Analysis of Coaxiality-Transmission Efficiency Vector Model of RV Reducer Based on ADAMS

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Abstract. Aiming at the influence of the coaxiality error of the transmission system on the detection accuracy of the RV reducer performance test device, taking RV-20E reducer as the research object, combined with the ADAMS dynamic simulation software, the RV reducer dynamic transmission coaxiality and transmission efficiency vector model is established, and the coaxiality of the transmission system of this model is simulated under different error ranges and no load. The transmission efficiency is 32.94% when coaxiality is within the allowable error range. The results verify the accuracy of the model. At the same time, when the concentricity exceeds the allowable range of error, it will have a great impact on the transmission efficiency. The design of the coaxiality adjustment mechanism of the RV reducer performance detection device has certain theoretical significance and practical value.

1. Introduction
As a new type of reducer, RV reducer has the characteristics of compact structure, low vibration, low energy consumption, two-stage reduction, and strong disc stability[1]. It is widely used in industrial robots, and its performance parameters will directly affect the efficiency of the robot.

Transmission efficiency is one of the most important performance indexes of RV reducer [2-3], and it is difficult to obtain technical data because of its confidentiality. Therefore, it brings some difficulty to its theoretical calculation. At the same time, the transmission efficiency parameters calculated by theory are often limited by various factors and can only be used as reference values. Therefore, domestic and foreign scholars have proposed many methods and factors to calculate and influence transmission efficiency, and achieved many achievements; Zhenzhen Sun[4] et al. put forward a method of combining macro parameter optimization and micro parameter optimization of gears to improve the transmission efficiency of the reducer. Tong Guan[5] et al. adopted the orthogonal test method to carry out range and variance analysis on the test data. The results show that the factors influencing the transmission efficiency of RV reducer from large to small are the interaction of output torque, input speed and output torque respectively. Xin Wang[6] et al. proposed to improve the existing RV reducer with variable tooth thickness in structure, and took the influencing factors of meshing efficiency as design variables. With the aim of improving transmission efficiency, and optimized and analyzed the variable tooth thickness RV reducer. Yang[7] et al. mainly studied the relationship between speed, load variation and transmission efficiency of annular CAM reducer during its working process. Experimental results showed that the transmission efficiency of annular CAM reducer could be improved by increasing load.
Ding[8] studied the influence of speed and load changes on the transmission efficiency of RV reducer during operation, and the results showed that the transmission efficiency of RV reducer is proportional to the load it bears within a certain range. The larger the load, the higher the transmission efficiency, which has nothing to do with the speed of the RV reducer. Wang[9] et al proposed a calculation model for transmission efficiency of planetary gear reducer. Through simulation of mechanical power loss and transmission efficiency of planetary gear reducer, it explained the influence of speed and torque on the mechanical power loss and transmission efficiency. However, the above results do not study and discuss the factors affecting the coaxiality of the transmission system, and the model established was too complex and has poor generalization ability, which brought inconvenience to the practical engineering application.

In this paper, taking the RV-20E reducer as an example, the RV reducer coaxiality-transmission efficiency vector model is established, and combined with ADAMS, the coaxiality of the model is simulated in different error ranges and the output end is under the condition of no load.

2. RV reducer transmission efficiency detection principle

The RV reducer transmission efficiency testing device is shown in Figure 1. The detection principle is as follows, the servo motor provides the driving force, which is transmitted to the input shaft of the reducer through the coupling to drive the reducer to work normally. The magnetic powder brake can simulate the actual working load of the reducer; In the normal operation of the reducer, the torque sensors installed at both ends of the reducer record the actual torque of the input shaft and the output shaft in real time, and the transmission efficiency can be calculated according to the definition of transmission efficiency[10]. Test experimental conditions: reducer no load, input shaft speed of 1400rpm. Test the actual torque of the input shaft and the output shaft during one revolution of the output shaft.

Figure 1. RV reducer transmission efficiency testing device
1. Servo motor 2. Plum coupling 3. Torque sensor 4. Elastic diaphragm encoder 5. Magnetic powder brake 6. Component support 7. Part base 8. Slider guide rail 9. The locating pin 10. The slider

3. Coaxiality-transmission efficiency vector model was established

The structural characteristics of the RV reducer ensure that the robot will not have large errors and operate normally when it is working, assuming that the tooth surface of the reducer is rigidly meshed, the transmission efficiency of RV-20E reducer is analyzed as follows.

3.1 RV-20E reducer transmission ratio

Figure 2. RV-20E reducer structure diagram
1. Sun wheel 2. Planet wheel 3. Crank shaft 4. Cycloid wheel 5. Pin wheel 6. The output tray 7. Needle tooth shell 8. The input shaft

1) The transmission ratio of the first-stage involute planetary wheel

\[ i_{12} = \frac{n_1 - n_6}{n_2 - n_6} = -\frac{Z_2}{Z_1} \]  

(1)

2) The transmission ratio of the second stage cycloid pin wheel planetary transmission

\[ i_{45} = \frac{n_4 - n_5}{n_5 - n_3} = 1 - \frac{n_4}{n_1} = \frac{Z_5}{Z_4} \]  

(2)

3) The RV-20E reducer structure transmission ratio

\[ i_{16} = \frac{n_1}{n_6} = 1 + \frac{Z_2Z_3}{Z_1(Z_5 - Z_4)} \]  

(3)

Where, \( n_1 \) and \( n_2 \) are the rotational speeds of the sun wheel and the planet wheel respectively, \( n_6 \) is the rotational speed of the output shaft (the output tray), \( Z_1 \) and \( Z_2 \) are respectively the number of teeth of the sun wheel and the planet wheel gear, \( n_3 \) and \( n_4 \) are the rotational speed of crankshaft and cycloid wheel respectively, \( n_5 \) is the rotational speed of the needle gear (the needle gear shell is fixed), \( Z_4 \) and \( Z_5 \) are the number of teeth of cycloid wheel and needle wheel respectively. According to the working and structural principles of the reducer, the speed of the output shaft is equal to the rotation speed of the cycloid wheel \( n_6 = n_4 \) and \( n_3 = n_2 \).

3.2 Vector model of transmission efficiency

1) Torque calculation formula

\[ \overrightarrow{T} = \overrightarrow{F}d \]  

(4)

2) Transmission efficiency calculation formula

\[ \eta = \frac{\overrightarrow{P}_2}{\overrightarrow{P}_1} = \frac{\overrightarrow{T}_2/9550}{\overrightarrow{T}_1/9550} = \frac{\overrightarrow{T}_2}{\overrightarrow{T}_1}\times100\% \]  

(5)

Where, \( P \) — Power, \( n \) — Speed, \( T \) — Torque, \( d \) — The radius of the shaft

3.3 Vector model of Coaxiality-Transmission Efficiency

Figure 3. Actual axis tilt model

Figure 3 shows the error model when the shaft produces radial tilt and displacement. Because the RV reducer runs at a constant speed under no load, the torque balance vector matrix can be listed for each shaft, as shown in formula (6).

\[
\begin{bmatrix}
\tan \beta \cdot \frac{l_1}{2} + a \cos \beta + \frac{d_1}{2} \\
\tan \beta \cdot \frac{l_1 + l_2}{2} + a \cos \beta + \frac{d_2}{2} \\
\vdots \\
\tan \beta \cdot \frac{l_1 + l_2 + \ldots + l_n}{2} + a \cos \beta + \frac{d_n}{2}
\end{bmatrix} = \overrightarrow{T}_{total}
\]  

(6)
Where, $\overline{T}_{\text{total}}$—shaft total torque, Nm, $ \overline{F}_n$—the mean force on each order axis, N, $l_n$—total length of order n axis, mm, $\beta$—radial tilt Angle, a — radial displacement, that is, input and output axial-radial backlash deviation, m, $d_n$—outside diameters of all axes, mm.

(Note: Since the RV reducer is a precision instrument and the size is $\leq 500$mm, it can be known that its grade is between IT1-IT5 by searching the standard tolerance table GB/T1800.1-2009, and the table can be found that $a_{\text{input}}=0.00000075-0.0000045m$ and $a_{\text{output}}=0.00000125-0.0000075m$)

Combining formula (5) and formula (6), the coaxial-transmission efficiency vector formula is obtained, as shown in formula (7).

$$
\begin{bmatrix}
\overline{T}_{\text{output}} \\
\overline{T}_{2\text{output}} \\
6\overline{T}_{3\text{output}}
\end{bmatrix} =
\begin{bmatrix}
\tan \beta_{\text{output}} \frac{l_{\text{output}}}{2} + \frac{a_{\text{output}}}{\cos \beta_{\text{output}}} + \frac{d_{\text{output}}}{2} \\
\tan \beta_{\text{output}} \frac{l_{2\text{output}}}{2} + \frac{a_{\text{output}}}{\cos \beta_{\text{output}}} + \frac{d_{\text{output}}}{2} \\
\end{bmatrix}
$$

4. Coaxiality and transmission efficiency vector model simulation analysis

4.1 Establishment of kinematic model based on ADAMS
In order to test the accuracy of the coaxiality and transmission efficiency vector model, the RV-20E reducer is simulated and analyzed based on ADAMS under the condition of no load. The steps of model establishment are as follows.

4.1.1 Establish 3d model and import it into ADAMS
Firstly, the three dimensional solid model of RV-20E reducer is established through SolidWorks, and then imported into ADAMS. The interface and model are shown in Figure4, and set the $v_{\text{input}}=1400r/min$, then $v_{\text{output}}=10r/min$.

Figure 4. Interface and model in ADAMS
### 4.1.2 Establishment of ADAMS constraints

Table 1. Establishment of model constraint pairs

| Component name                                      | Constraint type             |
|-----------------------------------------------------|----------------------------|
| Input shaft and ground                              | planar contact pair         |
| Input axis second axis and planetary shelf          | cylindrical pair            |
| Sun wheel and planet wheel                          | planar contact pair         |
| Crank shaft and planet wheel                         | Fixed pair                  |
| Crank shaft second order shaft and tapered roller bearing | Fixed pair            |
| Crank shaft fourth order shaft and needle roller bearing | planar contact pair |
| Crank shaft sixth order shaft and needle roller bearing | planar contact pair |
| Crank shaft eighth order shaft and tapered roller shaft | Fixed pair                |
| Cycloid wheel and needle roller bearing             | planar contact pair         |
| Crank shaft and output disc                          | planar contact pair         |
| Output disc second - order shaft and angular contact bearing | planar contact pair |
| Output disc third order shaft and cycloid wheel      | planar contact pair         |
| Needle teeth and needle shell                        | planar contact pair         |

### 4.1.3 Setting of ADAMS load

The contact force in RV-20E involute spur gear transmission is calculated by the impact function method. According to the Hertz static elastic contact theory, the following formula (8) is obtained.

\[
\begin{align*}
K &= 4R^{1/2}E / 3 \\
1 / R &= 1 / R_3 - 1 / R_4 \\
1 / E &= (1 - \mu_1^2) / E_1 + (1 - \mu_2^2) / E_2
\end{align*}
\]

Where, \( K \) is the stiffness coefficient (MPA.mm\(^{1/2}\)), \( R_3 \) is the pitch circle radius (mm) of the outer gear, \( R_4 \) is the pitch circle radius (mm) of the internal gear, \( \mu_1 \) is Poisson's ratio of involute center wheel material, \( \mu_2 \) is Poisson's ratio of involute planetary wheel material, \( E_1 \) is the elastic modulus (MPa) of the sun wheel material, \( E_2 \) is the elastic modulus (MPa) of the planetary wheel material.

The calculation results show that \( K = 2 \times 10^6 \text{MPa.mm}^{1/2} \), and the specific parameters of contact force are shown in Figure 5.
4.2 Analysis of Simulation Results of Transmission Efficiency

1) The structure of the input shaft is shown in Figure 6. When the sun wheel 1 of RV reducer is engaged and its input shaft does not produce shaft degree inclination, the combined torque on the ladder shaft is obtained through ADAMS simulation, as shown in Figure 7.

![Figure 6. Schematic diagram of input shaft structure](image)

![Figure 7. Input shaft torque diagram](image)
2) The structure of the output tray is shown in Figure 8. When the single cycloid 4 of the RV reducer is engaged and the output tray does not produce axial inclination, the combined torque on the step shaft is obtained through ADAMS simulation, as shown in Figure 9.

Figure 8. Schematic diagram of output tray structure

![Figure 8](image8.png)

Figure 9. Torque diagram of output tray

3) The average value of transmission efficiency is calculated from the simulation results, as shown in formula (9).

\[
\eta = \frac{0.1199}{0.0026 \times 140} \times 100\% = 32.94\%
\] (9)

4) Compare the calculated results with the standard values to verify the accuracy of the model.

Figure 10. RV-20E reducer transmission efficiency diagram

As can be seen from Figure 10, the transmission efficiency value of RV-20E reducer provided by Japan Emperor Company at \( v_{\text{output}} = 10\text{r/min} \) and \( T_{\text{output}} = 0.1199\text{Nm} \) is consistent with the data of 32.94% calculated by this model, which shows that the vector model is correct.
4.3 Comparison and analysis of Coaxiality-Transmission efficiency vector model

Next, the no-load simulation analysis was carried out when the model was in the error range of different coaxiality, and the transmission efficiency was obtained through calculation, as shown in Figure 11 below.

![Figure 11. Comparison of transmission efficiency](image)

As can be seen from Figure 11, when the coaxiality of the RV reducer transmission system exceeds the allowable error range, its transmission efficiency will constantly decrease, which will make the torque and torque data measured by the torque sensor unable to accurately reflect the accuracy of the transmission efficiency of the RV reducer, thereby severely reducing the detection accuracy of the device.

5. Conclusion

(1) The RV reducer coaxiality and transmission efficiency vector model is established, and the model is simulated and analyzed with ADAMS software under the condition of coaxiality allowable error range and no load. The results verify the accuracy of the mathematical model, and the transmission efficiency is 32.94%.

(2) The model is simulated and analyzed with ADAMS software when the coaxiality exceeds the allowable range of error and there is no load. The results show that when the coaxiality of the input-output shaft drive system is out of tolerance, the transmission efficiency of the RV reducer will change significantly, which has seriously affected the reliability and accuracy of the test data of the device.

(3) RV reducer transmission efficiency measurement method has not been systematized, many influencing factors in the measurement process have not been taken into account, the country has not issued the corresponding standard, which is not conducive to the classification and evaluation of the transmission efficiency accuracy of reducer. This study can not only provide theoretical basis and reference materials for the country in this aspect, but also promote the development of RV reducer performance manufacturing and improve the testing accuracy of the detection device.

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