DESIGN AND ANALYSIS OF CIRCULAR COMB TRANSMISSION MECHANISM FOR WOOLEN COMBING MACHINE

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In order to meet the requirements of the circular combing process of the woolen combing machine, this paper proposes to use three non-circular gears, namely Limacon gears and their conjugate non-circular gears, to drive the circular comb mechanism based on the research of the circular combing process. A mathematical model of the transmission of this circular comb mechanism is established by using geometric graphics and numerical analysis. Visual design software for this circular comb mechanism is developed in MATLAB, and the factors affecting the speed of the circular comb tip are analyzed by using this software. It is found that the range of variation of the circular comb tip speed increases with the increase of eccentricity, and different combing speeds can be obtained by adjusting the eccentricity of the Limacon gear. Based on the circular comb mechanism of the B311 - type combing machine, a case study is carried out. The developed software is used to meet the combing process requirements of "accelerating first and then decelerating". A virtual prototype simulation test is carried out on the example, and the experimental results are basically consistent with the theoretical calculation results, which shows the feasibility of the proposed circular comb mechanism and verifies the correctness of the established mathematical model and the developed visual design software.

Keywords: Woolen Combing Machine; Circular Comb Mechanism; Limacon Gear; Variable - speed Transmission; Visual Design Software

1 Introduction

The woolen combing machine [1] is a textile machinery and equipment that removes kinked particles in fibers, excludes short fibers, and combs the fibers into a uniform thickness. According to the classification, it can be divided into straight - type cotton combers, straight - type wool combers, and circular - type combers [2]. Among them, the circular - type comber is widely used in combers due to its unique advantages, and the typical representative is the B311 - type comber [3]. *GUO Bingchen* [4] proposed to evaluate the combing efficiency of the circular comb

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mechanism by the number of combing times and the combing speed of each fiber by steel needles, and analyzed the transmission performance of the circular comb mechanism driven by three identical eccentric gears. *WANG Shuhui et al.* [5] studied the influence of three factors, namely the number of needle rows, the needle density, and the combing gauge distribution, on the circular comb structure, and found that as long as the needle density of the rear - row needle plate is ensured, foreign matters such as wool pellets and grass scraps can be removed; *REN Jiazhi et al.* [6] carried out improvement research on the E7/8 - type comber by changing the crank radius, and found that when the crank radius is reduced, the combing speed when the sliver enters combing can be reduced, and the damage to the sliver can be reduced.

Based on the research of the combing process of the comber, three non - circular gears [7], namely Limacon gear and their conjugate non - circular gears, are used to drive the circular comb mechanism. The mathematical model of the circular comb transmission mechanism of this type of woolen combing machine is constructed by using numerical analysis and geometric graphic knowledge, and the visual analysis and design software of this type of circular comb mechanism is developed by Mat Lab to realize the digital design of the circular comb mechanism of the woolen combing machine. The factors affecting the characteristics of the circular comb mechanism are analyzed by using the developed visual design software to provide a theoretical basis for this type of circular comb mechanism. Based on the design parameters [4] of the circular comb mechanism in the B311 - type woolen combing machine, an example design is carried out, the motion characteristics of the example circular comb mechanism are analyzed, and the example is verified by the virtual prototype simulation test.

1 Process Principle

1.1 Combing Process Analysis

Before the sliver enters the circular comb for combing, the fibers are arranged in a disorderly manner. Therefore, when the sliver enters combing, the circular comb should have a low initial speed to avoid breaking the fibers due to excessive combing force; after the sliver enters the circular comb for combing, the fibers gradually become straight, and the combing speed can reach the maximum value; after the sliver is combed, the sliver is already relatively straight, but the needle density on the rear - row needle plate of the circular comb increases, and the needles become thinner. At this time, if the combing speed is too high, the needle plate is easily damaged or the fibers are broken. Throughout the combing process, the sliver needs to pass through eighteen rows of needles, covering an angle of about 132^{o}. [4]

In summary, in order to reduce the damage to the fibers during the combing process and improve the combing effect, when the circular comb needles of the woolen combing machine transmission mechanism insert into the fiber tuft to comb the fibers, the speed of the comb needles is required to change from gradually increasing to gradually decreasing. [4]

1.2 Working Principle

Fig.1 shows the circular comb transmission mechanism of the woolen combing machine. Its power transmission route is as follows: The power is provided by the motor to drive the driving pulley fixed on the motor shaft to rotate at a constant speed. Through the belt, the power is transmitted to the driven pulley, and the driven pulley rotates at a constant speed. At the same time, the Limacon gear "1" fixed on the same camshaft as the driven pulley rotates at the same motion law at a constant speed, and transmits the power to the non-circular gear "2" through the meshing of the tooth profiles. Since the pitch curve radius ratio of the Limacon gear "1" and the non-circular gear "2" is time-varying, the non-circular gear "2" rotates at a variable speed according to a certain law. At the same time, the non-circular gear "3" meshes with the non-circular gear "2", and the cylinder shaft coaxial with the non-circular gear "3" rotates at a variable speed.

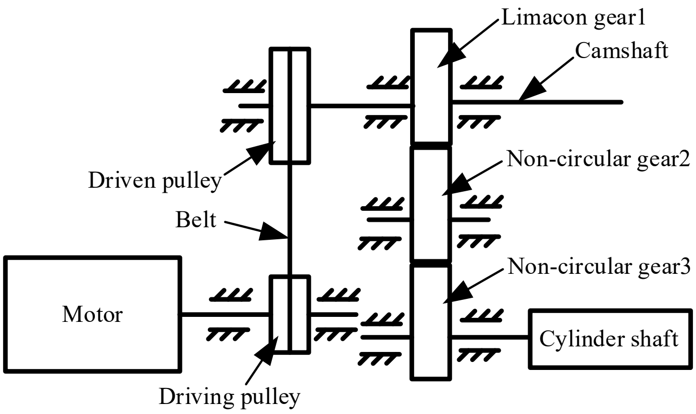

Fig.1 Circular comb transmission mechanism of woolen combing machine

2 Mathematical Model

In order to facilitate the establishment of the mathematical model of the circular comb transmission mechanism of the woolen combing machine, the parameter variables involved and their meanings are listed in Tab.1.

Table 1

Parameters

b	Diameter of generated circle (mm)	l	Fixed length (mm)
r_1	Pitch curve radius of Limacon gear 1 (mm)	r_2	Pitch curve radius of non-circular gear 2 (mm)
r_3	Pitch curve radius of non-circular gear 3 (mm)	φ_1	Angle of rotation of Limacon gear 1 (rad)
φ_2	Angle of rotation of non-circular gear 2 (rad)	φ_3	Angle of rotation of non-circular gear 3 (rad)
a_1	Center distance of the first-stage Limacon gear pair (mm)	a_2	Center distance of the second-stage non-circular gear pair (mm)
i_{12}	Transmission ratio of the first-stage Limacon gear pair	i_{23}	Transmission ratio of the second-stage non-circular gear pair
i_{13}	Total transmission ratio	v	Circular comb tip speed ($m.s^{-1}$)
n	Camshaft rotation speed (rpm)	R_1	Circular comb tip radius (mm)

2.1 Mathematical Model

In order to facilitate the analysis of the motion characteristics when the Limacon gear and non-circular gear are transmitted, a coordinate system xO_1y is established with the rotation center O_1 of the Limacon gear 1 as the origin, as shown in Fig.2.

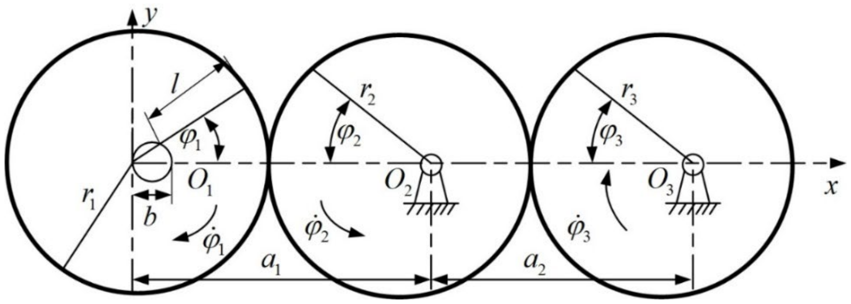

Fig.2 Three Limacon gear transmission mechanism

Fig.2 shows the generation principle diagram of the pitch curve of Limacon gear. In the coordinate system xO_1y , the generating circle is a circle with the center at (b/2, 0) and a radius of b/2. It is defined that the locus of any point on the generating circle along the radial direction at a distance of l from this point is the Limacon curve(the leftmost closed circle in the Fig.2). According to the geometric relationship, the pitch curve equation of the Limacon gear 1 [8,9] can be expressed as:

$$r_1(\varphi_1) = b\cos\varphi_1 + l \tag{1}$$

To ensure that the gear pair can achieve continuous transmission, when the driving gear rotates one circle, the driven gear meshed with it also rotates one circle accordingly [8], so the angles of rotation of the driving and driven gears need to satisfy the following equation:

$$2\pi = \int_0^{2\pi} \frac{r_1(\varphi_1)}{a_1 - r_1(\varphi_1)} \mathrm{d}\varphi_1 = \int_0^{2\pi} \frac{b\cos\varphi_1 + l}{a_1 - (b\cos\varphi_1 + l)} d\varphi_1 \tag{2}$$

Solving the above Eq.2 can obtain the fixed center distance a1 that enables the driving and driven gears to achieve continuous transmission. [9]

On the premise that the pitch curve equation $r_1(\varphi_1)$ of the Limacon gear 1 and the center distance a1 of the gear pair are known, the pitch curve equation $r_2(\varphi_2)$ and the angle - of - rotation characteristic equation $\varphi_2(\varphi_1)$ of the non-circular gear 2 are:

$$\begin{cases} r_2(\varphi_2) = a_1 - r_1(\varphi_1) \\ \varphi_2(\varphi_1) = -\int_0^{\varphi_1} \frac{1}{i_{12}} d\varphi_1 = -\int_0^{\varphi_1} \frac{r_1(\varphi_1)}{a_1 - r_1(\varphi_1)} d\varphi_1 \end{cases} \tag{3}$$

According to the non - circular gear transmission characteristics, the transmission ratio of the first - stage Limacon gear pair can be expressed as:

$$i_{12} = \frac{r_2(\varphi_2)}{r_1(\varphi_1)} = \frac{a_1 - (b\cos\varphi_1 + l)}{b\cos\varphi_1 + l} \tag{4}$$

Similarly, to ensure that the non-circular gear 2 and the non-circular gear 3 can be continuously transmitted, when the non-circular gear 2 rotates one circle, the non-circular gear 3 meshed with it just rotates one circle, so the second - stage non-circular gear transmission needs to satisfy the equation:

$$2\pi = \int_0^{2\pi} \frac{r_2'(\varphi_2')}{a_2 - r_2'(\varphi_2')} \mathrm{d}\varphi_1 \tag{5}$$

In the formula, $r_2'(\varphi_2') = r_2(\varphi_2 - 180^\circ)$, that is, the radius ratio on the pitch curve of the non-circular gear 2 meshed with the non - circular gear 3 lags 180º from the radius at the meshing point with the Limacon gear 1.

Solving the above Eq.5 can obtain the center distance a_2 of the second - stage non-circular gear pair. After obtaining the center distance a_2, the pitch curve equation and the angle - of - rotation equation of the non - circular gear 3 can be expressed as:

$$\begin{cases} r_3(\varphi_3) = a_2 - r_2'(\varphi_2') \\ \varphi_3(\varphi_2') = -\int_0^{\varphi_2'} \frac{1}{i_{23}} d\varphi_2' = -\int_0^{\varphi_2'} \frac{r_2'(\varphi_2')}{a_2 - r_2'(\varphi_2')} d\varphi_2' \end{cases} \tag{6}$$

Then the transmission ratio equation of the second - stage non - circular gear pair is:

$$i_{23} = \frac{r_3(\varphi_3)}{r_2'(\varphi_2')} \tag{7}$$

In summary, the relationship of the total transmission ratio i_{13} of the three non - circular gears can be expressed as:

$$i_{13} = i_{12} i_{23} = \frac{r_2(\varphi_2)}{r_1(\varphi_1)} \frac{r_3(\varphi_3)}{r_2'(\varphi_2')} \tag{8}$$

According to the rotation situation of the circular comb tip, the expression of the surface speed of the circular comb can be obtained as:

$$v = \frac{2\pi n}{60} R_1 i_{13} \tag{9}$$

2.2 Visual Design Software

In order to facilitate the analysis of the motion characteristics of the circular comb transmission mechanism of the woolen combing machine, based on the established mathematical model, visual design software is developed in MATLAB, as shown in Fig.3.

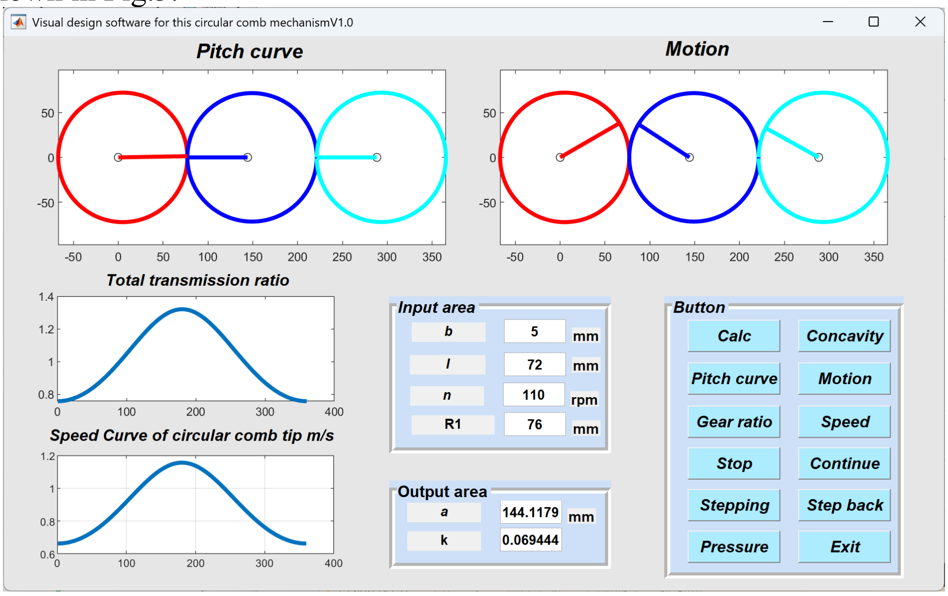

Fig. 3 Visual design software

Functions and steps: The designer can input the design parameters in the parameter input area. Through the button - controlled method, the software automatically displays the calculation results at the corresponding positions on the software interface and automatically draws the pitch curves of the three non - circular gears. At the same time, a simulation motion is carried out. Through the simulation motion, it can be observed whether the pitch curves of the three non - circular gears are always meshed, and the rationality of the design can be preliminarily judged.

2.3 Influence Factor Analysis

In order to design the circular comb transmission mechanism that meets the combing process, analyzing the mathematical model of the circular comb transmission mechanism, it is found that the main factors affecting the circular comb tip speed are the rotation speed n, the outer diameter R_1 of the circular comb tip, and the transmission ratio i_{13} of the three non-circular gears. Among them, the rotation speed n and the outer diameter R_1 of the circular comb tip only affect the magnitude of the circular comb tip speed and are positively linearly correlated. Therefore, these two influencing factors are not described in this paper. Since the radius ratio is time - varying when the three transmission gears are meshed, that is, the transmission ratio i_{13} is not a fixed value. According to the established mathematical model of the three non-circular gear transmissions, the main factors affecting the transmission ratio are the diameter of generated circle b and the fixed length l, and the influence laws of these two factors can be transformed into the influence of the eccentricity [9] $k = b/l$.

Figure 4 shows the circular comb tip speed curves corresponding to different eccentricities (the fixed length l is always 72mm, and the diameter of generated circle b are selected as 5mm, 10mm, 15mm, 20mm, and 25mm respectively). It can be seen from the curves in the figure that when the eccentricity of the Limacon gear is changed, the range of variation of the circular comb tip speed will also change. The larger the eccentricity, the larger the range of variation of the circular comb tip speed (the maximum speed becomes larger and the minimum speed becomes smaller), and the variation law is the same as that of the Limacon gear transmission ratio. For the requirements of different combing speeds, it can be achieved by changing the eccentricity of the Limacon gear.

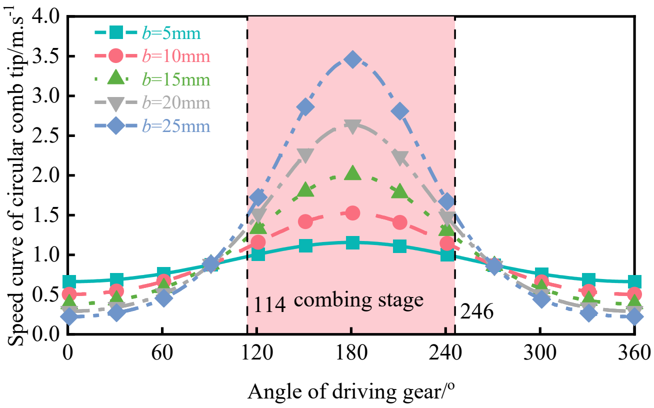

Fig.4 The influence law of eccentricity on comb tip

3 Example and Virtual Prototype Simulation Test

An example design is carried out for the basic parameters of the B311-type comber [4]. The basic parameters are listed in Tab.2.

Table 2

Basic Parameters

Design parameter value rotation speed n	110rpm	Outer diameter R_1 of circular comb tip	76mm
Diameter of generated circle b	5mm	Fixed length l	72mm

The design parameters are input into the developed visual design software to obtain the transmission ratio curves of each non-circular gear pair, as shown in Fig.5. It can be seen from the curves in the figure that the transmission ratio curve i_{12} when the Limacon gear 1 meshes with the non - circular gear 2 is basically the same as the transmission ratio curve i_{23} when the non - circular gears 2 and 3 are meshed and transmitted, but there are differences. The reason for the differences is as follows: In order to ensure that the gears are always meshed during the operation process, the center distance a of the gear pair that meets the continuous transmission requirements is calculated by numerical analysis, and then the pitch curve of the driven gear is obtained. The obtained pitch curve of the driven gear is different from the shape of the Limacon circle, so gear 2 does not belong to the Limacon gear category. The range of variation of the transmission ratio i_{13} when the three gears are transmitted is greater than that of the single - gear - pair transmission ratio because the total transmission ratio i_{13} is the product of i_{12} and i_{23}, satisfies Eq.8.

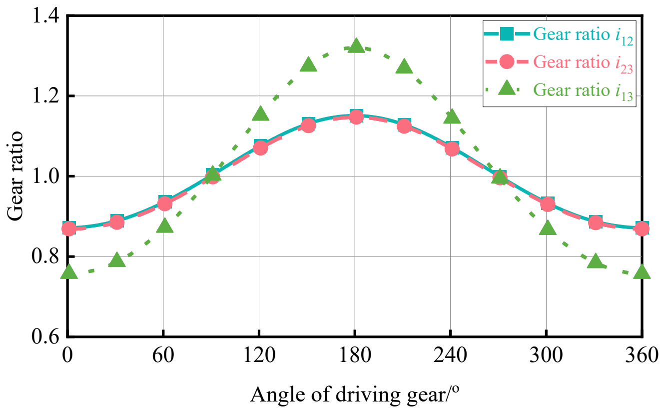

Fig. 5 Gear Ratio

The circular comb tip speed variation curve obtained by software calculation is shown in Fig.6. The circular comb combing stage is from 114° to 246°, lasting for 132°, and the sliver has just been combed by eighteen rows of needles. When the sliver just enters combing, the circular comb tip speed is 0.97794m.s^{-1}. After entering combing, the circular comb tip speed first increases and then decreases, and the highest speed reaches 1.156002m.s^{-1}. When the sliver leaves combing, the circular comb tip speed is 0.980111m.s^{-1}, which meets the combing process requirements.

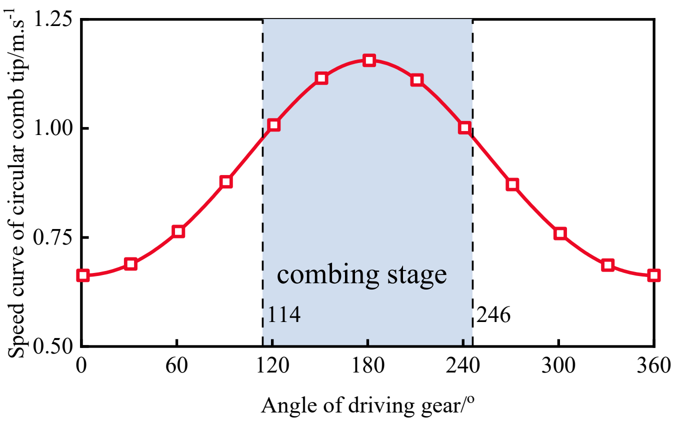

Fig.6 Speed Curve of circular comb tip

The example design parameters are designed by using the developed visual design software, and the solid model of each component is carried out. Generation of tooth profile of non-circular gear is based on the following equation:

$$\frac{dy}{d\theta} = \cos^2 \alpha_0 \left[R(\theta) - \frac{dR(\theta)}{d\theta} \tan \alpha_0 \right] \tag{10}$$

Where dy is the displacement of the contact point, as projected onto the normal direction to the non-circular gear crossing O_1 and O_2, α_0 is the pressure angle of the shaper, the value is 20°, $d\theta$ is the rotation of the non-circular gear. In order to calculate coordinates of the tooth profile of non-circular gear, a software for generating tooth profile is developed in MATLAB, as shown in Fig.7. The module of the gears is 3mm, the number of teeth of the cutting tool is 12. Import the data in Table 2 into the software in Fig. 3 to obtain the coordinates of the pitch curves of non - circular gear, and then import the coordinates into the tooth profile generation software in Fig. 7 to obtain the tooth profile coordinates of the non - circular gear. Import the obtained tooth profile coordinates into the 3D modeling software SolidWorks to generate the solid model of the non - circular gear.

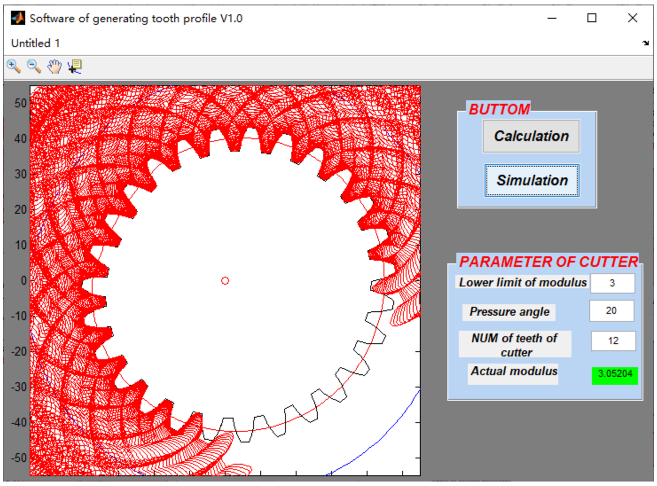

Fig.7 Software of generating tooth profile

According to the mating relationships of each component, the main components in the circular comb transmission mechanism of the woolen combing machine are virtually assembled to obtain a virtual assembly as shown in Fig.8.

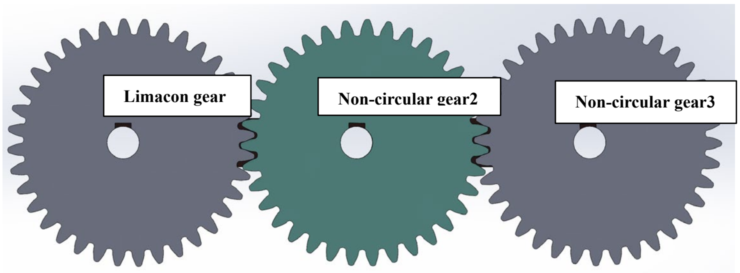

Fig.8 Three non - circular gear virtual assemblies

A virtual prototype simulation test is carried out by using the Motion plug-in SolidWorks [10], and the simulation test results are compared with the theoretical calculation results, as shown in Fig.9. It can be seen from the circular comb tip speed comparison curve in the figure that the tip speed obtained by the virtual prototype simulation test is basically the same as the tip speed curve obtained by theoretical calculation, which indicates the correctness of the established mathematical model of the circular comb transmission mechanism of the woolen combing machine, the accuracy of the developed visual design software, and the feasibility of the circular comb mechanism driven by three non-circular gears in practical applications.

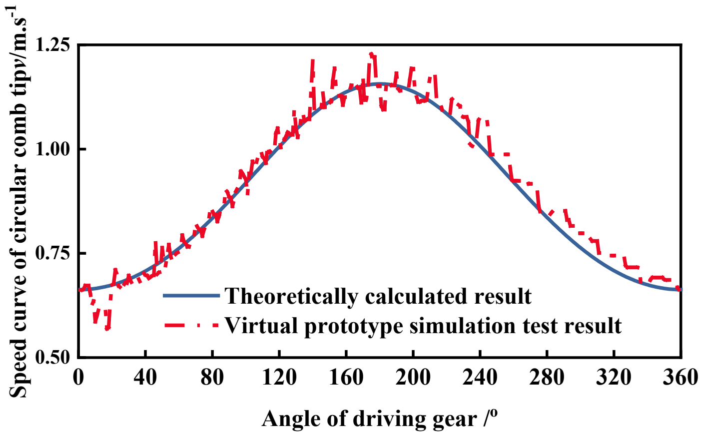

Fig.9 Speed comparison

4. Conclusions

Based on the analysis of the combing process, this paper uses three non - circular gears to drive the circular comb mechanism, establishes a mathematical model of the circular comb transmission mechanism of the woolen combing machine by using geometric mathematics and numerical analysis, develops visual design software by MATLAB, and analyzes the factors affecting the circular comb tip speed. Through example design, a virtual prototype simulation test is carried out on the content of this paper, and the following conclusions are obtained:

1) Using three non - circular gears to drive the circular comb mechanism can realize the combing process of "the combing speed gradually becomes faster first and then gradually becomes slower".

2) Through example calculation and virtual prototype simulation test, it is found that the theoretical calculation results are basically the same as the simulation test results, which verifies the correctness of the established mathematical model and the developed visual design software, and shows the feasibility of the circular comb mechanism driven by three non - circular gears.

3) The developed visual design software provides a convenient and fast design method for the design of the circular comb transmission mechanism of the woolen combing machine.

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