Structural Design and Vibration Simulation of A New Type of Hollow High Precision Reducer with Integrated Structure

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Abstract. A new type of hollow and high precision reducer for robot is designed. By machining the track in the outer ring of input shaft and cycloid wheel, the traditional structure of crankshaft and bearing is replaced. The 4-DOF dynamic model is used for modeling, and the fixed step and 4-order Runge Kutta method of MATLAB software is used for solving, and the accuracy simulation of the reducer is completed. Compared with the existing reducer, the vibration and comprehensive performance of the new hollow high-precision reducer with integrated structure is better than the existing reducer.

1. Introduction
The rigid flexible coupling integrated joint is the core component of the humanoid robot, which is composed of motor, reducer, brake and sensor[1]. It realizes the functions of joint motion, posture keeping and position control[2]. It has the characteristics of compact structure, small volume, large load, lightweight and integration. Among them, reducer is the core component of rigid flexible coupling integrated joint. As the core basic component of reliable and accurate operation of robot, reducer has been monopolized by foreign enterprises due to its high technical threshold and high added value. RV transmission is a kind of transmission mode based on the principle of pin pendulum planetary transmission, which is widely used in the field of robotics[3]. RV Reducer has the advantages of compact structure, large transmission ratio, high motion accuracy and strong bearing capacity. At present, it has the trend of gradually replacing harmonic reducer[4].

2. Structure Design of Reducer
The new type of hollow reducer with integrated structure is optimized for weight reduction on the traditional RV Reducer. The specific structure, i.e. transmission mode, is shown in the figure below, mainly including cycloid gear, needle gear, input shaft, output shaft, etc. The traditional cycloid reducer has the advantages of small volume and large load, but it inevitably has the disadvantages of complex structure, heavy mass, difficult assembly and large accuracy error.

The new type of hollow high-precision reducer described in this paper starts with the structural optimization. The reducer shown in the figure below no longer uses the crankshaft of the traditional RV Reducer, but uses the Swiss ultra precision grinding machine to process the steel ball raceway on the input shaft to realize the eccentric movement of the cycloid, and processes the inner raceway of the cycloid, and designs the steel ball cage to fix the steel ball with mechanical constraints. The structure greatly reduces the manufacturing difficulty, effectively improves the rotary accuracy and reduces the manufacturing error. Through the above structure, the traditional deep groove ball bearing is replaced,
the machining error and assembly error caused by multiple machining are avoided, and the overall assembly accuracy is reduced to less than 4 μm.

![Figure 1. Structure and schematic diagram of reducer](image1)

3. Dynamic Model of Degree of Freedom

![Figure 2. Four degree of freedom dynamic model](image2)

Figure 2 shows the dynamic model of the reducer input shaft, steel ball and cycloid wheel. In the model, the influence of oil film produced in the process of ball motion on transmission is not considered.

\[
\begin{align*}
    m_i \ddot{x}_i + c_i \dot{x}_i + F_x &= w_x \\
    m_i \ddot{y}_i + c_i \dot{y}_i + F_y &= w_y \\
    m_o \ddot{x}_o + c_o \dot{x}_o - F_x &= 0 \\
    m_o \ddot{y}_o + c_o \dot{y}_o - F_y &= 0
    \end{align*}
\]
Where: $m_i$, $m_o$, $c_i$, $c_o$ - mass of input shaft and cycloid wheel, damping between input wheel and cycloid wheel; $x_i$, $y_i$ - displacement in X and Y direction of input shaft; $x_o$, $y_o$ - displacement in X and Y direction of outer ring; $w_x$, $w_y$ - component in X and Y direction of radial force acting on input shaft; $F_x$, $F_y$ - total recovery force in X and Y direction of steel ball acting on inner ring of bearing.

The total deformation of the $j$-th ball is a function of the angular position $\theta_j$ of the $j$-th ball, the displacement of the mass center of the input shaft and cycloid, and the bearing clearance $c$, which is expressed as follows:

$$\delta_j = (x_i-x_0) \cos \theta_j + (y_i-y_0) \sin \theta_j - c$$

(2)

Where: $j = 1, 2, N$, $N$ is the number of steel balls.

When the input shaft track is deformed, the ball will produce a force. The control function $\lambda_j$ is as follows:

$$\lambda_j = \begin{cases} 1 & \delta_j > 0 \\ 0 & \delta_j \leq 0 \end{cases}$$

(3)

The $j$-th steel ball angle position $\theta_j$ is a function of time $t$, and its equation is as follows:

$$\theta_j = \frac{2\pi(j-1)}{N} + \omega_c \cdot t + \theta_0$$

(4)

Where: $\theta_0$ - current angular position of the cage; $\omega_c$ - acceleration of the cage.

The nonlinear contact forces in X and Y directions of $N$ steel balls are as follows:

$$\begin{align*}
F_x &= K \sum_{j=1}^{N} \lambda_j \delta_j^{1.5} \cos \theta_j \\
F_y &= K \sum_{j=1}^{N} \lambda_j \delta_j^{1.5} \sin \theta_j
\end{align*}$$

(5)

Where, $K$ is the contact stiffness of the input shaft and cycloid wheel, which is related to the material properties and structural parameters of the part, taking $K = 10$ [2].

4. Vibration Simulation Analysis

MATLAB is an efficient engineering calculation language, which integrates the functions of calculation, visualization and programming into a working environment[5]. Assuming that the initial velocity and displacement are 0, the damping coefficients $c_i$ and $c_o$ of the system are 200N · s / m, equation (1) is solved in MATLAB by using the four order Runge Kutta method with constant step size. When the radial load in Y direction is 100N, the radial load in X direction is 0N, and the rotating speed is 3800r / min, only the vibration of bearing in Y direction is considered, and the vibration characteristics of bearing outer ring center of mass are shown in Figure 3-5.

| Table 1. Input shaft and cycloid calculation parameters | parameter | numerical value |
|-------------------------------------------------------|-----------|----------------|
| Cycloid wheel mass $m_o$                              | 0.56kg    |
| Input shaft mass $m_i$                                | 0.14kg    |
| Number of steel balls $N$                             | 17        |
| Diameter of steel ball $D_w$                          | 6.35mm    |
| Contact angle $\alpha$                                | 0         |
According to figure 3-5, the period of acceleration vibration response is 0.0079s, which is equal to the period of displacement and velocity vibration response. According to formula (6), the frequency of the ball passing through the outer ring is 127.06Hz.

$$f_{bo} = N_f = \frac{N}{2} \left(1 - \frac{D_w}{d_m}\right) f_i$$

(6)

**Table 2. Comparison between simulation value and theoretical calculation value**

|               | Simulation cycle | Theoretical cycle | Error |
|---------------|------------------|-------------------|-------|
|               | 0.0079s          | 0.00787s          | 0.38% |

According to the error in Table 2, it can be seen that the simulation period is in good agreement with the theoretical calculation period, and the correctness of the dynamic model is verified.
5. Test Verification

![Reducer vibration measuring platform](image)

The vibration test platform of reducer is as shown in the figure. The test platform is arranged in a row, with three-phase asynchronous motor as the experimental prime mover. Connect two vibration measuring sensors to the input and output of the reducer respectively. The magnetic powder brake is used as the load at the output end of the reducer, and the current of the magnetic powder brake is adjusted by the controller to change the output load value. According to the national standard GB / T 24610-2009 rolling bearing vibration measurement method[6], the vibration value simulated by MATLAB is calculated according to formula (7).

\[
L + 20 \log \frac{a}{g}
\]

(7)

Where: \( a \) - RMS value of vibration acceleration; \( g \) - Reference acceleration, \( 9.81 \times 10^{-3} \text{ m/s}^2 \)

| Vibration simulation | Test measurement | Error |
|----------------------|------------------|-------|
| 29.7                 | 31.52            | 6.12% |

Because the dynamic model ignores the influence of the track surface quality, lubricating oil film and the actual working conditions on the vibration value, the simulation value is smaller than the measured value; at the same time, it can be seen that the simulation value is consistent with the experimental measurement value, which verifies the correctness of the model.

By comparing FR series reducer manufactured by harmonic drive company, the vibration level of the reducer with this structure is better than that of the existing products, and some indexes are the same as the existing reducer.

6. Conclusion

The calculation, analysis and test by establishing the dynamic model can be summarized as follows:

(1) The vibration displacement, velocity and acceleration of the structure integrated hollow reducer are calculated by using the 4-DOF dynamic model and the fourth-order Runge Kutta algorithm, and the simulation value is consistent with the theoretical calculation value.

(2) By machining the track in the inner ring of cycloid wheel and the outer ring of output shaft, the new type of hollow reducer with integrated structure can save the assembly error and multiple machining error brought by the original bearing, reduce the overall vibration level of the reducer, improve the stability of transmission, and its comprehensive performance is superior to that of harmonic reducer.
7. Acknowledgments
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8. References
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