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Optimization for Kinematics Accuracy Reliability of Beating-up Mechanism of High-speed Rapier Loom

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Abstract

The problems of reliability, stability and kinematics accuracy of domestic high-speed rapier loom are urgent to be solved. For the limitations of used methods of solving kinematics accuracy reliability, the mathematical solution model and index of kinematics accuracy reliability of beating-up mechanism were established based on the geometrical principle of reliability index. The particle swarm optimization was improved. Then using improved particle swarm optimization, the kinematics accuracy reliability of beating-up mechanism of high-speed rapier loom was optimized. The computational precision and effectiveness of solving are both improved. Thus a new valid method is provided for the solution of kinematics accuracy reliability of beating-up mechanism of high-speed rapier loom.

Keywords: Beating-up Mechanism; Kinematics Accuracy Reliability; Conjugate Cams; Reliability Index; Improved Particle Swarm Optimization

1 Introduction

With the development of high-speed rapier loom, its high precision, high speed and high automation have become more and more important. Kinematics accuracy reliability has been gradually emphasized. However, its theories and methods are still very deficient. At the present, the main study methods are Taylor expansion method [1], Monte-Carlo method [2], function substitution method [3] and probability density evolution method [4]. The Taylor expansion method is a common method to solve kinematics accuracy reliability. This method which needs to get the first order and higher order partial derivative of the state functions generally is difficult to solve high-dimension and advanced non-linear problems. For the research on reliability theory of beating-up mechanism of high-speed rapier loom shown as Fig. 1, it is very essential to search for high-precise, fast, effective and easy handled methods to solve the kinematics accuracy reliability. Combined with the advantages of particle swarm optimization including easy parameter setting, fast convergence speed and high precision, a new method of solving the kinematics accuracy reliability of high-speed rapier loom was proposed by improving the basic particle swarm optimization with

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introducing inertia weight parameter, and the kinematics accuracy reliability of conjugate cams beating-up mechanism was analyzed and tested.

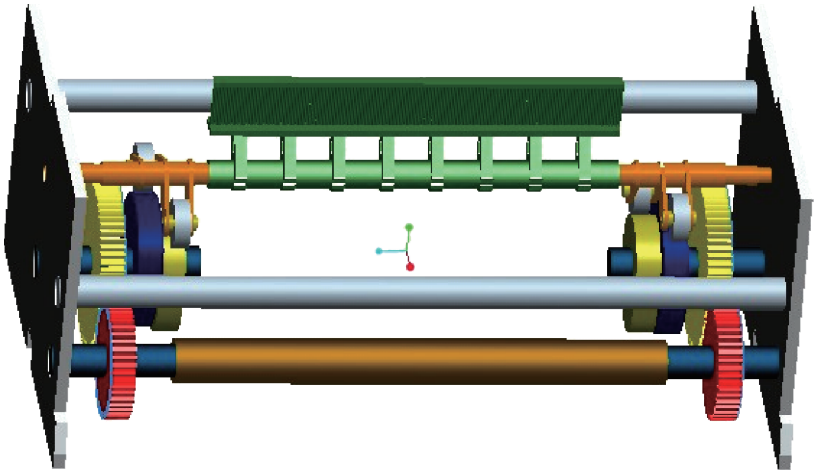


Fig. 1: Parameterized model of beating-up mechanism

2 Improved Particle Swarm Optimization

2.1 Particle Swarm Optimization

Particle Swarm Optimization was proposed in 1995 by Eberhart, an American electrical engineer and Kennedy, an American social psychologist, which was an optimization algorithm to simulate the intelligent behaviors of biotic population [5, 6]. The algorithm stemmed from the simulation study to social systems of birds by Reynolds in 1987, which was also a Complex Adaptive System (CAS). In PSO, the feasible solution of each optimization problem can be imagined as a single particle in a search space. The particle flies in the space with a fixed speed, which decides the direction and distance of its flight. Each particle is offered an adaptive value by optimization function, which is searched by following the current optimized particle in the space. The algorithm generates a set of initial population randomly and finds an optimal solution by a step-by-step iteration. Each particle updates itself by tracing two extremes and finally searches the optimal solution.

Its mathematical description [7] is as follows: supposing the population search space as D-dimension, the number of particles as N; the space location of the particle i is $X_i = (x_{i1}, x_{i2}, \cdots, x_{iD})$, and the optimal location is $P_i = (p_{i1}, p_{i2}, \cdots, p_{iD})$, the flight speed of the particle is V_i=$(v_{i1}, v_{i2}, \cdots, v_{iD})$; the optimal location searched by all the particles in the population by the current time is $P_g = (p_{g1}, p_{g2}, \cdots, p_{gD})$; as to each generation, its D-dimension evolves by the following formula:

$$v_{id}(k+1) = v_{id}(k) + c_1 \times r_1 \times (p_{id} - x_{id}(k)) + c_2 \times r_2 \times (p_{gd} - x_{id}(k)) \quad (1)$$

$$x_{id}(k+1) = x_{id}(k) + v_{id}(k+1) \quad (2)$$

In which, k is the current number of iteration; c_1 and c_2 are learning factor or acceleration factor, nonnegative constant, used to adjust the flight step of the particle; r_1 and r_2 are random

number; the second term in the formula represents the cognitive ability of individual particle, decided by experience and thinking of the particle; the third term in the formula is called social cognitive ability of the particle, providing information sharing and interaction among particles.

2.2 Improved Particle Swarm Optimization with Introducing Inertia Weight

In particle swarm optimization, as the number of iterations increases, each particle will get more and more similar. It is easy to fall into the problem of local optimum. In order to promote the optimization ability of whole particle swarm, Shi and Eberthat provided an improved method of particle swarm with introducing inertia weight w into the relation between the update speed and displacement in IEEE International Conference on Evolutionary Computation [6]. Introducing the inertia weight can adjust the optimization speed and developing capacity of the algorithm, whose speed-updating formula can be improved as the following:

$$v_{id}(k+1) = w \times v_{id}(k) + c_1 \times r_1 \times (p_{id} - x_{id}(k)) + c_2 \times r_2 \times (p_{gd} - x_{id}(k)) \tag{3}$$

Inertia weight decides the impact of the particle's last generation's speed to the current speed, which increases the algorithm performance greatly. When the inertia weight is relatively big, the particle owns relatively great speed, which make the global optimization capabilities of the algorithm is relatively strong; on the contrary, relatively small inertia weight increases the local optimization capabilities of the algorithm. Over large inertia weight will lead to lower optimal point searching capability, which does not fit the complex nonlinear optimization process; Undersize inertia weight will make the algorithm fall into local optimum or affect the convergence speed of the algorithm. In order to find a proper inertia weight selecting method, researchers did a large number of researches [8, 9]. Recently, widely used inertia weight is a linearly decreasing inertia weight, which can significantly promote the searching speed and capability of the particle by strengthening the particle's exploiting capability in initial searching phase and digging the relatively optimal point carefully after finding the point. The method of linearly decreasing the inertia weight is as follows [8]:

$$w(k) = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} * k \tag{4}$$

In the formula, k is the current number of iterations; $iter_{\max}$ is the maximum number of iterations. A lot of scholars conclude after repeated tests: when $w_{\max}$ is 0.9, $w_{\min}$ is 0.4, the effect is relatively great. These values differ from different type of optimization question.

The introduction of the inertia weight greatly strengthens the convergence speed and performance of the particle swarm optimization and the basic particle swarm optimization is changed a little. It makes the operation relatively simple and also makes the particle swarm optimization applied successfully to lots of practical problems. Therefore, this paper will use the improved particle swarm optimization to solve the kinematics accuracy reliability of beating-up mechanism of high-speed rapier loom.

3 Geometrical Principle of Calculating the Kinematics Accuracy Reliability Index

The geometrical definition of β by Haosfer and Lind is the smallest distance between origin of coordinate and limit state surface in a standard normal space [10]. The point on the smallest distance and limit state surface is called design checking point $X^* = (X_1^*, X_2^*, \cdots, X_n^*)$.

In analysis of kinematics accuracy reliability, the limit state function with n random variables is

$$Z = g(X) = g(x_1, x_2, \cdots, x_n) = 0 \tag{5}$$

The random variables are mutually independent normally distributed variables in the formula. The result of standard normalization to the variables is:

$$d_i = \frac{x_i - \mu_{xi}}{\sigma_{xi}} \tag{6}$$

In the formula, μ_{xi} and σ_{xi} are mean value and standard deviation separately. Transfer the limit state function in $X = \{x_1, x_2, \cdots, x_n\}$ space to $D = \{d_1, d_2, \cdots, d_n\}$ space to solve the x_i in the function:

$$x_i = \mu_{xi} + \sigma_{xi} d_i \tag{7}$$

Substituting Eq. (7) into Eq. (5), Eq. (5) can be expressed as:

$$Z' = g'(X) = g'(d_1, d_2, \cdots, d_n) = 0 \tag{8}$$

According to the geometrical definition of reliability index β, in standardized normal space, the solving of reliability index β can change into the extreme solving problem under the condition of constraint of the following equation:

$$\begin{aligned} &\beta = \min \sqrt{\sum_{i=1}^{n} d_i^2} \\ &s.t. \quad g'(d_1, d_2, \cdots, d_n) = 0 \end{aligned} \tag{9}$$

To sum up, the calculation of the reliability index can change into extreme solving problem with constraint expressed by the formula above.

4 Example of Solving the Kinematics Accuracy Reliability of Beating-up Mechanism

4.1 Calculation Steps of Kinematics Accuracy Reliability of Beating-up Mechanism

The maximum speed of high-speed rapier loom is more than 500 r/min. Taking a beating-up mechanism for example the design speed is 600 r/min. The kinematics accuracy reliability of

conjugate cams beating-up mechanism has been solved by the use of improved particle swarm optimization. The calculation steps are as follows:

(1) Determining the design variables

Beating-up mechanism has four main structural parameters, including the allowable limit error δ, the pendulum length l, center distance a, roller radius r. Therefore, the design variables are as follows:

$$X = (x_1, x_2, x_3, x_4) = (\delta, l, a, r) \tag{10}$$

(2) Calculating kinematics accuracy of beating-up mechanism

According to the relationship between the motion vector [11], the ideal output swing angle ϕ^* of beating-up mechanism is as follows:

$$\phi^* = f(l^*, a^*, r^*, \theta) = \arccos\left(\frac{a^2 + c^2 - b^2}{2ac}\right) + \arccos\left(\frac{l^{*2} + c^2 - r^{*2}}{2l^*c}\right) - \varphi_0 \tag{11}$$

The ideal values were indicated by $*$. ϕ_0 represents the angle between the rocker shaft pendulum and central distance of the main cam in the initial position.

Its actual output swing angle can be expressed as:

$$\varphi = \varphi^* + \Delta\varphi \tag{12}$$

So kinematics accuracy of beating-up mechanism is:

$$\Delta\varphi = \varphi - \varphi^* = f(l^* + \Delta l, a^* + \Delta a, r^* + \Delta r, \theta) - f(l^*, a^*, r^*, \theta) \tag{13}$$

(3) The constraint equation of kinematics accuracy of beating-up mechanism

According to state functions and the definition of limit state equation, the limit state equation of kinematics accuracy of beating-up mechanism can be expressed as:

$$Z = g(X) = g(x_1, x_2, x_3, x_4) = \delta - \Delta\varphi = 0 \tag{14}$$

Because of the design variables are mutually independent normal variables, so its standard normalized as follows:

$$\left.\begin{aligned} \hat{\delta} &= \frac{\delta - \mu_\delta}{\sigma_\delta} \\ \hat{l} &= \frac{l - \mu_l}{\sigma_l} \\ \hat{a} &= \frac{a - \mu_a}{\sigma_a} \\ \hat{r} &= \frac{r - \mu_r}{\sigma_r} \end{aligned}\right\} \tag{15}$$

The μ_δ and σ_δ represent the mean and standard deviation of allowable limit errors. The μ_l and σ_l represent the mean and standard deviation of pendulum length. The μ_a and σ_a represent the

mean and standard deviation of central distance. The μ_r and σ_r represent the mean and standard deviation of roller radius. Solving the formula, the parameters δ, l, a and r are as follows:

$$\left.\begin{aligned} \delta &= \mu_\delta + \hat{\delta}\sigma_\delta \\ l &= \mu_l + \hat{l}\sigma_l \\ a &= \mu_a + \hat{a}\sigma_a \\ r &= \mu_r + \hat{r}\sigma_r \end{aligned}\right\} \tag{16}$$

Finally, the constraint equations can be obtained as follows:

$$Z' = g'(\delta', l', a', r') = g'(\mu_\delta + \hat{\delta}\sigma_\delta, \mu_l + \hat{l}\sigma_l, \mu_a + \hat{a}\sigma_a, \mu_r + \hat{r}\sigma_r) = 0 \tag{17}$$

4.2 Solving the Kinematics Accuracy Reliability of Beating-up Mechanism by Improved Particle Swarm Optimization

According to the design variables agencies, the objective function and the constraint equation, a mathematical model of the kinematics accuracy reliability of beating-up mechanism is established as follows:

$$\begin{aligned} &R = \Phi(\beta) \\ &\beta = M\inf(x) = Min\sqrt{\sum_{i=1}^{n}\varphi_i^2} \\ &\varphi_i = \frac{x_i - \mu_{x_i}}{\sigma_{x_i}}, \quad x_i \geq 0, (i = 1, 2, 3, 4) \\ &s.t. \;\; X = \{x_1, x_2, x_3, x_4\} \in \Omega, \\ &\Omega = \{\varphi \Big| g'(\Phi) = 0\} \end{aligned} \tag{18}$$

Now the improved particle swarm optimization is used to solve the mathematical model above, and simulation is conducted using MATLAB software. Take the scale of the particle swarm as 100, the maximum number of iterations as 100 to get the calculation result of beating-up mechanism kinematics accuracy reliability shown in Table 1, which is transferred into failure probability

Table 1: The reliability index and kinematics accuracy reliability of beating-up mechanism

Cam angle $\theta(^\circ)$	Reliability index β	Kinematics accuracy reliability R	Cam angle $\theta(^\circ)$	Reliability index β	Kinematics accuracy reliability R
30	2.477668	0.9815217493	210	2.814555	0.9924217493
60	2.642209	0.987866744	240	2.864819	0.9934636109
90	2.512747	0.9835096465	270	2.698786	0.9895574353
120	2.669530	0.9887664964	300	2.631017	0.9875822518
150	2.498472	0.9824106937	330	2.642796	0.9879781916
180	2.701574	0.9896080139	360	2.542777	0.9843732261

curve shown in Fig. 2. In a whole operating cycle, kinematics accuracy failure probability is between 0.005 and 0.020. Compared with kinematics accuracy failure probability of swing roller cam mechanism shown in Fig. 3 from [12] which is between 0.014 and 0.026, the results prove that the solution of improved particle swarm optimization to the kinematics accuracy reliability problem of beating-up mechanism meets the calculation accuracy.

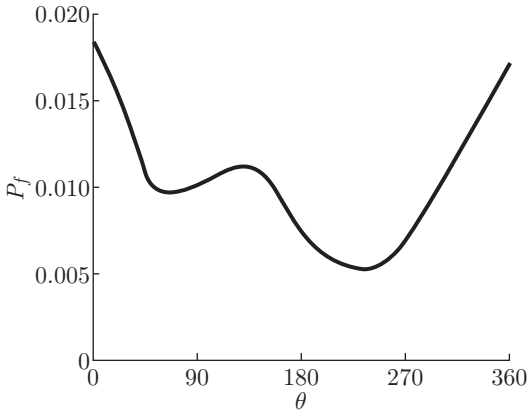


Fig. 2: Failure probability of beating-up mechanism

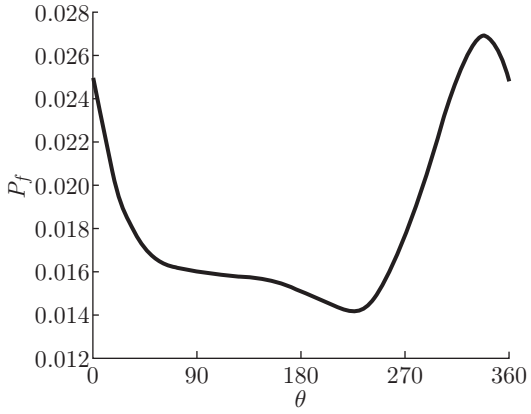


Fig. 3: Failure probability of swing roller cam mechanism

5 Conclusions

In high-speed rapier loom, the kinematics accuracy reliability problem of beating-up mechanism is a high-dimension and non-linear problem. For the reliability theory of beating-up mechanism of rapier loom, to find an accurate, fast and effective method is worth studying.

According to the geometrical principle of kinematics accuracy reliability index, with the combination of the advantages of particle swarm optimization, the algorithm was improved by introducing inertia weight parameter and a new theory method of solving kinematics accuracy reliability of high-speed rapier loom was explored. The analysis results show that improved particle swarm optimization needn't to calculate complex partial derivatives, and can meet the calculation accuracy. Combined with other methods and through setting conditions of constraint, it also can be

used to solve kinematics accuracy reliability problem with high-dimension and non-linear problems [8]. Under the complex operation condition of high-speed rapier loom, this method can provide a new technological approach to study kinematics accuracy reliability of conjugate cams beating-up mechanism.

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