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Simulation Research on Non-Bevel Gear Transmission Mechanism

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1. Introduction

As a new type of gear transmission mechanism, the non-bevel gear mechanism can realize the transmission of variable speed ratio between intersecting shafts and has the advantages of compact structure and high transmission efficiency [1-2]. At present, the non-bevel gears have been applied in limited-slip differential, variable gear pumps, stepping devices, etc. [3-7].

The pitch curve of the non-bevel gear is complex. The spherical pitch curve is not a circle. In addition to its symmetry, any two teeth have different tooth profile curves, and the left and right tooth profile curves of a tooth are also different [8-13], which causes large vibration and impact in the transmission process of non-bevel gears.

How to make the non-bevel gear run more smoothly in the transmission process is the current research focus. Lin Chao, Hou Yujie. analyzed the transmission characteristics of non-bevel gears, deduced the corresponding formula, obtained the motion law, and change the relationship of their transmission. Li Wenchang, Jia Jumin, et al. used the method of geodesic curvature preserving mapping to design the non-bevel gear by changing its transmission ratio law, and carried out kinematic simulation analysis on it, and reached the conclusion that its transmission can be more stable by increasing the number of teeth and reducing the locking coefficient. Tan Weiming greatly reduced the fluctuation of gear pump operation by adding the number of non-bevel gears in the high order elliptic gear pump and using the method of mutual compensation; Among them, when three third order elliptic gears are combined, the structure has the best effect of reducing fluctuations.

To sum up, the current research on the performance of non-bevel gear transmission is mostly on the theoretical level, and the research on how to reduce the vibration and impact in the transmission process is less, and the research on electromechanical integration control is not involved.

ADAMS can well reflect the actual physical model, and its simulation results are also close to the actual analysis results [14]. MATLAB / Simulink is a powerful control simulation module that integrates many functions in a visual environment [15], which can quickly and conveniently build simulation models.

This research adopts the method of joint simulation of ADAMS and MATLAB to control the rotational speed of the driving wheel in the non-bevel gear pair, thus reducing the vibration and impact in the meshing transmission, and providing a new method for studying the complex transmission system of the non-bevel gear.

2. Model and analysis of non-bevel gear

2.1. Design of pitch curve

The transmission ratio function of the non-bevel gear is [16]:

$$i_{12}=\frac{Z_1}{Z_2}\left[1-c\sin\left(N_1\varphi_1+\frac{3\pi}{2}\right)\right], \tag{1}$$

where: Z_1, Z_2 is the number of teeth of gear *1* and gear *2*; c is the control the limit of change of the transmission ratio of the non-bevel gear, a constant coefficient less than 1, which can also be regarded as the eccentricity of the gear; N_1 is the order of non-bevel gear; φ_1 is the angle of driving wheel.

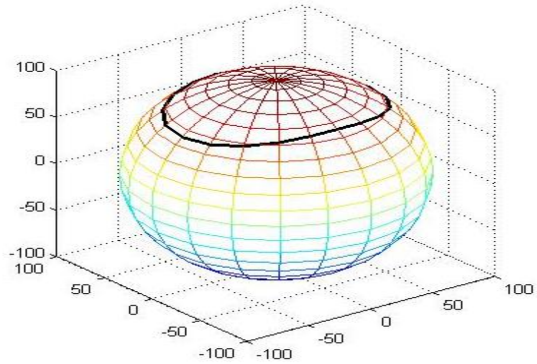

Fig. 1 Pitch curve of non-bevel gear

When the included angle between shafts of non-bevel gears is 90°, the transmission ratio function can be expressed as [17]:

$$i_{12}=\frac{w_1}{w_2}=\frac{z_2}{z_1}=\frac{d\varphi_1}{d\varphi_2}=\tan\delta_2=\cot\delta_1, \tag{2}$$

where: δ_1, δ_2 is the half of the cone-apex angle of gear *1* and gear *2*; φ_1, φ_2 is the angle of gear *1* and *2*; $d\varphi_1$, $d\varphi_2$ is instantaneous angular speed of gear *1* and gear *2*.

$$\vec{r}(\delta,\varphi) = Rsin\delta cos\varphi\vec{i} + Rsin\delta sin\varphi\vec{j} + Rcos\delta\vec{k}, \quad (3)$$

where: R is the spherical radius. $\vec{i}$, $\vec{j}$, $\vec{k}$ is the direction vector perpendicular to each other. Combine Eqs. (1)-(3), and take $c = 0.2$, $R = 100$, $Z_1 = Z_2 = 54$, $N_1 = 2$. Then using MATLAB software to program, the spherical pitch curve of the second-order single non-bevel gear can be obtained, as shown in Fig. 1.

2.2. Establishment of model

The plane rectangular coordinate equation of the gear tooth profile is [18].

$$\begin{cases} x_b = x_a - scos\alpha_n cos(\psi - \alpha_n) \\ y_b = y_a - scos\alpha_n cos(\psi - \alpha_n) \end{cases}, \quad (4)$$

$$\begin{cases} x_b = x_a + scos\alpha_n cos(\psi - \alpha_n) \\ y_b = y_a + scos\alpha_n sin(\psi - \alpha_n) \end{cases}, \quad (5)$$

$$\begin{cases} x_b = x_a + scos\alpha_n cos(\psi + \alpha_n) \\ y_b = y_a + scos\alpha_n sin(\psi + \alpha_n) \end{cases}, \quad (6)$$

$$\begin{cases} x_b = x_a + scos\alpha_n cos(\psi + \alpha_n) \\ y_b = y_a + scos\alpha_n cos(\psi + \alpha_n) \end{cases}, \quad (7)$$

where: ψ is the angle between the tangent direction of any point on the pitch curve and the X-axis; s is the arc length of the pitch curve between the intersection point of the pitch curve and the tooth profile and the intersection point of the tooth profile normal and the pitch curve from the intersection point of the tooth profile to the n point; a_n is the rack tool tooth profile angle.

According to the inverse projection relationship, the author adopts the method of projecting the equivalent tooth profile to the spherical involute tooth profile and combines it with the differential geometry knowledge [19]. The author gives the relevant parameters of the number of teeth, module, eccentricity, external taper, and so on of the non-bevel gear.

Using MATLAB and UG drawing software, the author has obtained the non-bevel gear model, as shown in Fig. 2.

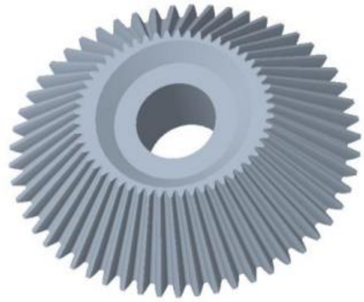

Fig. 2 Non-bevel gear model

2.3. Effect of order and eccentricity on the transmission ratio

According to Eq. (1), it can be seen that the order N_1 and eccentricity c have an impact on the transmission ratio function.

When taking eccentricity $c = 0.2$, $N_1 = [2, 3, 4]$, The change rule of the non-bevel gear transmission ratio is obtained by rotating the active wheel for one rotation, as shown in Fig. 3.

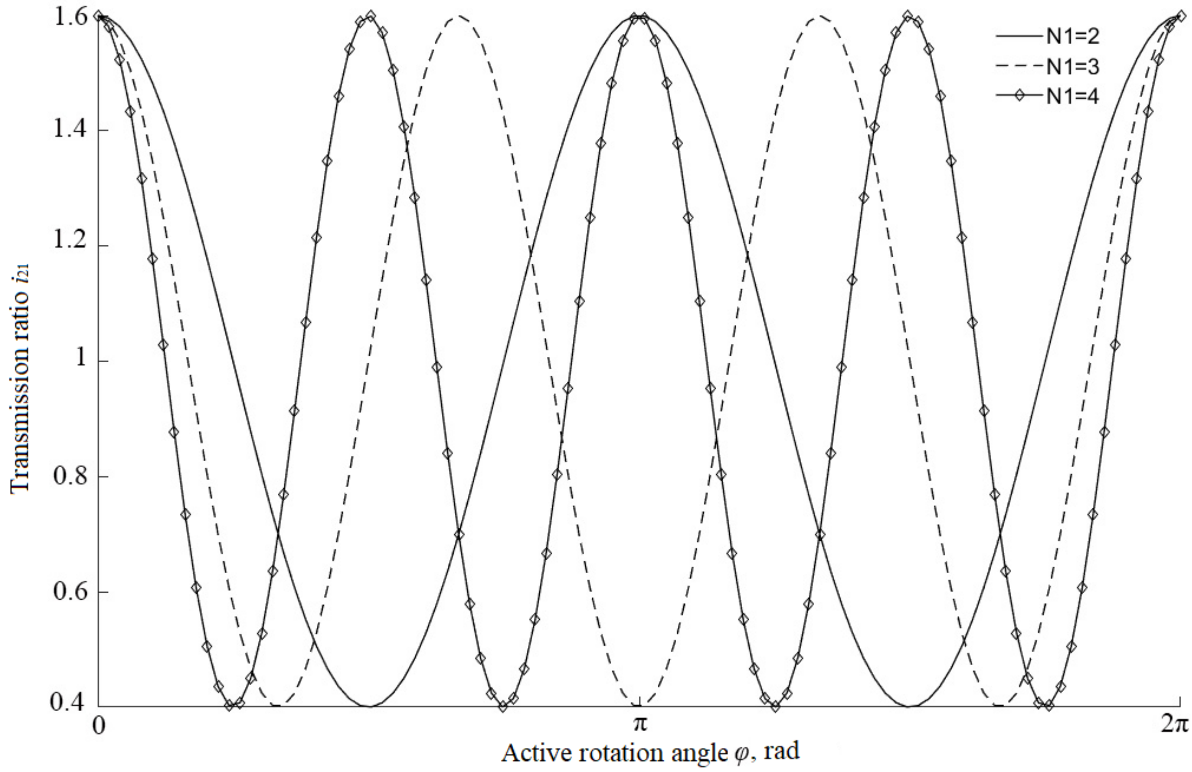

Fig. 3 Effect of order on the transmission ratio

Fig. 4 Effect of eccentricity on the transmission ratio

It can be seen from Fig. 3 that when the eccentricity is fixed, the order increases, the upper and lower amplitudes of the transmission ratio curve remain unchanged, the cycle decreases, and the frequency increases.

When the order $N_1 = 2$ the eccentricity $c = [0.1, 0.2, 0.3, 0.4, 0.5]$ and taking the non-bevel gear as an example, the influence of the eccentricity of the non- bevel gear on the transmission ratio is obtained by turning the driven wheel at least one week, the curve is shown in Fig. 4.

It can be seen from Fig. 4 that when the order is fixed, with the increase of eccentricity, the transmission cycle does not change. While the fluctuation amplitude of the transmission ratio curve increases. The vibration and impact increase in the meshing transmission of non-bevel gears, which affects the smoothness and service life of gear movement.

Therefore, the eccentricity should be minimized when the predetermined transmission ratio is met.

3. ADAMS and MATLAB joint simulation

The use of joint simulation technology can avoid the derivation of complex differential equations, facilitate the intuitive and timely discovery of problems in the design model, improve the design efficiency and reduce cost.

3.1. Establishment of the virtual model

Simple geometric models, they can be modeled directly in ADAMS. For more complex models and assemblies, it is necessary to use other drawing software for modeling (such as Solid Works, UG, Creo, etc. [20]), and save the established models in the format of .X_T or. STP, and import them into ADAMS.

The author takes the non-bevel gear pair with the second order and the eccentricity of 0.2 as an example to carry out the joint simulation (if the non-bevel gear with different orders and eccentricity is selected, it only needs to change the parameters corresponding to the "Fcn" user defined function in the MATLAB/Simulink control module, which does not affect the overall frame of the control module). The use of joint simulation technology can avoid the derivation of complex differential equations, facilitate the intuitive and timely discovery of problems in the design model, improve the design efficiency, and reduce cost.

In the drawing software, the author establishes the assembly model of non-bevel gear, and saves it as. STP format, and imports it into ADAMS to open. At the same time, set the basic information of non-bevel gear according to the actual situation.

The material of the gear is defined as steel. The driving wheel and driven wheel are respectively added with rotating pairs with "ground" as the reference objects. The driving wheel is fixed with the driving shaft. The driven wheel is fixed with the driven shaft.

The added part motion pairs are shown in Table 1 [21].

Table 1

Added part motion pairs

Pick part 1	Pick part 2	Motion pair
Driving wheel	Driven wheel	Contact
Driving wheel	Driven shaft	Fix
Driven wheel	Driven shaft	Fix
Capstan shaft	Ground	Revolve
Driven shaft	Ground	Revolve

The author adds drive to the driving wheel and load to the driven wheel, and the contact of the two gears is set as "collision contact".

The setting of collision parameters [22] is shown in Table 2.

Table 2

Collision contact parameters

Parameter/unit	Numerical value
Stiffness, N/mm	100000
Force index	1.5
Damping, N.s/mm	50.0
Penetration depth, mm	0.1

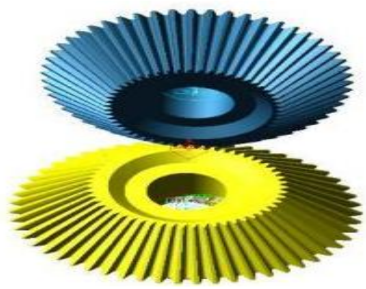

Fig. 5 ADAMS model of non-bevel gear

The virtual model of the non-bevel gear mesh is shown in Fig. 5.

Between ADAMS and MATLAB/Simulink, the data is transferred by one-way state variables [23]. In the calculation process, the unidirectional state variable is an array containing a series of numerical values, representing input, output, and other parameters prepared in advance [24].

3.2. Definition of input and output variables

In ADAMS, the set output variable is the input variable of the MATLAB/Simulink control system. Through the analysis and calculation of the control system, the generated output signal is returned as the input variable of ADAMS, and the data transfer relationship between ADAMS and MATLAB/Simulink is shown in Fig. 6.

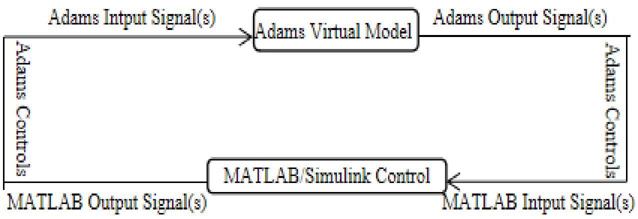

Fig. 6 Input and output relationship of ADAMS/MATLAB

The input and output variables set by the author in ADAMS are as follows:

1. Define the input driving wheel rotation speed and driven wheel load as input_av, load_force;

2. Define the output driven wheel angular velocity, angular acceleration, and collision contact force as output_av, output_ac, contact_force. The author sets parameters inADAMS/Control and establishes the connection with MA-TLAB / Simulink.

3.3. Generation of mechanical system in MATLAB / Simulink

Open the MATLAB Software and enter the. m file name generated by export in the command line window to generate input and output information, as shown in Fig. 7.

```
>> Controls_Plant_1

ans =

    '08-Jul-2021 17:29:53'


%%% INFO : ADAMS plant actuators names :
1 input_av
2 load_force
%%% INFO : ADAMS plant sensors   names :
1 output_av
2 output_ac
3 contact_force

>> adams_sys
```

Fig. 7 Input and output information generated by MATLAB

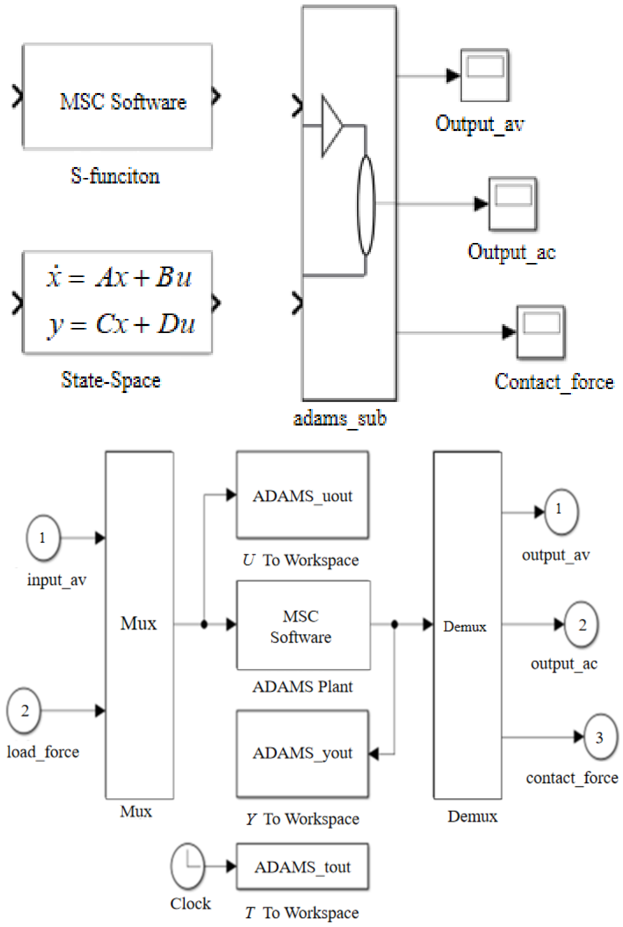

Fig. 8 Adams sub module

4. Analysis of simulation results

4.1. Only constant value input

When only one constant value signal is provided, the joint simulation system block diagram is shown in Fig. 9.

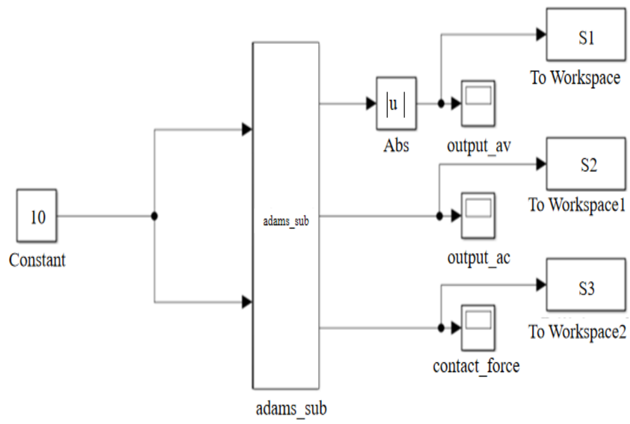

Fig. 9 Joint simulation system block diagram

The angular velocity simulation results of the driven wheel are shown in Fig. 10.

It can be seen from Fig. 10 that when the driving wheel rotates at a constant speed at a certain angular speed, the driven wheel rotates periodically in the form of a cosine function; Compared with the curve motion analyzed theoretically, its speed fluctuates periodically between 15 and 25, and the fluctuation amplitude is large. The trend of the driven wheel motion curve obtained by the joint simulation of ADAMS and MATLAB is generally consistent. The results verify the feasibility and effectiveness of joint simulation.

The frequency of the two curves is slightly different, mainly because of the error in the design and calculation during the gear modeling process, and there is a certain gap between the two meshing teeth during assembly, which makes the two curves not completely coincide.

When analyzing and optimizing the non-bevel gear transmission, the influence of this error can be ignored.

The angular acceleration curve of the driven wheel is shown in Fig. 11.

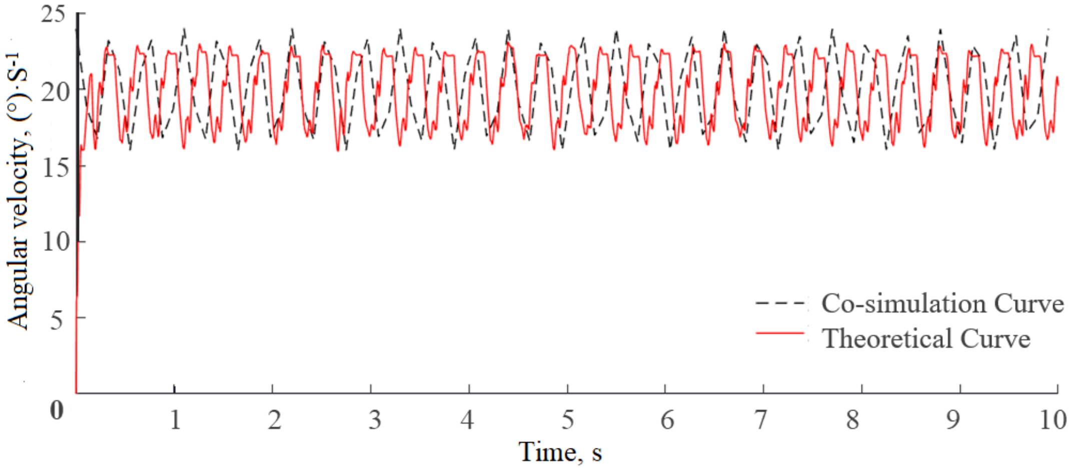

Fig. 10 Driven wheel angular velocity curve

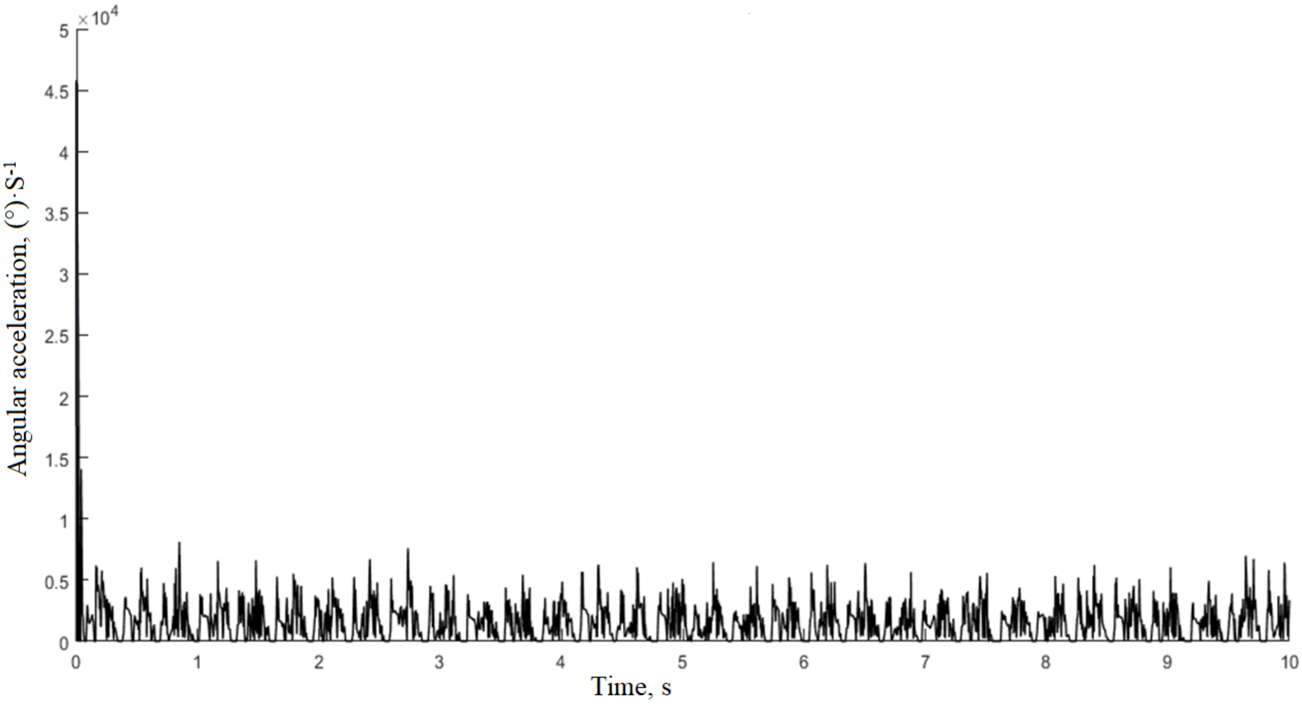

Fig. 11 Driven wheel angular acceleration curve

It can be seen from Fig. 11 that during the meshing process, the angular acceleration curve of the non-bevel gear is periodically changing. When the input speed of the driving wheel is 10°/s, the angular acceleration of the driven wheel can be as high as 500°/s^2; Combined with the fluctuation of the angular velocity curve of the driven wheel in Fig. 9, it is shown that there is no small vibration and impact in the transmission process, which greatly reduces the smoothness of the movement of the non-bevel gear and shortens the service life. The impact contact force curve is shown in Fig. 12.

In Fig. 12, it can be seen that during the transmission process, the contact force of the two teeth of the non-bevel gear changes from entering the engagement to disengaging (the positive and negative signs represent the direction of the force), and the maximum collision contact force is about 175 N; When a pair of teeth are separated, the next pair of teeth will enter the mesh, so that the driving wheel will continuously rotate with the driven wheel. The results further verify the feasibility and effectiveness of joint simulation.

4.2. Addition of PI control module

In the continuous system, PID is a mature and widely used control method [25-27]. It has the advantages of simple structure, reliable operation, and convenient adjustment, so it has been widely used in industry. The control law of PID is:

$$u(t) = k_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t)\,dt + T_d \frac{de(t)}{dt} \right]. \tag{8}$$

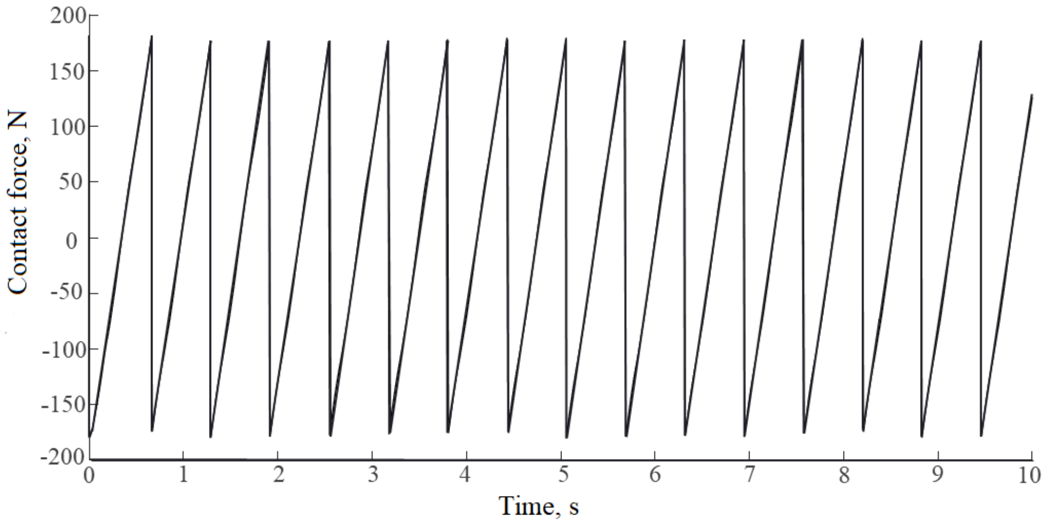

Fig. 12 Impact contact force

where: $e(t)$ is the control deviation; k_p is the proportional coefficient; T_i is the integral time constant; T_d is the differential time constant.

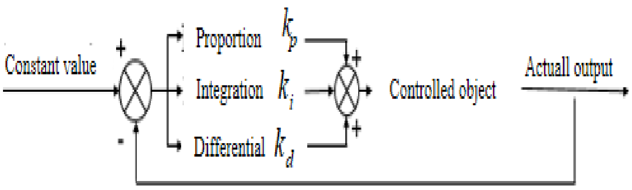

Fig. 13 Schematic block diagram of analog PID control system

In PID control, the proportion link can amplify or reduce the deviation signal of the control system in proportion; The integration link can eliminate the static error and make the dynamic state response slow; The differential link can reflect the variation trend of the deviation signal, and reduce the time of the transition process and the overshoot [28] by introducing the correction signal. The system principle block diagram is shown in Fig. 13.

Because the non-bevel gear is a variable ratio transmission, to make the transmission process run more smoothly, real-time control and adjustment of the driving wheel speed is one of the methods.

The author carries out PI adjustment control on the speed of the driving wheel of the non-bevel gear transmission, and join in the "Fcn" module to calculate the transfer function. Its control system block diagram is shown in Fig. 14.

By adjusting the proportional coefficient k_p and the integral coefficient k_i [29], the angular velocity and angular acceleration curves of the driven wheel of the non-bevel gear transmission mechanism after control are obtained as shown in Figs. 15 and 16.

It can be seen from Fig. 15 that after adding PI control, the motion trend of the driven wheel has not changed, and it still rotates periodically in the form of the cosine function. However, compared with Fig. 10, the fluctuation amplitude of the driven wheel angular velocity curve is significantly reduced and the period is significantly increased. It can be seen from the inverse relationship between the period and frequency that the frequency is reduced.

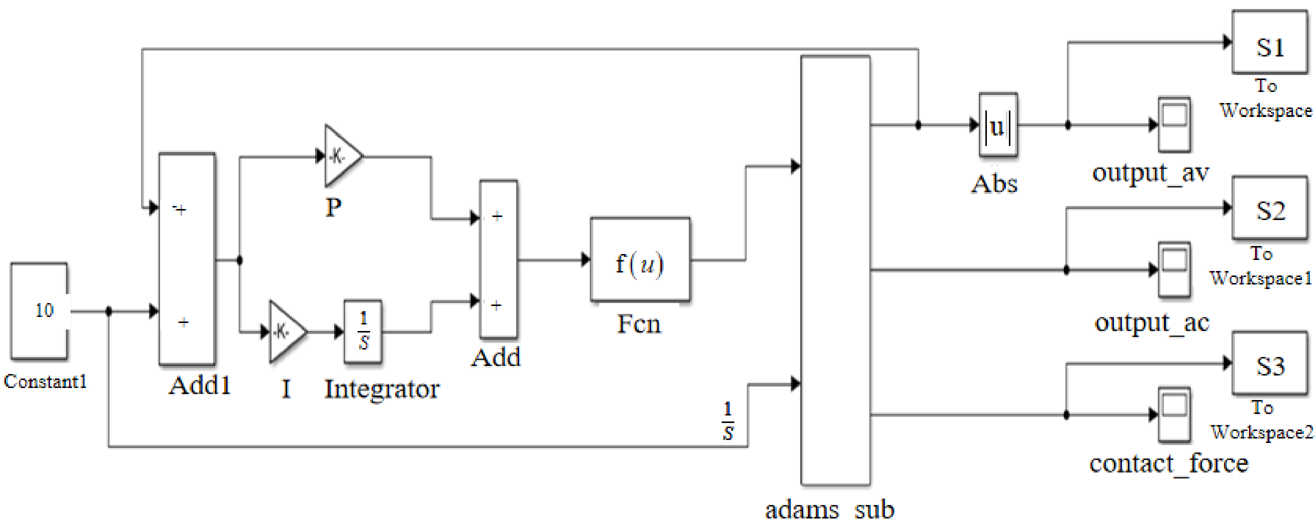

Fig. 14 Structure diagram of the control system for joint simulation of non-bevel gear transmission

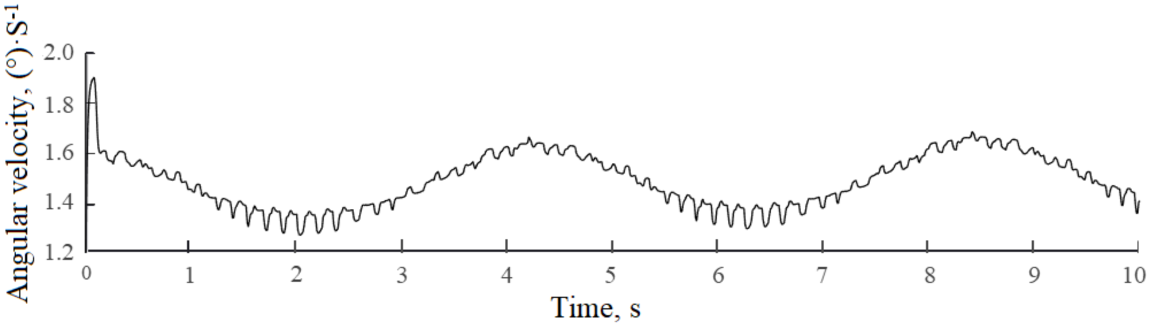

Fig. 15 Curve of the angular velocity of the driven wheel after control

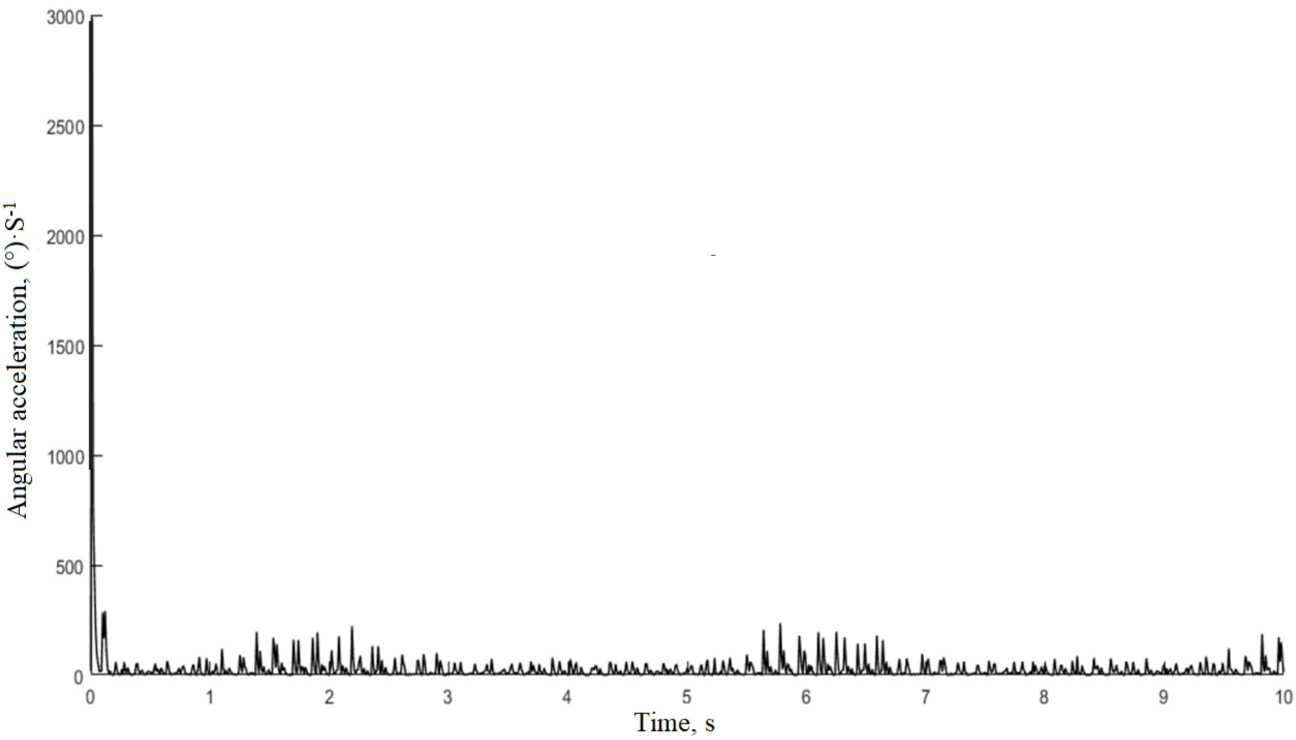

Fig. 16 Angular acceleration curve of the driven wheel after control

The angular acceleration curve is shown in Fig. 16. Compared with Fig. 11, the fluctuation range and frequency of the angular acceleration curve in Fig. 16 are significantly reduced, that is, the vibration and impact of non-bevel gears in a meshing transmission are reduced, and the operation is more stable. The results show that the control scheme is feasible and provides a new method for the further design and optimization of non-bevel gear transmission, which is conducive to the application and popularization of non-bevel gear.

5. Conclusion

The non-bevel gear mechanism is a new type of transmission mechanism, which can not only realize the transmission of the intersecting shaft with variable speed ratio, but also carry out axial feed motion, and has certain development potential.

To reduce the vibration and impact in the transmission process of the non-bevel gear mechanism, the author uses the method of joint simulation of ADAMS and MATLAB to control the speed of the driving wheel in the non-bevel gear pair, to reduce the vibration and impact in the meshing transmission.

The specific research steps and conclusions are as follows:

1. Using the method of combining MATLAB and UG software, the non-bevel gear model is established. The influence of order and eccentricity on transmission ratio is analyzed, and the conclusion is drawn that the period of the transmission ratio curve decreases with the increase of order; The amplitude of the fluctuation of the transmission ratio curve increases with the increase of the eccentricity.

2. Import the assembled model into ADAMS, build the virtual prototype model of gear mechanism dynamics, and set the input and output. Through data transfer between ADAMS/Control interface and MATLAB/Simulink. A joint simulation system of non-bevel gear transmission is built.

3. By comparing the simulation results, the results show that the added PI control system can effectively reduce the vibration and impact in the non-bevel gear transmission. The results verify the correctness and feasibility of the control strategy.

Joint simulation technology provides a new way to analyze and optimize the performance of non-bevel gear transmission. In the follow-up research work, the author will make further research on the joint simulation control algorithm of non-bevel gear transmission smoothness.

Acknowledgments

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SIMULATION RESEARCH ON NON-BEVEL GEAR TRANSMISSION MECHANISM

S u m m a r y

In the process of meshing transmission of non-bevel gear, there are problems of vibration and impact. Therefore, a simulation control method of non-bevel gear transmission based on ADAMS and MATLAB is proposed. Firstly, the design modeling of non-bevel gear is briefly introduced, and the influence of order and eccentricity on its transmission ratio is analyzed. Then, the established non-bevel gear model is imported into ADAMS, and the constraints, motion pairs, driving force, input and output variables are set. The data transfer relationship is established by using ADAMS/Control module and MATLAB/Simulink interface. The non-bevel gear mechanical system module is generated in MATLAB/Simulink. Finally, the co-simulation control system is built in MATLAB/Simulink module, and the control simulation analysis is carried out. The results show that: by comparing and analyzing the simulation results with only constant input and adding PI control module, it can be seen that after adding PI control module, the amplitude and frequency of the angular velocity and angular acceleration curve of the driving wheel are significantly reduced, that is, the vibration and impact in non-bevel gear transmission are reduced, which verifies the correctness and feasibility of the control strategy. It provides a new method for the control design and development of vibration damping performance of non-bevel gear drive. The results are beneficial to the application and popularization of non-bevel gears.

Keywords: non-bevel gear, transmission mechanism, ADAMS, MATLAB/Simulink, joint simulation.

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