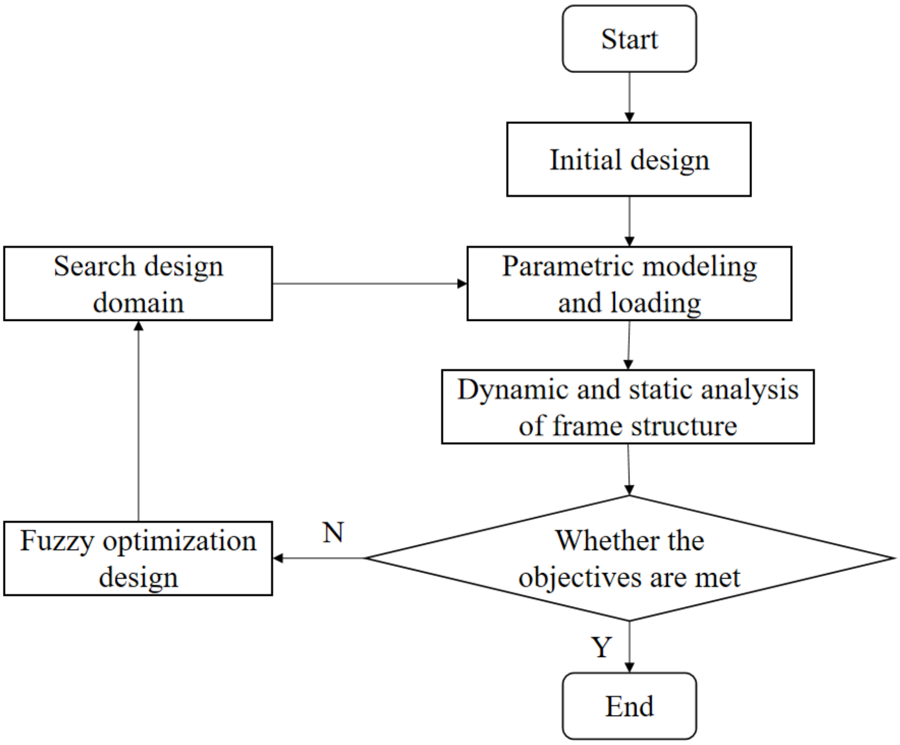

Fig.1 Fuzzy Finite Element Optimization Algorithm Block Diagram

After the above solution and iteration, the optimization results are as follows:

$$X = [c \quad b \quad \delta]^T = [168 \quad 203 \quad 12.7]^T \qquad w(x) = 128.13 \tag{15}$$

Compared with the initial general optimization design, the quality is reduced by 7.1%.

6. Conclusion

To sum up, to strengthen the application and development level of construction machinery under mechatronics, we should pay full attention to the scientific application and innovative development of technology. Its application in construction machinery has greatly promoted the progress and development of China's machinery industry. Although the degree of electromechanical integration is still low at present, its role, status and value are undeniable. In this paper, the method of combining finite element with fuzzy optimization is adopted, so that the established optimization mathematical model is closer to the objective reality. The calculation results show that the fuzzy finite element method adopted in this paper can reflect the fuzziness of the problem and the practicality of the engineering structure. It is expounded theoretically that the calculation and analysis method of introducing fuzzy reliability will make the analysis result more in line with the engineering practice, so it has important theoretical and practical significance.

References

[1] Zhi P, Li Y, Chen B, et al. Fuzzy optimization design-based multi-level response surface of bogie frame. International Journal of Structural Integrity,vol. 10, no. 2, pp. 134-148, 2019.

[2] Wei W, Tian Z, Peng C, et al. Product family flexibility design method based on hybrid adaptive ant colony algorithm. Soft Computing, vol. 23, no. 20, pp. 10509-10520, 2019.

[3] B T aran, Pirmohammadi A. Designing an optimal fuzzy sliding mode control for a two-link robot. Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 42, no. 1, pp. 1-12, 2020.

[4] Hafez A T, Kamel M A. Cooperative Task Assignment and Trajectory Planning of Unmanned Systems Via HFLC and PSO. Unmanned Systems, vol. 7, no. 2, pp. 65-81, 2019.

[5] Huang Q, Yang J, Feng X, et al. Automated Trading Point Forecasting Based on Bicluster Mining and Fuzzy Inference. IEEE Transactions on Fuzzy Systems, vol. 28, no. 2, pp. 259-272, 2020.

[6] Chandrasekhar N, Ragavendran M, Vasudevan M. Finite element modeling and optimization of hybrid laser–TIG welding of type 316L(N) austenitic stainless steel. Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 42, no. 10, pp. 1-13, 2020.

[7] Karami M, Vatankhah R, Khosravifard A. A modified fuzzy-tuned artificial bee algorithm to optimal location of piezoelectric actuators and sensors for active vibration control of isotropic rectangular plates. Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 43, no. 2, pp. 1-11, 2021.