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The Design Method of Hypocycloid and Epicycloid of Ball-type Speed Reducer

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Abstract— *In this paper, the transmission principle of cycloid ball reduction mechanism and the modeling method of cycloidal disc are studied. The motion transmission process of cycloid ball reduction mechanism is analyzed. Based on the forming principle of cycloid, the parametric equations of hypocycloid and epicycloid are derived, and the basic parameters affecting the cycloid waveform are obtained. According to the parametric equations, the corresponding relation among the parameters and the range of the parameters are determined, and the 3D modeling method of cycloidal disc is proposed.*

Keywords— *Cycloid steel ball reducer, transmission principle, design of cycloidal parameter, UG 3D modeling.*

I. INTRODUCTION

Reducer plays an important role in industrial manufacture, especially in the field of industrial robot. At present, the Japanese enterprises occupy most of the reducer market, the market share of domestic reducer is very small. According to relevant statistics, the total demand for industrial robot reducers in China exceeded 470,000 units in 2018. It is estimated that the incremental demand in 2019 will exceed 600,000 units, of which the localization rate will exceed 30%. Analysis of the trends in robots indicates that robots are gradually being miniaturized. However, when applied to small robots [1], most commercially available reducers are limited in structure and vibration, so the cycloidal ball reducer has great advantages as a new type of reducer. The cycloid steel ball reducer transmits motion and power through the steel balls, with complicated motion of the steel ball in the tooth profile formed by the intermeshing hypocycloid and epicycloid to complete the reduction transmission process [2-3]. In the early 1990s, Terada and Makino introduced the transmission principle of the ball reducer in detail, and put forward the application of the ball reducer to the robot joint. A prototype of reducer was manufactured, and the performance of the prototype was tested to improve the structure of reducer [4-5]. At present, the researches concerning cycloid steel ball reducer mainly focus on the structure and working principle, the tooth profile and meshing theory, the mechanical performance and the reliability analysis, etc. [6]. Ren Xiuzhi optimized the design parameters by multi-objective optimization algorithm based on the basic principle of cycloid transmission, and designed a special cycloid processing device for the complicated machining process of the cycloidal disc [7]. Wang Wei used traditional design method and multi-objective optimization algorithm to design parameters. The analysis results showed that the result of optimization algorithm was optimal [8]. In order to make more thorough theoretical research through modeling and simulation, in this paper, the modeling method of the cycloidal disc based on UG is proposed on the basis of the existing researches.

II. TRANSMISSION PRINCIPLE OF CYCLOID BALL REDUCER

The structure of the cycloid ball reducer that consists of reduction section and the motion transmitting section shown in Fig. 1. The epicycloid wave groove and the hypocycloidal wave groove form a closed circular orbit, the rolling balls 7 move complicatedly in this orbit. The hypocycloidal disc 6 is driven to do planetary motion by the eccentric input shaft, the constant velocity output mechanism eliminates the rotation of the hypocycloidal disc, making it rotate in a plane. The epicycloid disc 8 rotates at low speed under the transmission of the steel ball to form reduction section. The motion transmitting section consists of circular straight grooves on the left side of the hypocycloidal disc, the center disc 5 with circular grooves on its both sides, circular straight grooves on the left side of the fixed end cover 3 and many rolling balls 4. The motion transmitting section is determined according to the principle of parallelogram mechanism.

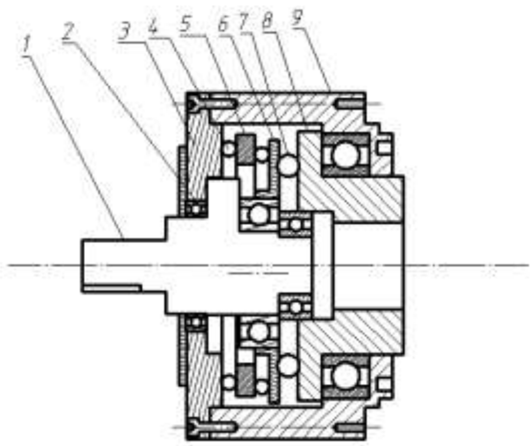

Fig. 1. Transmission principle of the cycloid steel ball reducer
1 Eccentric input shaft 2 bearing 3 fixed end cover 4 balls for motion transmitting 5 center disc 6 Hypocycloidal disc 7 balls for reduction 8 Epicycloid disc 9 cage

III. THE GENERATION PRINCIPLES OF HYPOCYCLOID AND EPICYCLOID

The theoretical tooth profile curve of cycloid reduction mechanism is a pair of intermeshing curtate hypocycloid and curtate epicycloid. The formation methods of the hypocycloid

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and epicycloid include enveloping method and non-enveloping method. Non-enveloping method is regarded as an example to derive the epicycloid equation. The generation principle of epicycloid shown in Fig. 2. The epicycloid is the locus of the arbitrary point N on the rolling circle O_0 without slipping around the epicycloid basic circle O .The locus of M is curtate epicycloid when it occurs within the rolling circle. The number of epicycloid wave is Z_1 which is an integer and $Z_1 = r_1/r_0$. The generation principle of hypocycloid which is similar to that of epicycloid shown in Fig. 3.

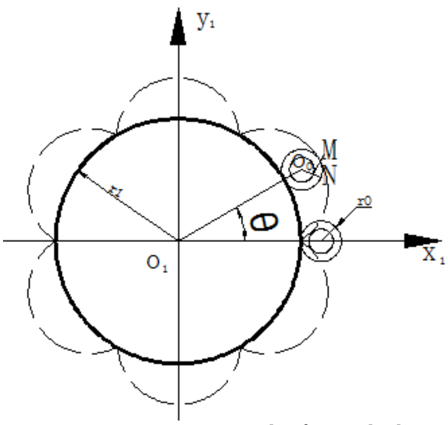

Fig. 2. Generation principle of epicycloid

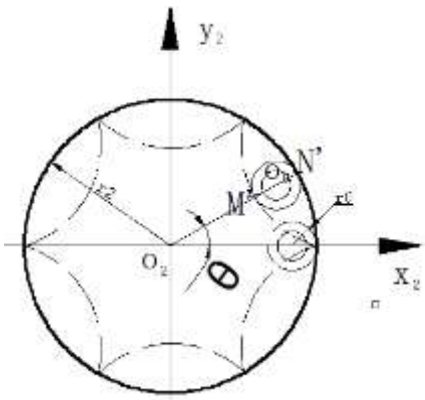

Fig. 3. Generation principle of hypocycloid

Epicycloid curve is defined as (1) and the hypocycloidal curve is defined as (2).

$$\begin{cases} X_1 = (r_1 + r_0)\cos\theta_1 - r_0\cos((Z_1+1)\theta_1) \\ Y_1 = (r_1 + r_0)\sin\theta_1 - r_0\sin((Z_1+1)\theta_1) \end{cases} \quad (1)$$

$$\begin{cases} X_2 = (r_2 - r_0)\cos\theta_2 + r_0\cos((Z_2-1)\theta_2) \\ Y_2 = (r_2 - r_0)\sin\theta_2 - r_0\sin((Z_2-1)\theta_2) \end{cases} \quad (2)$$

In the above equations:

Z_1 —the number of epicycloid wave;

Z_2 —the number of hypocycloidal wave;

r_1 —the radius of epicycloid basic circle;

r_2 —the radius of hypocycloidal basic circle;

r_0 — the radius of rolling circle.

Curtate epicycloid parametric equation is defined as (3) and the curtate hypocycloidal parametric equation is defined as (4)

$$\begin{cases} X_1' = (r_1 + r_0)\cos\theta_1 - Kr_0\cos((Z_1+1)\theta_1) \\ Y_1' = (r_1 + r_0)\sin\theta_1 - Kr_0\sin((Z_1+1)\theta_1) \end{cases} \quad (3)$$

$$\begin{cases} X_2' = (r_2 - r_0)\cos\theta_2 + Kr_0\cos((Z_2-1)\theta_2) \\ Y_2' = (r_2 - r_0)\sin\theta_2 - Kr_0\sin((Z_2-1)\theta_2) \end{cases} \quad (4)$$

In (3) and (4), K is cycloid factor which is defined as (5).

$$K = \frac{O_0M}{r_0} \quad (5)$$

With the hypocycloidal and epicycloid tooth number difference of two, the relationship between the number of steel balls and the cycloidal wave numbers shown as (6).

$$\begin{aligned} n_b &= Z_2 - 1 \\ n_b &= Z_1 + 1 \end{aligned} \quad (6)$$

In the equation(6): n_b —the number of steel balls.

The epicycloid parametric equation and the hypocycloidal parametric equation which are derived from (6) are defined as (7) and (8).

$$\begin{cases} X_1' = Z_b r_0\cos\theta_1 - Kr_0\cos(Z_b \times \theta_1) \\ Y_1' = Z_b r_0\sin\theta_1 - Kr_0\sin(Z_b \times \theta_1) \end{cases} \quad (7)$$

$$\begin{cases} X_2' = Z_b r_0\cos\theta_2 + Kr_0\cos(Z_b \times \theta_2) \\ Y_2' = Z_b r_0\sin\theta_2 - Kr_0\sin(Z_b \times \theta_2) \end{cases} \quad (8)$$

The shape of cycloidal wave is related to n_b , K and r_0 .

IV. THE DESIGN OF HYPOCYCLOIDAL AND EPICYCLOID PARAMETERS

A. Basic parameters of cycloidal wave

According to (7) and (8), parameters of cycloidal wave include, n_b , k, r_0 and n_b is determined by reduction ratio, r_0 is determined by the radius of the steel ball, the cycloid factor defines the shape of cycloidal curve.

$K \in (0,1)$, the profile of the cycloidal groove varies with the value of K. In general, the closer the value of K is to 1, the sharper the tooth profile of the cycloidal groove is. The closer the value is to 0, the smoother the tooth profile of the cycloidal groove is. The value of K affects the range of the top cutting area of the cycloidal groove directly. The top cutting area enlarge with the increasement of k, resulting in reduction in bearing capacity. K should be selected reasonably according to the number of steel balls shown in Table I [9].

TABLE I. Recommended value of K

Z_b	K
$Z_1 \le 11$	0.42~0.50
12~28	0.42~0.63
29~49	0.52~0.75
50~70	0.68~0.79
71~90	0.71~0.80

B. Parametric design procedure of cycloid and formulas for calculation

- Select the reduction ratio.
- Determine the number of steel balls based on the reduction ratio, input speed, and input power.

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- Determine the number of hypocycloidal and epicycloid waves by determining the relationship between the number of hypocycloid and epicycloid waves and the number of steel balls determined according to the meshing principle.
- Select the eccentricity and the standard steel ball diameter in the series table.
- Calculate the basic parameters of the hypocycloid and epicycloid.

TABLE II. Formulas for cycloidal parameters calculation.

S.No.	Name	Signal	Formula
1	the number of steel balls	n_b	Be determined by reduction ratio
2	eccentricity	A	Be determined by transmitting power and the size of model
3	the radius of steel balls	d_b	Be determined by transmitting power and the size of model
4	the radius of epicycloid basic circle	r_e	$r_e = R_b n_e / n_b$
5	the radius of hypocycloidal basic circle	r_h	$r_h = R_b n_h / n_b$
6	the radius of rolling circle	r_0	$r_0 = R_b / n_b$
7	The radius of the circle consists of steel balls	R_b	$R_b = n_b r_0$
8	the number of epicycloid wave	n_e	$n_e = n_b - 1$
9	the number of hypocycloidal wave	n_h	$n_h = n_b + 1$
10	trochoid factor	K	$K = A n_b / 2R_b$
11	The ball diameter coefficient	K_2	$k_2 = R_b \times sin(\pi / r_b)$ (r_b is the radius of steel ball)

Recommended value range of K_2 is $1.0 \le k_2 \le 1.15$.

V. Modelling Method of Cycloidal Disc

- The basic model of epicycloid is set up by UG according to size parameters such as the diameter of trochoidal disc and the diameter of central hole and the width of cycloidal disc.
- Input epicycloid parameterized equation to UG shown as (9) and utilize Rule curve order of UG, then get curtate epicycloid. Epicycloid theoretical curve shown in Fig.4.
- Select double circle as cycloidal groove's cross section shape shown in Fig.5. The depth of cycloidal groove is defined as (10). Then through sweeping, cutting, and array orders of UG epicycloid groove can be gotten shown in Fig 6.

$$\begin{aligned} & t = 1 \\ & alpha = 2\pi * t \\ & R_b = n_b r_0 \\ & xt = R_b * cos(alpha) - K * r_0 * cos(n_b * alpha) \\ & yt = R_b * sin(alpha) - K * r_0 * sin(n_b * alpha) \\ & zt = 0 \end{aligned} \tag{9}$$

$$h = r_b - r_b \times sin\beta \tag{10}$$

Fig.4. Epicycloid theoretical curve

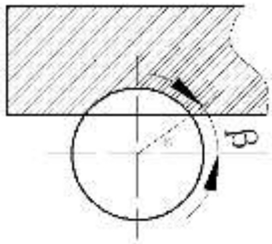

Fig. 5. Epicycloid theoretical curve

Fig. 6. Epicycloid theoretical groove

VI. Conclusion

In this paper, the transmitting process of cycloid ball reducer is discussed, the principle of the cycloidal formation is analyzed, and hypocycloid and epicycloid equations are established. Then the procedure of cycloid parametric design procedure is given, cycloidal disc is set up through UG three-dimensional entity modeling. At the same time, with its own powerful parametric modelling function, UG could make parameterization and serialization design of cycloidal disc come true.

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