Tolerance Optimization Design Based on Neural Network and Genetic Algorithm

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Abstract: Aiming at the characteristics of highly non-linear relationship between tolerance and cost in product manufacturing, a tolerance optimization method based on neural network and genetic algorithm is proposed. This method uses genetic algorithm to obtain global optimal solution with strong robustness by probability search strategy in a wide range of solution space, and the advantages of neural network in solving highly non-linear problems. The function relationship of tolerance cost with black box characteristics is obtained by simulating tolerance cost with neural network. Then genetic algorithm is used in tolerance allocation to minimize total cost, and optimization is carried out under the constraints of meeting assembly tolerance requirements and meeting standard tolerance grade. At the same time, tolerance optimization system is developed based on VC and Matlab, and the object of tolerance allocation is the locker mechanism of aircraft cabin door. The results show that the results of comprehensive allocation using neural network and genetic algorithm are superior to those of traditional methods.

1. Introduction

Tolerance design includes tolerance analysis and tolerance synthesis. Tolerance synthesis, also known as tolerance distribution, refers to the requirement of ensuring product assembly technology to specify the economic and reasonable tolerance of each component ring dimension [1]. In tolerance distribution, it is necessary to take into account the product function, size, geometry, material performance, field equipment, process method and manufacturing cost of components. Therefore, tolerance allocation can have many different tolerance allocation schemes, which is a rather complex multi-solution problem.

The development of tolerance design has gone through more than a century, but until 1978, the concept of computer-aided determination of geometric shape, size and position tolerance of parts was put forward in document [2]. The geometric shape of parts was described by mathematical equation, and then the dimension and tolerance design of parts was carried out. Since then, computer-aided tolerance design (CAT) has been widely used. Concern. In 1988, document [3] proposed the method of transferring tolerance requirement from design stage to manufacturing stage to solve tolerance problem in process design, which set off the climax of CAT research, and then the research of CAT entered a period of great development.

In the aspect of tolerance synthesis, scholars at home and abroad have done a lot of research. Document [4] puts forward rule-based synthesis, and gives various commonly used tolerance synthesis theories and methods; Document [5-6] puts forward tolerance robust design and corresponding deterministic algorithm; Document [7] puts forward a cost-tolerance model based on BP neural network; Document [8] allocates tolerance for processing quality, and mentions it. A method based on genetic algorithm is proposed. In China, a tolerance optimization design method based on assembly success rate is proposed in reference [9]. In reference [10], a product tolerance optimization design method based on cluster intelligence is proposed, and multi-objective comprehensive optimization is carried out by using particle swarm optimization method.

These studies have greatly expanded the scope of CAT research, but for some models with complex Tolerance-Cost relationship, the traditional Tolerance-Cost model is used to simulate and fit, and then the constructed optimization model is used to allocate the tolerances of each part in the assembly. The results are often errors and can not obtain satisfactory optimization results; while the Tolerance-Cost model and tolerance optimization model are used as optimization models. Consideration as a whole will solve this problem well.

Considering that tolerance optimization is a combination process of Tolerance-Cost model and tolerance optimal allocation in manufacturing, this paper proposes a method of tolerance optimal allocation based on BP neural network and genetic algorithm, and validates the method with an example of aircraft door lock mechanism.

2. Tolerance-Cost Model

It is very important to build a practical model for tolerance optimization design, because the model plays a key role in the practical application of tolerance allocation. Because the geometry, size and material of various parts are different, the cost in manufacturing will be different, so it is difficult to take into account the processing materials, dimensions and methods of parts. A precise mathematical model is used to describe the relationship between tolerance and cost. Generally speaking, the smaller the tolerance, the larger the processing cost, and vice versa, the smaller the cost. In order to effectively express the relationship between tolerance and processing cost, this paper sets part material as aluminium alloy, and uses cutting parameters and processing equipment (mainly CNC machine) for medium batch parts processing. Bed) as a benchmark, taking plane processing characteristics as the research object, the tolerance and processing cost are simulated.

2.1 Traditional Tolerance-Cost Model

For the research of tolerance cost model, a lot of research results have been made, and more Tolerance-Cost models have been put forward, such as traditional exponential model, negative square model, reciprocal power exponential model and so on. [7] The common point of these models is that in a specific processing environment, sufficient statistical data of tolerance cost are collected, and then the parameters of the model are determined by optimization methods such as least square method.

However, these traditional Tolerance-Cost models can not accurately describe the complex mathematical relationship between tolerance costs. Neural network method has a strong advantage in solving highly non-linear problems, and the fitting error can be controlled in a very small range. By giving a small number of training samples as input and output, the input-output relationship can be well reflected. Therefore, it is more appropriate to use neural network to describe Tolerance-Cost model.

2.2 Establishment of Tolerance-Cost Model by BP Neural Network

In this paper, the improved LM (Levenberg-Marquardt) algorithm is used to train the BP neural network to simulate the corresponding relationship between tolerance and cost. The BP network based on LM algorithm overcomes the problem that the gradient descent of BP algorithm decreases gradually with the increase of iteration times, thus the convergence speed is slower, the iteration times can be reduced and the convergence of the network can be accelerated.

The main parameters to be determined are: the number of layers of the network used, the number of neurons in each layer, the transmission function of each layer and the learning algorithm of the network.

1) Layers of the network. Research [11] shows that if the number of hidden layer neurons in BP network can be set freely according to the need, then a three-layer network can achieve arbitrary non-linear mapping. Considering the high accuracy requirement of this model, a BP neural network with input layer, hidden layer and output layer is adopted.

2) Number of neurons in each layer. A three-layer BP network with infinite hidden layer neurons can realize any non-linear mapping from input to output, but for a finite mapping from input to output, there is no need for infinite hidden layer nodes. For the selection of the number of hidden layer nodes, up to now, no good analytic formula has been found, but the number of nodes can be determined according to experience. Formula [11] is

$$n = n_i + n_0 + a \tag{1}$$

Among them, 'n' is the number of hidden layer nodes; 'n_i'is the number of input nodes; 'n_0' is the number of output nodes; 'a' is a constant between 1 and 10.

In this paper, the input node is tolerance and its corresponding process type. The number of nodes is 2, and the output is its corresponding cost. The number of nodes is 1. The number of hidden layer nodes is n=10.

3) Transfer function of each layer of the network. Generally speaking, BP network with three layers adopts Sigmoid-type transfer function in hidden layer, while output layer is selected according to the range of output results. In addition, Tansig function is selected as hidden layer transfer function in order to make the network reach a stable state faster in training (that is, to make the weight and threshold of the network adjust faster). In order to improve the training speed and sensitivity and avoid the saturation area of sigmoid function effectively, it is necessary to normalize the input and output data. Because tolerances are not uniformly distributed in the production process, the normalization method of tolerances in this paper is [8].

$$y= 2/\pi \arctan x \tag{2}$$

Among them, x is the original value of tolerance and Y is the value after normalization.

4) System model. The network model used in this system is shown in Figure 1.

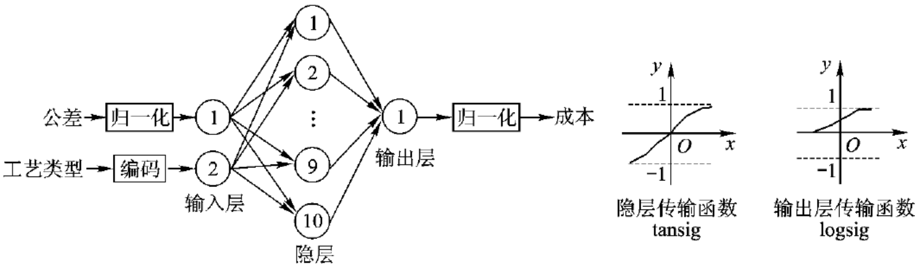

Figure 1. Tolerance-Cost Neural Network Diagram

2.3 Neural Network Simulation

Using neural network to optimize needs corresponding tolerance and cost data as expert samples to train the network. In reality, the factory is based on the production process as a unit, while the cost is measured by the working hours. The data of tolerance and cost are difficult to be counted. Therefore, this paper uses the data of literature [12] as the sample data for optimization.

Based on the platform of MATLAB and VC, the Tolerance-Cost model of neural network simulation is developed. The mixed programming mode of MATCom and VC includes compiling the MATLAB code into DLL or executable program based on MatCom, and using five methods such as MATLAB Engine and Matlab‘s C/C++ mathematical library.

In this paper, the dynamic DLL library generated by Matlab is invoked by VC. The functions of the neural network toolbox are packaged into DLL and then invoked in VC. Figure 2 shows the process of training Tolerance-Cost sample data using BP network.

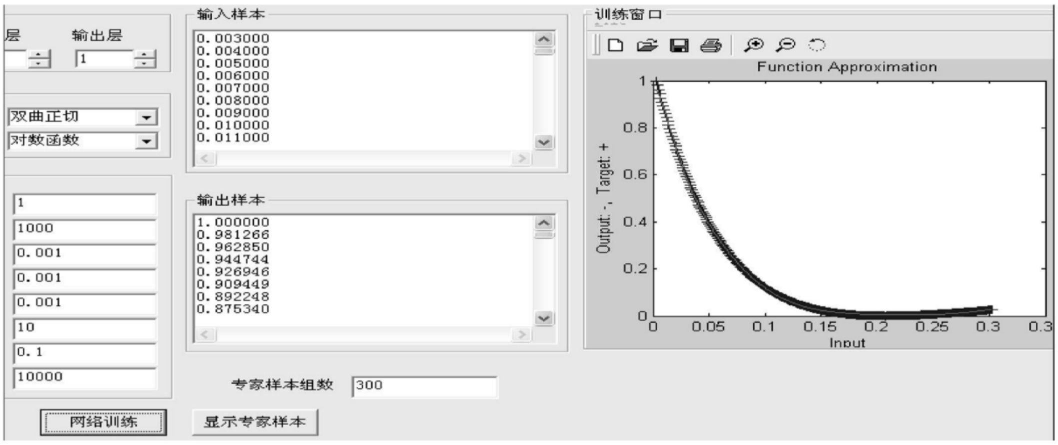

Figure 2. VC calls MATLAB to train neural network

3. Optimization Based on Genetic Algorithms

3.1 Traditional Distribution Method

The tolerance relation between the closed ring and the constituent ring under the extreme value method is as follows

$$\sum T = \sum_{i=1}^{n-1} Ti \tag{3}$$

Among them, $\sum T$ denotes the tolerance of closed rings; n denotes the number of rings; Ti (i = 1, 2... (n-1) denotes the tolerances of the constituent rings.

When $\sum T$ is known and Ti is unknown, Formula (3) is an indefinite equation with numerous solutions. Considering different emphasis, such as processing accuracy and process capability, the traditional methods to solve this problem include equal tolerance method, equal precision method and equal process capability method.

These traditional allocation methods are too simple. They are only suitable for the initial stage of tolerance design and can obtain simple tolerance allocation results. The genetic algorithm can not only converge to the global optimal solution, but also has faster convergence speed, high optimization efficiency and robustness. It is more suitable for obtaining the global optimal tolerance allocation results.

3.2 Genetic Algorithms for Tolerance Allocation

This paper needs to optimize the dimension tolerance of each component ring. On the premise that it meets the requirements of standard tolerance grade and the technical requirements of the corresponding closed ring, the processing cost of each component ring is the lowest.

$$\left.\begin{aligned} &\min C(\sum T) = \sum_{i=1}^{n-1} C(Ti) \\ &s.t.Ti = \sum_{i=1}^{M} ST_j I\Gamma_j \\ &\sum T \geq f\,(T_1,\ T_2,\ldots,T_{n-1}) \end{aligned}\right\} \tag{4}$$

Where $I\Gamma_j$ denotes whether the optimized tolerance level of each component ring is $I\Gamma_j$, if the selected level is j, $I\Gamma_j$ = 1, otherwise $I\Gamma_j$ = 0; ST_j denotes the standard tolerance value corresponding to the component ring when the tolerance level is j; $f\,(T_1,T_2,\ldots T_{n-1})$ represents the relationship between the tolerances of each component ring and the tolerances of the closed ring.

According to the technical requirements, the values are different. When considering that the success rate of assembly meets the 6σ rule:

$$\mathrm{f}\left(T_1, T_2, \ldots T_{\mathrm{n-1}}\right) \geq \sqrt{\sum_{\mathrm{i=1}}^{\mathrm{n-1}} \xi_{\mathrm{i}}^2 \mathrm{k}_{\mathrm{i}}^2 T_{\mathrm{i}}^2} \tag{5}$$

By using genetic algorithm, the standard tolerance level is coded, and penalty function is added to express the corresponding constraints. Taking tolerance cost as the value of fitness function, this problem can be solved more conveniently.

Standard tolerance level coding. Coding is to represent the solution of the problem by a code, so that the state space of the problem corresponds to the code space of GA. The coding of the optimal solution that meets the requirements is obtained by GA search and corresponds to the performance of the problem. Research [13] shows that the binary coding scheme can contain the largest number of patterns, the genetic algorithm can deal with the most patterns in the population of definite size.

In this paper, the binary coding method is adopted, and the final coding is the combination of tolerance grade numbers of each component ring. The tolerance grade numbers of each component ring are composed of 3-bit binary codes.

The total coding length is

$$C_L = 3(n-1) \tag{6}$$

The total encoding method is

$$a_{11}a_{12}a_{13}a_{21}a_{22}a_{23}\ldots a_{(n-1)1}a_{(n-1)2}a_{(n-1)3}$$

The possible combinations are $2^3 \mathrm{x} 2^3 \mathrm{x} \ldots \mathrm{x} 2^3 = (2^3)^{(\mathrm{n-1})}$ kinds.There are eight alternative tolerance levels for each component ring: IΓ5-IΓ12, so there is a dimension chain with five components. Its individual code is $a_{11}a_{12}a_{13}a_{21}a_{22}a_{23}a_{31}a_{32}a_{33}a_{41}a_{42}a_{43}a_{51}a_{52}a_{53}$. Each character represents 0 or 1, and the meaning of an individual coded 011010000100 after decoding is shown in Table 1.

Table.1. The Significance of Individual Decoding

组成环	对应的编码	解码为十进制数	对应的公差等级
A	011	3	IΓ8
B	010	2	IΓ7
C	000	0	IΓ5
D	100	4	IΓ9

Conversion of constraints. According to formula (4), the problem to be solved in this paper contains two constraints. For these two constraints, two different methods are adopted in this paper.

① Encoding method is used to ensure that the individual generated is always within the feasible solution space. For example, eight grades of tolerance grade IT4-IT11 are corresponded to each other in the range of 000-111. Thus, the first constraint condition is solved:

$$T\mathrm{i} = \sum_{\mathrm{j}=L}^{M} ST_j \mathrm{I}\Gamma_j \tag{7}$$

② By adding penalty function, the fitness of an individual who is not in the solution space is reduced, thus the probability of the individual inheriting into the next generation population is reduced.

$$Fc(x)=\begin{cases} F(x) & \text{When x satisfies } \sum T \geq f(T_1, T_2, \ldots, T_{n-1}) \\ F(x)-P(x) & \text{Others} \end{cases} \quad (8)$$

FC (x) denotes the modified fitness function and P (x) denotes the selected penalty function.

In this paper, P(x) = F (x) is chosen as the penalty function, so that the probability of inheritance of unsatisfactory individuals to the next generation population is 0. This reduces the diversity of the population, but speeds up the convergence speed of the algorithm. An example shows that the method is effective in setting the penalty function.

3.3 System Workflow

Based on the above theoretical methods, a tolerance optimization system based on genetic algorithm is developed by using dynamic DLL library generated by VC calling matlab. The tolerance values obtained by neural network optimization are invoked in the system, and the tolerance optimization design based on neural network and genetic algorithm is completed. The working flow of the whole system is shown in Figure 3.

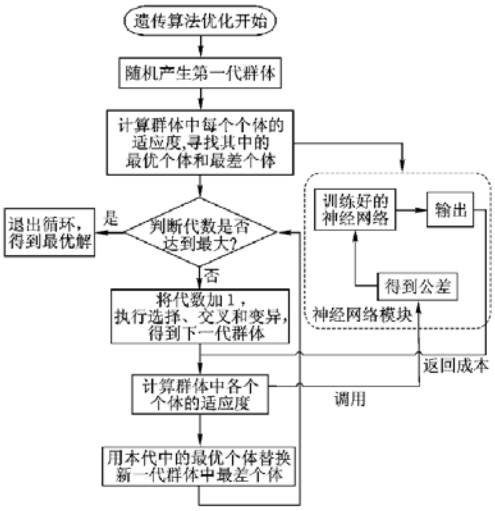

Figure 3. Systems Engineering Flow Chart

4. Example analysis

4.1 Example

This example takes the tolerance design of the lock-hook mechanism in the cabin door as the research object, and verifies the feasibility of the proposed algorithm and the superiority of tolerance distribution by using neural network and genetic algorithm. Fig. 4 shows the assembly part of the lock shaft and the lock-hook component in the cabin door motion mechanism component. Fig. 5 is the corresponding dimension chain. In order to ensure that the lock is open or the lock is in the chains. It is necessary to check the clearance size A0 between the hook and the eccentric bushing. According to the design requirements, the clearance A0 should be in the range of 4.00-4.75 mm.

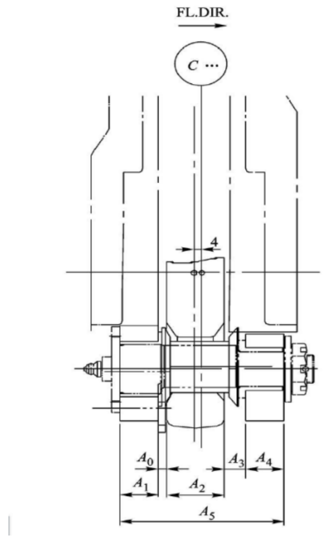

Figure 4. Door lock mechanism diagram

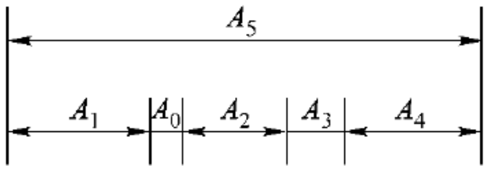

Figure 5. The corresponding dimension chain

The basic dimensions of each part are A1 = A4 = 34.0 mm, A2 = 28.5 mm, A3 = 10.5 mm, A5 = 111.0 mm. The corresponding dimension chain equation is

$$A_0 = A_5 - A_1 - A_2 - A_3 - A_4 \tag{9}$$

The objective function is to minimize the total cost of Formula (4). The tolerance cost is fitted exponentially by MATLAB, and the result is as follows:

$$y = 1.102^{e^{-21.44^x}} \tag{10}$$

The fitting image is shown in Fig. 6.

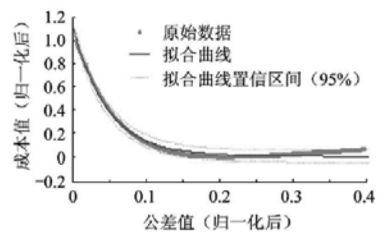

Figure 6 a. Fitting curve

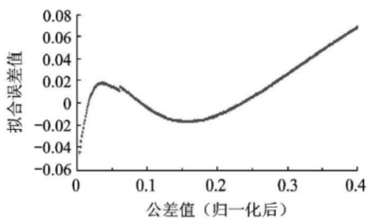

Figure 6 b. Fitting Residual Error Diagram

4.2 Comparison of experimental results

In this paper, the model of tolerance cost obtained by neural network and exponential method and the method of equal tolerance allocation are adopted respectively. Taking three combinations of methods as examples: the combination of neural network and genetic algorithm, the combination of neural network and equal tolerance method, and the combination of exponential method and equal tolerance method. The data results of tolerance value and total cost (normalized) are shown in Table 2.

Table.2. Comparisons of tolerances and costs obtained by various methods

分配方法	组成环名称	分配的公差值 /mm	对应的成本（归一化后）	总成本（归一化后）
神经网络＋隧传算法	A_1	0. 10	0 117 925	0. 712499
	A_2	0. 08	0 185 123	
	A_3	0. 07	0 259 193	
	A_4	0. 10	0 117 925	
	A_5	0. 14	0 032 333	
神经网络＋等公差法	A_1	0. 05	0 390 189	0. 927596
	A_2	0. 10	0 117 925	
	A_3	0. 25	0 009 003	
	A_4	0. 05	0 390 189	
	A_5	0. 30	0 020 290	
指数法＋等公差法	截图(Alt + A)	0. 05	0 377 240	0. 890571
	A_2	0. 10	0 129 138	
	A_3	0. 25	0 005 180	
	A_4	0. 05	0 377 240	
	A_5	0. 30	0 001 773	

4.3 Analysis of experimental results

From the results of Table 2, we can see that the total tolerance cost obtained by combining genetic algorithm with neural network is reduced by 30.189% and 24.993% respectively compared with the other two methods, which achieves better results.

5. Conclusion

In this paper, the characteristics of neural network and genetic algorithm are synthetically used to solve the two problems of Tolerance-Cost relationship and tolerance allocation in tolerance optimization. The tolerance cost is simulated by neural network, and the tolerance cost function with black box characteristics is obtained. On this basis, the minimum cost is taken as the objective function, and the assembly tolerance requirement and standard tolerance are taken as constraints, and the genetic algorithm is used. The algorithm is optimized, and the feasibility of this method is verified by an example. The results show that the cost of product can be significantly reduced by using this method for tolerance allocation.

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