DESIGN AND ANALYSIS OF PRODUCT-INTEGRATED GUIDE MECHANISM DRIVEN BY A NON-CIRCULAR GEAR

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For the purpose of optimizing the motion characteristics of the guide bar mechanism and enable the guide bar to perform uniform-speed reciprocating motion within a certain stroke range, a guide mechanism driven by non-circular gear is proposed. The transmission ratio of non-circular gear is constructed by the Fourier series equation.

In order to facilitate the control of the transmission ratio of non-circular gear train, a method of designing non-circular gear train by constructing the transmission ratio equation using Fourier series equations is proposed. By combining Fourier series equations with non-circular gear transmission characteristics, a transmission ratio equation is constructed using Fourier series equations. Based on gear transmission characteristics, the pitch curve equations and transmission characteristic equations of driving and driven non-circular gears are constructed. For the sake of facilitating the selection of various design parameters, the effects of Fourier parameters and on the transmission ratio curve are analyzed.

The guide mechanism can achieve an approximately constant speed motion law, verifying the feasibility of the non-circular gear constructed by the Fourier series equation of the transmission ratio.

Key words: guide mechanism; non-circular gear; Fourier series; transmission ratio

1 Introduction

The comber is a key equipment in the worsted and linen spinning processes, and its performance directly affects production output, quality, and cost [1]. The drafting mechanism is one of the key components in the comber [2], and the performance of the drafting mechanism directly affects the shape of the sliver formation and indirectly affects the subsequent combing process [3]. The combing process requires that the drafting rod in the drafting mechanism has a constant-speed drafting motion law. The simple sine mechanism realizes the sine motion law

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and cannot well meet the requirements of the combing process [4]. Regarding the research on the drafting mechanism, Wang Haocheng et al. [5] used MAPLE to simulate and analyze the drafting mechanism driven by elliptical gears, improved the design efficiency of the sine-elliptical mechanism through dynamic graphics technology, and proposed a three-stage transmission equipment for the drafting mechanism with a series drive of an elliptical gear train, a cylindrical gear train, and a sine mechanism, with a relatively low overall transmission efficiency; Tao Dehua et al. [6] used a first-order Fourier gear and its second-order conjugate non-circular gear to drive the sine mechanism to achieve an approximately constant-speed drafting motion, and used a genetic algorithm to optimize and obtain a new type of drafting mechanism that can achieve a longer constant-speed section, but the obtained speed curve has a concave part in the constant-speed section.

Gear mechanism is a mechanical transmission device widely used in transmitting torque and power. Common circular gears are used in constant speed ratio transmission conditions.[7,8] For variable speed ratio transmission conditions, ordinary circular gears are difficult to meet the requirements. Non-circular gears, on the basis of having the characteristics of stable transmission of gear mechanisms, also have the complex motion characteristics of cam mechanisms and can achieve the transmission function of variable speed and high torque. [9] Common non-circular gear mechanisms include elliptical gear [10], eccentric gear [11], Limacon gear [12,13], sinusoidal gear [14], and Fourier series gear [15], etc. Among them, due to the multiple design parameters of Fourier series non-circular gears, under the premise of ensuring stable transmission characteristics, more complex variable speed transmission can be realized and widely used in various occasions. [16]

Xu Gaohuan et al. [15] constructed the pitch curve radial equation of non-circular gears using Fourier series equations, determined the center distance value of the gear train through numerical optimization method, and then obtained a Fourier non-circular gear mechanism capable of continuous transmission and applied it to the differential pump to obtain a new differential pump driving mechanism suitable for low pulsation and large load conditions. [16]; *Ye Jun et al.* [17] applied Fourier non-circular gears to the transverse sealing mechanism. By comparing with the transverse sealing mechanism driven by eccentric non-circular gears, it was verified that better transverse sealing effect could be obtained when driven by Fourier non-circular gears; *Tao Dehua et al.*[6] proposed to use first-order Fourier non-circular gears and their second-order conjugate non-circular gears to drive the guide bar mechanism. Taking the constant speed guide bar as the goal, the Fourier non-circular gear parameters were optimized using the genetic algorithm to realize the functional requirements of the constant speed guide bar.

The above-mentioned Fourier non-circular gears are all types of non-circular gear pitch curves constructed using Fourier series equations. The transmission ratio of the gear train is not easy to control. Therefore, in this paper, on the premise of giving the gear train, the transmission ratio equation of non-circular gear train is directly constructed using Fourier series equations. Through the meshing theory of non-circular gears, the pitch curve equations and transmission characteristic equations of driving and driven gears are constructed. Using the single-factor analysis method, the influence laws of each design parameter and on the transmission ratio are studied.

To verify the feasibility of the non-circular gear constructed by the Fourier series equation of the transmission ratio, the non-circular gear is used to drive the product-integrated guide mechanism. The Fourier parameters that can make the rod achieve approximate constant speed during the reciprocating stroke are calculated. The transmission ratio and the corresponding non-circular gear under this set of design parameters can make the rod achieve the constant speed guide motion law.

2 Guide mechanism

According to the textile process of forming yarn into yarn cakes, the rod of guide mechanism needs to meet the requirements — achieving approximately constant speed guide performance within a certain range of motion. [6]

The guide mechanism driven by non-circular gear with the transmission ratio constructed by Fourier series equation is proposed, as shown in the Fig.1.

The operating principle of the guide mechanism is as follows: The power provided by the motor drives the driving gear "1" fixed on the main shaft O_1 to rotate at a constant speed. Through the meshing transmission between the tooth profiles, the power is transmitted to the driven conjugate non-circular gear "2" that is always meshed with the gear "1". Since the ratio of the pitch curve radius vectors of the driving gear train varies with time, the driven conjugate non-circular gear "2" rotates at a variable speed according to a certain law. Because the crank 3 and the gear "2" are fixed on the same transmission shaft O_2, the motion characteristics of the crank "3" are the same as those of the gear "2". The power is transmitted to the rod "5" through the slider "4", and the rod "5" makes a reciprocating linear motion. During the guiding process, it is required that the motion characteristics of the rod in the two reciprocating strokes are close to the constant-speed motion law.

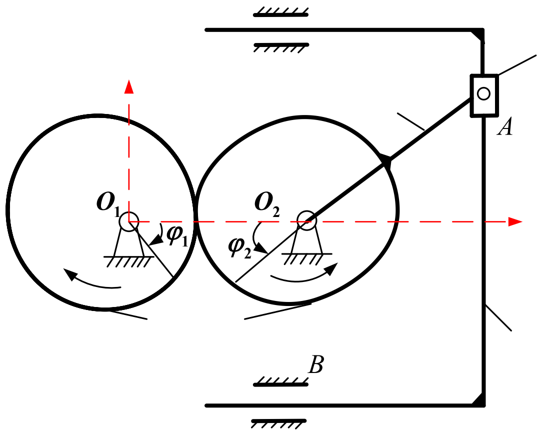


Fig.1 Product-integrated guide mechanism

2 Fourier Series

Fourier transform refers to that any function can be represented by a series of sine and cosine functions. The general expression can be expressed as

$$f(x)=\frac{1}{2}a_0+\sum_{k=1}^{\infty}\left(a_k\cos(kx)+b_k\sin(kx)\right) \tag{1}$$

Using the Fourier series equation to construct the gear transmission ratio curve and introducing the relevant parameters of non-circular gears into equation (1) to obtain the general mathematical model of the transmission ratio

$$i_{21}=\frac{1}{i_{12}}=\frac{n_1}{n_2}+\sum_{k=1}^{N}\left(a_k\cos(kn_1\varphi_1)+b_k\sin(kn_1\varphi_1)\right) \qquad \varphi_1\in[0,2\pi] \tag{2}$$

Where i_{12} is the transmission ratio of non-circular gear, n_1 and n_2 are the orders of the driving and driven gear respectively, a_k and b_k are the cosine - term and sine - term coefficient of k-th term respectively, φ_1 is the rotational angle of driving gear.

Fig.2 shows the transmission ratio with $n_1=n_2=1$; $N=3$; $a_1=0.05$; $b_1=0.02$; $a_2=0.03$; $b_2=0.05$; $a_3=0.06$; $b_3=0.03$. The transmission ratio curve is smooth and presents a three-peak type, because N=3 and both a_k and b_k are not zero.

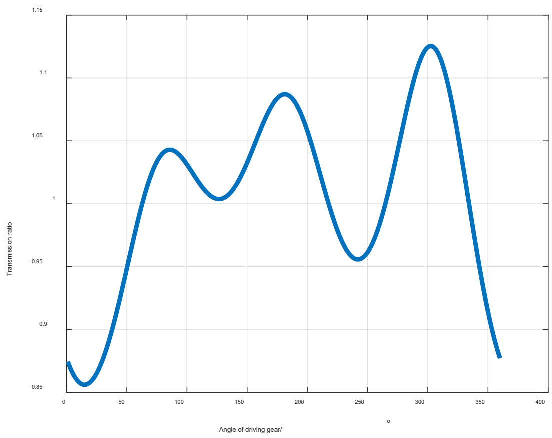


Fig.2 Transmission ratio with n_1=n_2=1; N=3; a_1=0.05; b_1=0.02; a_2=0.03; b_2=0.05; a_3=0.06; b_3=0.03

Based on the constructed mathematical model of the transmission ratio of non-circular gear train, given the center distance a of the non-circular gear train, the mathematical model of the pitch curve of the driving and driven gear can be expressed as

$$\left\langle \begin{aligned} & r_1(\varphi_1) = \frac{a}{1+i_{12}(\varphi_1)} = \frac{a i_{21}(\varphi_1)}{1+i_{21}(\varphi_1)} \\ & r_2(\varphi_2(\varphi_1)) = a - r_1(\varphi_1) \\ & \varphi_2(\varphi_1) = \int_0^{\varphi_1} i_{21} d\varphi_1 \end{aligned} \right. \tag{3}$$

Where r_1 and r_2 are the radii of the pitch curves of the driving and driven gear respectively; a is the distance of non-circular gear train; φ_2 is the rotational angle of driven gear.

The distance a is 100mm, Fig.3 shows the pitch curves of non-circular gear where the transmission ratio is construct with n_1=n_2=1; N=3; a_1=0.05; b_1=0.02; a_2=0.03; b_2=0.05; a_3=0.06; b_3=0.03. The pitch curves of the driving and driven gear in the figure are smooth without mutation, indicating that the non-circular gear obtained by fitting the transmission ratio with Fourier equation has good transmission characteristics.

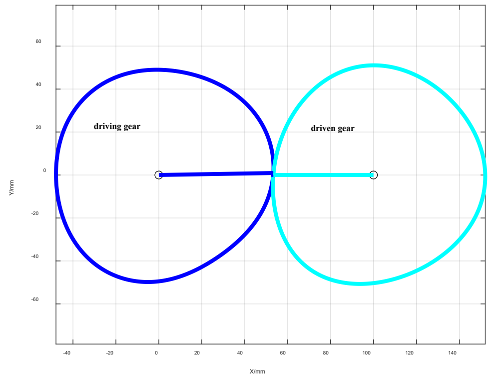


Fig.3 Pitch curves with $n_1=n_2=1$; $N=3$; $a_1=0.05$; $b_1=0.02$; $a_2=0.03$; $b_2=0.05$; $a_3=0.06$; $b_3=0.03$

To ensure the continuous transmission of non-circular gear train, when the driving gear rotates n_2 circles, the driven gear rotates corresponding n_1 circles. Then the rotational angles of the driving and driven gears should satisfy the following equation:

$$\varphi_2=\frac{2\pi}{n_2}=\int_0^{\frac{2\pi}{n_1}} i_{21}d\varphi_1=\int_0^{\frac{2\pi}{n_1}}\frac{r_1(\varphi_1)}{a-r_1(\varphi_1)}d\varphi_1 \tag{4}$$

3 Software for designing and analyzing

For the sake of analyzing the non-circular gear with the transmission ratio constructed by Fourier series equation, a visual design platform of this non-circular gear is developed in MATLAB, as shown in Fig.4. The effect factor on motion characteristics of non-circular gear can be analyzed by the software, and user can obtain the design parameters of non-circular gear for the design requirement.

The designer can input the design parameters of the Fourier equation on the design platform interface, and output the relevant parameters in real time through the button control method, including the transmission ratio curve fitted by the Fourier equation and the angular velocity curve of the driven gear, and display the non-circular gear pitch curve of the transmission ratio fitted by the Fourier equation and conduct simulation motion to preliminarily verify the rationality and accuracy of the design, and save the design calculation results.

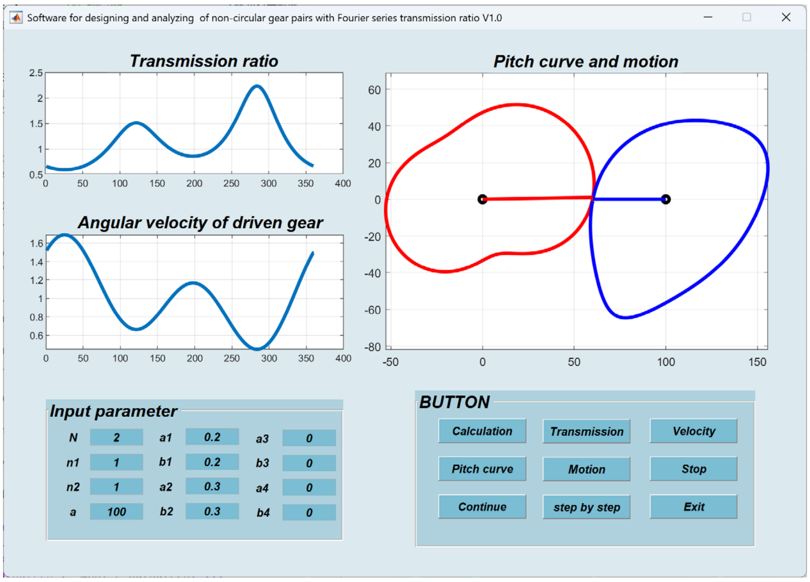


Fig.4 Software for designing and analyzing non-circular gear with Fourier series transmission ratio

If the output results of the input design parameters do not meet the design requirements, the relevant design parameters can be adjusted in real time for optimal design.

4. Parameter Influence Analysis

When $a_i = b_i = 0$, $i \in [1, N]$, the transmission ratio equation Eq.2 is $i_{21} = 1/i_{12} = n_1/n_2$, the transmission ratio curve fitted by the Fourier series equation is a straight line, that is, the corresponding pitch curve equation Eq.3 represents the pitch curve of cylindrical gears.

Due to limited space, this paper analyses the influence of the first 3 items of Fourier parameters on the constructed transmission ratio, the transmission ratio equation Eq.2 is

$$i_{21} = \frac{1}{i_{12}} = \frac{n_1}{n_2} + \sum_{k=1}^{3}\left(a_k \cos\left(kn_1\varphi_1\right) + b_k \sin\left(kn_1\varphi_1\right)\right) \ \varphi_1 \in [0, 2\pi] \quad (5)$$

In the analysis process, the single-factor analysis method is used. When analyzing the influence law of a certain factor, n_1/n_2 is set to $1/1$, and the other design parameters are all set to 0.

4.1. Parameter a_1

When n_1/n_2 is set to $1/1$, except for a_1, set all other parameters to 0. The transmission ratio equation Eq.2 is

$$i_{21} = 1/i_{12} = 1 + a_1 \cos(\varphi_1) \tag{6}$$

Fig.5 shows the transmission ratio of non-circular gear train corresponding to different Fourier parameters a_1. From the transmission ratio curve in the Fig.5, it can be seen that: ① Within one transmission cycle, the transmission ratio curve presents a "single-peak" type, and its peak-peak value changes with the change of parameter a_1. It is manifested that the maximum value of the transmission ratio increases with the increase of parameter a_1, and the minimum value decreases with the increase of parameter a_1. ② The transmission ratio curve is always symmetrical about the polar angle $\varphi_1 = 180^o$, that is, the maximum value of the transmission ratio is always located at the polar angle and is not affected by the change of parameter.

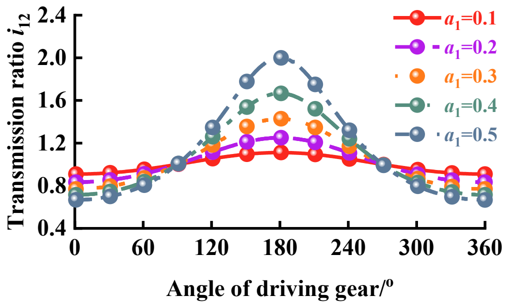


Fig.5 The influence of a_1 on the transmission ratio

4.2. Parameter b_1

When n_1/n_2 is set to $1/1$, except for b_1, set all other parameters to 0. The transmission ratio equation Eq.2 is

$$i_{21} = 1/i_{12} = 1 + b_1 \sin(\varphi_1) \tag{7}$$

Fig.6 shows the transmission ratio curve corresponding to different Fourier parameters b_1. From the transmission ratio curve in the figure, it can be seen that: ① Within one transmission cycle, the variation law of the peak-peak value of the transmission ratio is consistent with the influence of parameter b_1. The transmission ratio curve in Fig.6 can be obtained by advancing the transmission ratio curve obtained in Fig.5 by 90°, which is in line with the Fourier series expression (7). ② When $b_1 \neq 0$, the transmission ratio curve fitted by the Fourier series is not symmetrical about the polar angle $\varphi_1 = 180^o$, and the transmission ratio changes slowly in the polar angle interval $\varphi_1 \in [0, 180^o]$ than in the interval $\varphi_1 \in [180^o, 360^o]$.

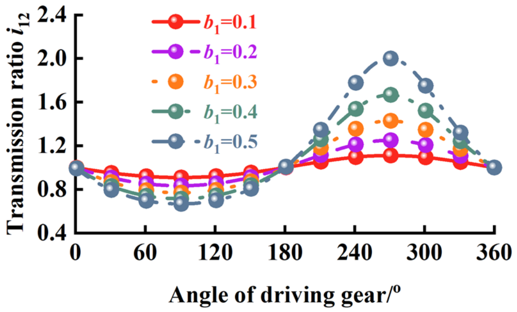


Fig.6 The influence of b_1 on the transmission ratio

4.3. Parameter a_2

When n_1/n_2 is set to $1/1$, except for a_2, set all other parameters to 0. The transmission ratio equation Eq.2 is

$$i_{21} = 1/i_{12} = 1 + a_2 \cos(2\varphi_1) \tag{8}$$

Fig.7 shows the transmission ratio of non-circular gear train corresponding to different Fourier parameters a_2. From the transmission ratio curve in the figure, it can be seen that: ① Within one transmission cycle, the transmission ratio curve constructed by Fourier series presents a "double-peak" type and is symmetrical about the polar angle $\varphi_1 = 180^o$. The variation law of the peak-peak value is consistent with the influence of parameter a_1, and only the corresponding polar angle is reduced to twice the corresponding a_1. ② When $a_2 \neq 0$, the maximum value of the transmission ratio is located at the polar angles $\varphi_1 = 90^o$ and $\varphi_1 = 270^o$, and the values are the same.

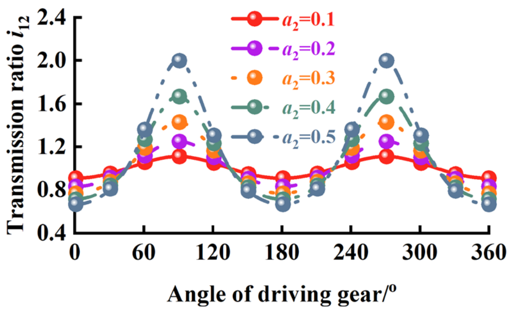


Fig.7 The influence of a_2 on the transmission ratio

4.4. Parameter b_2

When n_1/n_2 is set to $1/1$, except for b_2, set all other parameters to 0. The transmission ratio equation Eq.2 is

$$i_{21} = 1/i_{12} = 1 + b_2 \sin(2\varphi_1) \tag{9}$$

Fig.8 shows the transmission ratio of non-circular gear train corresponding to different Fourier parameters b_2. From the transmission ratio curve in the figure, it can be seen that: ① Within one transmission cycle, the variation law of the peak-peak value of the transmission ratio is consistent with the influence of parameter b_2. The transmission ratio curve in Fig.8 can be obtained by advancing the transmission ratio curve obtained in Fig.7 by 45°, which is in line with the Fourier series expression (9). ② When $b_2 \neq 0$, the maximum value of the transmission ratio is located at the polar angles $\varphi_1 = 135^o$ and $\varphi_1 = 315^o$, and the values are the same.

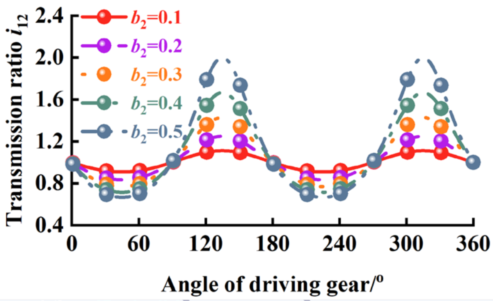


Fig.8 The influence of b_2 on the transmission ratio

4.5.Parameter a_3

When n_1/n_2 is set to $1/1$, except for a_3, set all other parameters to 0. The transmission ratio equation Eq.2 is

$$i_{21} = 1/i_{12} = 1 + a_3 \cos(3\varphi_1) \tag{10}$$

Fig.9 shows transmission ratio of non-circular gear train corresponding to different Fourier parameters a_3. From the transmission ratio curve in the figure, it can be seen that: ① Within one transmission cycle, the transmission ratio curve constructed by Fourier series presents a "triple-peak" type and is symmetrical about the polar angle $\varphi_1 = 180^o$. The variation law of the peak-peak value is consistent with the influence of parameters a_1 and a_2, and only the corresponding polar angle is reduced to three times the corresponding a_1. ② When $a_3 \neq 0$, the maximum value of the transmission ratio is located at the polar angles $\varphi_1 = 60^o$, $\varphi_1 = 180^o$, and $\varphi_1 = 300^o$, and the values are the same.

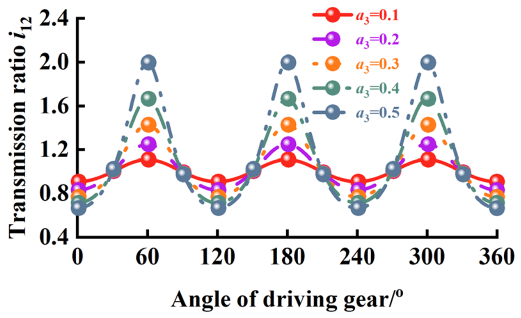


Fig.9 The influence of a_3 on the transmission ratio curve

4.6. Parameter b_3

When n_1/n_2 is set to $1/1$, except for b_3, set all other parameters to 0. The transmission ratio equation Eq.2 is

$$i_{21} = 1/i_{12} = 1 + b_3 \cos(3\varphi_1) \tag{11}$$

Fig.10 shows the transmission ratio of non-circular gear train corresponding to different Fourier parameters b_3. From the transmission ratio curve in the figure, it can be seen that: ① Within one transmission cycle, the variation law of the peak-peak value of the transmission ratio is consistent with the influence of parameter a_3. The transmission ratio curve in Fig.10 can be obtained by advancing the transmission ratio curve obtained in Fig.9 by 30°, which is in line with the Fourier series Eq.11. ② When $b_3 \neq 0$, the maximum value of the transmission ratio is located at the polar angles $\varphi_1 = 90^o$, $\varphi_1 = 210^o$ and $\varphi_1 = 330^o$, and the values are the same.

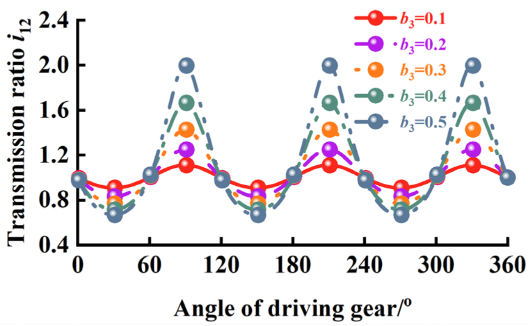


Fig.10 The influence of b_3 on the transmission ratio curve

4.7. Comparison of transmission ratio maximum and minimum values

Fig.11 shows the maximum and minimum values of the transmission ratio obtained by the above 6 groups of design parameters. Comprehensive analysis shows that:

① When $a_k = b_k$,the peak-peak value and maximum and minimum values of the transmission ratio are the same, but the positions of the maximum and minimum values differ by polar angle $90/k^o$, and the maximum value of the transmission ratio corresponding to b_k is advanced by $90/k^o$ compared with the maximum value of the transmission ratio corresponding to a_k .

② The maximum value of the transmission ratio increases with the increase of design parameters a_k (or b_k), and the minimum value decreases with the increase of design parameters a_k (or b_k). The peak-peak value of the transmission ratio increases with the increase of design parameters a_k (or b_k), that is, the variation range of the transmission ratio increases with the increase of design parameters a_k (or b_k).

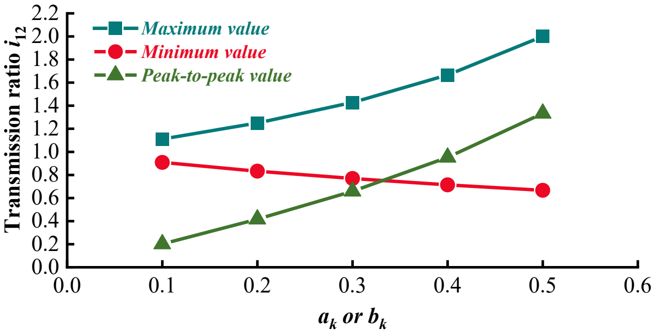


Fig.11 Transmission ratio maximum and minimum values

5 Mathematical model of guide mechanism and result

The crank 3 (in Fig.1) is fixedly connected to the driven non-circular gear 2 (in Fig.1), that is, the rotation centers of the two are the same hinge O_2, and the motion characteristics of the crank 3 is equal to the driven non-circular gear 2. The rod 5 moves along the X-axis of the frame, and its motion characteristics are the same as those of the slider 4 in the X-axis direction. According to the geometric relationship, the velocity equation of the guide rod can be obtained as

$$v = -\Omega(\varphi_2) l_1 \sin\varphi_2 \tag{12}$$

where v is the velocity of the rod 5, $\Omega(\varphi_2)$ is the angular velocity of driven gear 2 (or crank 3), l_1 is the length of crank 3. φ_2 is the rotational angle of driven gear2, it can be obtained by solving Eq.4.

For the convenience of subsequent silk reeling process, the shape of the silk thread package should be as close to a trapezoid as possible. It is required that when the silk thread is wound, the winding angles should be as equal as possible, the winding barrel rotates at a constant angular velocity. As long as it is ensured that the guide rod has an approximately constant velocity motion law for a long time during the reciprocating stroke, the equal winding angle winding process can be ensured. According the requirement of the rod of product-integrated guide mechanism.

5.1 Objective function

Let the average speed of the rod within the effective stroke be $\overline{v}$, then

$$\overline{v} = \sum_{i=0}^{M} \frac{v_i}{M} \tag{13}$$

where M is the number of equally divided points within the effective stroke, and v_i is the speed of the rod when the driving gear is in different positions. The difference between the rod speed and the average speed at different positions is

$$\Delta v_i = v_i - \overline{v} \tag{14}$$

where Δv_i means speed fluctuation. The larger its value, the greater the adverse impact on the working performance. In order to make the larger Δv_i be more significantly reflected in the objective function, the mean square deviation of the guide bar speed is used as the objective function F, that is

$$F = \sqrt{\sum_{i=1}^{M} (v_i - \overline{v})^2 / M} \tag{15}$$

The value of the objective function F will reflect the fluctuation of the rod speed. The smaller F is, the smaller the fluctuation of the rod speed within the effective stroke, and the closer the speed of the rod at each position is to the average speed.

5.2 Constraint equation

According to the characteristics of non-circular gear transmission, to ensure the smooth transmission of non-circular gears, when designing the pitch curve of non-circular gears, ensuring that the pitch curve has no concave inward can ensure that no undercut will occur during the generation of the tooth profile, which affects the transmission. The expression for ensuring that the pitch curve has no concave inward is

$$\begin{cases} 1 + i_{12} + \dfrac{i^2{}_{12}}{d\varphi_1^2} \geq 0 \\ 1 + i_{12} - i_{12}\dfrac{i^2{}_{12}}{d\varphi_1^2} + \left(\dfrac{i_{12}}{d\varphi_1}\right)^2 \geq 0 \end{cases} \tag{16}$$

During the optimization process, Equation (16) is used as a constraint condition.

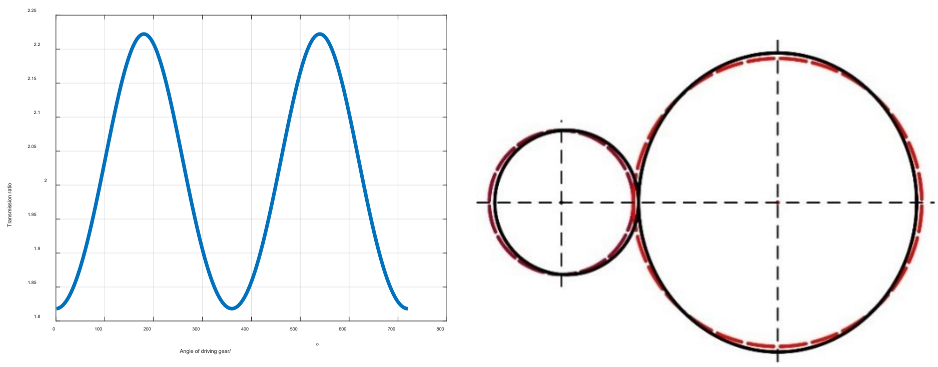
5.3 Optimization method

The fmincon function in the Matlab optimization toolbox is an effective method for solving nonlinear constrained extreme optimization problems. Using the first-order derivative information of the objective function and the constraint function, starting from a given initial point, under the condition of satisfying the constraints, iterate along the direction of the decreasing objective function, and finally converge to the optimal solution. The optimization problem in this paper is a nonlinear constrained extreme optimization problem. Therefore, the format [X, FVAL]= fmincon(fun, x_0, A, b, Aeq, beq, lb, ub, nonlcon) is adopted, where fun is the objective function of the minimum value; x_0 is the initial value; A and b are linear inequality constraints; Aeq and beq are linear equality constraints; lb is the lower boundary; ub is the upper boundary; nonlcon is the nonlinear constraint condition.

5.4 Result analysis

A set of design parameters is obtained, N=1, $n_1 : n_2 = 1:2$, $a_1 = 0.055$, $b_1 = 0$, the transmission ratio equation is $i_{21} = \frac{1}{i_{12}} = 0.5 + 0.055\cos(\varphi_1)$.

Fig.12(a) shows the transmission ratio of non-circular gear which can make the rod achieving approximately constant speed guide performance within a certain range of motion. Fig.12(b) shows the pitch curve of the non-circular gear corresponding to the transmission ratio (black solid line) and the cylindrical gear (red dotted line).



(a) Transmission ratio (b) Pitch curves

Fig.12 The transmission ratio and pitch curve of non-circular gears that can drive the guide bar mechanism to achieve approximately constant-speed guide

The velocity of the rod driven by non-circular gears and cylindrical gears are shown in Fig.13. It can be seen from the velocity curve of the rod in the figure that: ① The velocity curve of the rod driven by the cylindrical gear presents a sine shape, and there is no constant-speed section during the reciprocating stroke; ② The rod driven by the non-circular gear obtained by fitting the transmission ratio with the Fourier equation has an approximately constant-speed section during the reciprocating stroke. According to the winding process with equal winding angles, the wound package better meets the requirements of the subsequent silk reeling process.

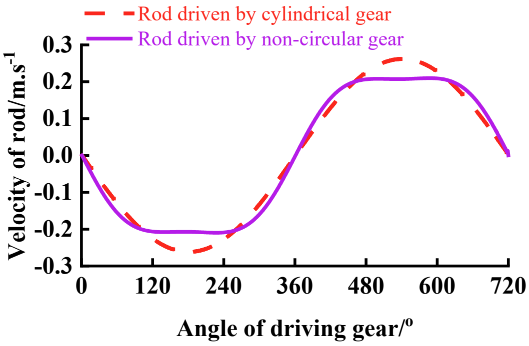


Fig.13 Comparison of the speed curves of the guide rod driven by non-circular gears and cylindrical gears

6 Conclusions

This paper aims at the motion law of the guide bar mechanism which requires approximate constant speed in the reciprocating stroke, and proposes a transmission mechanism of a non-circular gear driving a sine mechanism with the transmission ratio fitted by a Fourier equation. The Fourier equation is used to fit the transmission ratio and the mathematical equation of the non-circular gear pitch curve by means of numerical analysis. The influence law of the Fourier equation parameters on the transmission ratio is analyzed by single factor. It is obtained that the transmission ratio curves corresponding to the parameters a_k and b_k only have a 90 deg phase difference. When $a_k = b_k$, the extreme values of the transmission ratio are the same. By setting different Fourier parameters, different transmission ratio curves can be fitted, and thus non-circular gear train with different transmission characteristics can be obtained. By connecting the non-circular gear and the sine mechanism in series for transmission, the motion law that the guide bar realizes approximate constant speed in the reciprocating stroke can be obtained. Taking the mean square deviation of the speed as the optimization objective function, the fmincon function in the MATLAB optimization toolbox is used to solve the minimum value of the mean square deviation of the guide bar, and the Fourier design parameters meeting the requirements of the constant speed guide bar are obtained. Compared with the guide bar mechanism driven by cylindrical gears, the results show the feasibility of the proposed non-circular gear driven guide bar mechanism.

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