Viser Technology Pte. Ltd.
Mechanical Engineering Science
DOI: 10.33142/mes.v3i1.4331

Research Article Open Access

Research on Influence Mechanism of Transmission Accuracy for Harmonic Drive Mechanism Considering Multi-factor Coupling

Peng ZHAO*, Shuang ZHANG, Yang LIU

Academy of China Changfeng ELectro-mechanical Technology, Haidian District, Beijing 100039

***Corresponding Author:** Peng ZHAO, E-mail: blackhouse02@126.com*

Abstract:
The influence mechanism of transmission accuracy for harmonic drive mechanism considering multi-factor coupling was studied. According to analysis of influence factors of transmission accuracy for harmonic drive mechanism, it was obtained that the transmission errors of harmonic drive mechanism include processing errors and installation errors. The transmission error is produced by eccentric vector, it directly affects the rotation angle of output shaft and it makes harmonic drive mechanism produce backlash. Then analyze the movement error caused by the rigid wheel machining error, the flexible wheel machining error, the assembly error of the rigid wheel and the flexible wheel, the wave generator component, and the comprehensive expression method of motion error generated by each error source was obtained. The performance test device of space drive mechanism was used to test, and the law of the transmission accuracy of harmonic drive mechanism with temperature, speed and assembly clearance was obtained. The test results show that the transmission accuracy of harmonic drive mechanism decreases with increasing temperature, and the speed has little effect on the transmission accuracy of harmonic drive mechanism; the assembly quality has a significant impact on harmonic drive accuracy.

Keywords: *harmonic drive mechanism; transmission accuracy; error source*

1 Introduction

With the continuous development of aerospace technology and continuous improvement of space mission requirements, the application of space harmonic drive mechanisms is becoming more and more extensive, it shows a diversified development trend. The harmonic drive mechanism has a large transmission ratio and a wide range; stable transmission, high carrying capacity, small volume and weight for transmitting unit torque; small and uniform tooth surface wear, high transmission efficiency, and high transmission accuracy; small backlash and achievable Zero backlash transmission; can ensure the transmission of movement to the confined space. Due to its many advantages, harmonic drive has been widely used.

The spatial harmonic drive mechanism is a highly reliable and long-life product. Its system composition is very complex. Operating conditions such as load, working conditions, temperature, and vacuum will affect its performance. Its performance will gradually degrade with the prolonged use of time. Reliability and life will gradually decrease [1-2]. The space drive mechanism has poor observability and detection in the space operating environment, difficult to accumulate information, and less available information. It is also difficult to simulate and verify on the ground. It is a real poor information and small sample product. It is necessary to study the reliability of the space drive mechanism. There is enough scientific experiment to support, and through the organic combination of experimental data and related theories, it can accurately grasp the influence mechanism of the transmission accuracy and reliability of the space drive mechanism.

2 Analysis of Influencing Factors on Transmission Accuracy of Harmonic Drive Mechanism

According to the motion principle of the harmonic drive mechanism, the cross-section of flexible wheel is a circle before assembly. When the wave generator and the flex bearing are installed in the flexible wheel, the flexible wheel is forced to deform, and the teeth and rigid The teeth of the wheel are completely meshed, the teeth at the short shaft are completely disengaged, and the teeth in different sections along the circumference of the flexible wheel between the long and short shafts are in different transition states that are meshing in or meshing out. Therefore, when

Received 1 April 2021; Accepted 16 May 2021

the rigid wheel is fixed, the wave generator is input, and the flexible wheel is output, the meshing depth of the teeth of the flexible wheel and the rigid wheel will affect the output angle of the flexible wheel to a certain extent [3].

Obviously, when there is an error in the size or assembly of the various components that make up the harmonic reducer, it will directly or indirectly affect the coaxiality of the rigid wheel axis and the flexible wheel axis. If the theoretical axis of the rigid wheel and the theoretical axis of the flexible wheel do not coincide, the meshing of the gear teeth will change. Therefore, the offset between the axis of the three major parts and their theoretical axes can be used to quantify the transmission errors caused by different machining errors and assembly errors [4].

The main components of the harmonic reducer are the flexible wheel, rigid wheel and wave generator. The rigid wheel of the reducer is fixed, the driving part is the wave generator, and the driven part is the flexible wheel. According to its structure, it can be seen intuitively that the machining and installation errors of various parts and their shapes have the following main effects on the transmission error: 1) Transmission error is generated by the eccentric vector; 2) It directly affects the rotation angle of the output shaft; 3) Make the harmonic reducer produce hysteresis.

3 Transmission error caused by the error source of the harmonic drive mechanism

Combining the meshing characteristics of the harmonic drive, according to its transmission principle, analyze the size and frequency of the motion error that each error source can produce.

According to the working principle of harmonic gear transmission, there are two meshing areas at both ends of the cam long shaft. In each area, there are multiple pairs of gear teeth participating in meshing at the same time, but the meshing degree of each pair of gear teeth is different (as shown in Fig. 1). Now the cam long shaft is used as the dividing line to divide the meshing into two parts: the working tooth side and the non-working tooth side. Among them, the working tooth side plays a transmission role. The correct meshing area of the harmonic gear drive can only be carried out in a local area. The teeth participating in the meshing outside this area are in sharp point contact or no contact at all. Although the flexible wheel has elasticity and can play a certain deformation coordination effect, it is possible to expand the correct meshing area, but this expansion is extremely limited, and it is generally larger under load, and under no load. The next is smaller. When there is an eccentricity error in the flexible or rigid wheel, the eccentric error vector has different effects on the gear tooth meshing degree of the two meshing areas. In the area close to the eccentric error vector, the eccentricity makes the meshing area expand, that is, the correct meshing tooth pair As the number increases, the number of sharp point contacts decreases; however, the effect is just the opposite in the other meshing area. Due to the influence of various eccentric errors in the harmonic gear transmission, the above-mentioned situation is bound to occur in the meshing characteristics of the harmonic gear transmission [5].

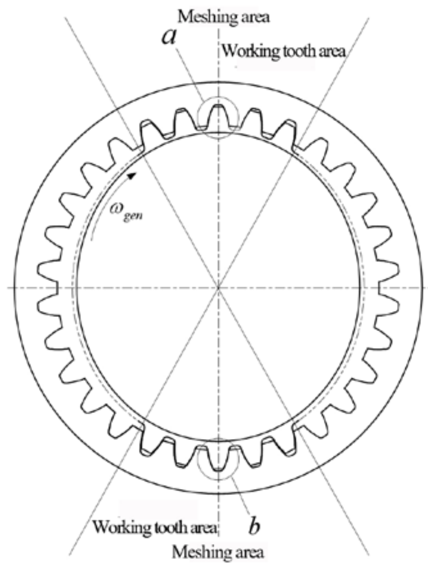


Fig.1 Harmonic gear drive transmission principle diagram

3.1 Motion error caused by rigid wheel machining error

Due to the geometric eccentricity and movement eccentricity of the rigid wheel during processing, the base circle and index circle center of the rigid wheel do not coincide with the center of rotation, resulting in a comprehensive error vector $_{21}$. Since the rigid wheel is fixed, the comprehensive error vector e_{21} will remain unchanged during meshing process. Suppose the comprehensive error vector e_{21} is exactly on the *OY* axis (as shown in Fig. 2), and the angle θ is between the long axis of cam and the eccentric error vector e_{21}. The eccentricity error vector can be divided into two parts at the gear tooth meshing node: normal displacement and tangential displacement. The normal displacement in the *n*-*n* direction is the increment along the meshing line, which will produce movement errors; the tangential displacement in the τ - τ does not produce motion error [6].

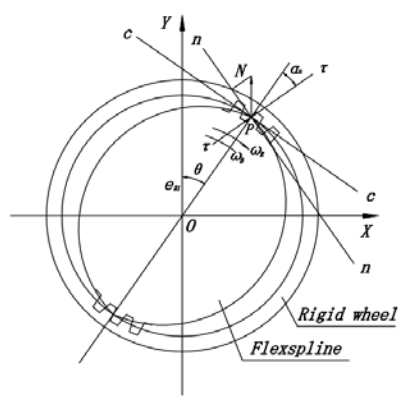


Fig.2 Influence of Rigid Wheel Eccentricity on Transmission Error

If the rotation angular velocity ω_b of wave generator is used as the independent variable, the expression of the motion error due to the machining error of the rigid wheel can be obtained as:

$$\Delta_G = \Delta_{21} + \Delta_{22} = \frac{1}{2}\Delta F_{p2}\sin(2\omega_b t) + \frac{1}{2}\Delta f_{f2}'\sin(2\omega_b z_G t)$$

where, $\Delta f_{f2}'$——Comprehensive error of adjacent teeth in tangential direction of rigid wheel;

z_G——Teeth number of rigid wheel;

t——time.

3.2 Motion error caused by flexible wheel machining error

The flexible wheel also has a comprehensive eccentricity caused by geometric eccentricity and movement eccentricity during processing, so that the centers of the base circle and the index circle do not coincide with the center of rotation. Suppose its comprehensive eccentricity is e_{11} . Since the transmission of the harmonic gear is relatively large, the comprehensive eccentric vector can be regarded as constant during the half-turn of the wave generator. Since the flexible wheel is rotating, there is always a certain moment when the eccentric vector coincides with the *OY* axis. It is assumed that the integrated eccentric vector e_{11} coincides with the *OY* axis at a certain moment. Eccentric vector $_{11}$ will cause the lower meshing area of the rigid wheel and the flexible wheel to weaken and the upper meshing area to strengthen. Since the considered state is that the comprehensive eccentricity e_{11} of the flexible wheel is fixed, and the teeth of the flexible wheel actively engage with the teeth of the rigid gear during meshing, the error will cause uneven transmission of the flexible wheel and cause movement errors. Analyze the movement error caused by the integrated eccentricity e_{11} of the flexible wheel processing is the same as the movement error caused by the integrated eccentricity of the rigid wheel [7].

Therefore, the expression of the motion error due to the processing error of the flexible wheel is

$$\Delta_R = \Delta_{11} + \Delta_{12} = \frac{1}{2}\Delta F_{p1}\sin\left(2\omega_b\frac{z_G}{z_R}t\right) + \frac{1}{2}\Delta f_{f1}'\sin(2\omega_b z_G t)$$

Where, Δ_{11}——The motion error value caused by the processing error of the flexible wheel;

ΔF_{p1}——Cumulative error of the flexible wheel;

z_G——Teeth number of rigid wheel;

z_R——Teeth number of flexible wheel;

ω_b——The angular velocity of the wave generator;

t——time.

3.3 Motion error caused by assembly error of rigid wheel and flexible wheel

The rigid wheel and the flexible wheel have assembly errors, which cause the relative meshing position of the rigid wheel and the flexible wheel to change, and the manufacturer's various assembly eccentricities. The eccentricity will affect the accuracy of the harmonic gear transmission movement, thereby causing movement errors. The eccentricity error vector caused by various errors between the rigid wheel and the flexible wheel can be divided into two types [8].

(1) Generate a fixed eccentric vector

Such eccentric vectors include: the run out of the mounting hole of the rigid wheel, the fit clearance between the mounting hole of the rigid wheel and the rigid wheel, the radial run out of the output shaft bearing, the fit gap between the two shells, the fit gap between the output shaft bearing and the hole, and the output shaft Bearing radial run out and output shaft bearing radial clearance, etc., the movement error caused by the eccentricity formed by the fit clearance and the run out error is similar to the movement error caused by the eccentricity formed by the machining error of the rigid wheel itself. Therefore, it can be used similarly to analyze the motion error caused by the comprehensive eccentricity formed by the rigid wheel processing error, and the motion error generated by each error source can be obtained as

$$\Delta_1 = \frac{e_1\sin 2(\theta + \alpha_n)}{\cos\alpha_n}$$

Substituting the rotational angular velocity ω_b of the wave generator into the calculation formula of the motion error

$$\Delta_1 = \frac{e_1\sin(2\omega_b t + \varphi_1)}{\cos\alpha_n}$$

Where, Δ_1——The movement error caused by the eccentric vector of the rigid wheel installation pair produced in the rigid and flexible wheel pairs;

e_1——The value of the eccentricity error caused by the fit clearance or beating that affects the installation accuracy of the rigid wheel;

ω_b——The angular velocity of the wave generator;

φ_1——The phase angle of the corresponding eccentricity error vector.

Since the various eccentricities produced during the assembly process are random, their phase angles are also randomly distributed, so that the movement errors generated by some eccentric vectors will cancel each other out, and finally a movement error value caused by the installation eccentricity will be formed.

(2) The eccentricity error vector formed by the assembly error

This kind of vector rotates with the flexible wheel, including: the eccentric vector error formed by the beating of the output shaft and the fit clearance between the output shaft and the flexible wheel. The method of analyzing the type of error is similar to the motion error caused by the processing error of the flexible wheel itself, and the motion error generated is

$$\Delta_2 = \frac{e_2\sin 2(\theta + \alpha_n)}{\cos\alpha_n}$$

Substituting the rotational angular velocity ω_b of the wave generator into the calculation formula of the motion error

$$\Delta_2 = \frac{e_2 \sin\left(2\frac{z_G}{z_R}\omega_b t + \varphi_2\right)}{\cos\alpha_n}$$

Where, Δ_2——The movement error caused by the eccentricity of the rigid wheel installation in the rigid and flexible wheel pairs;

e_2——The fit clearance or runout value that affects the installation accuracy of the flexible wheel;

ω_b——The angular velocity of the wave generator;

z_G——Teeth number of rigid wheel;

z_R——Teeth number of flexible wheel;

φ_2——The phase angle of the error vector.

3.4 Motion error caused by wave generator components

In the harmonic gear drive, the harmonic gear drive has an additional wave generator than the general gear drive. The manufacturing and assembly errors of the wave generator directly affect the radial change of the flexible wheel, which changes the meshing relationship between the rigid spline and the flexible wheel, which also causes movement errors. The machining and installation errors of the rigid wheel form a composite eccentricity error. The wave generator has an eccentricity error vector. Because the eccentricity error vector of the rigid wheel and the eccentricity vector of the wave generator are superimposed on each other, additional motion errors are generated [9]. The frequency generated by this eccentricity error is the same as the rotation frequency of the wave generator, that is, when the wave generator rotates one revolution, this movement error is repeated once, and its approximate mathematical expression is

$$\Delta_3 = \frac{e_{3f} \sin\left(\omega_b t + \theta_{3f}\right)}{\cos\alpha_n}$$

Where, Δ_3——Motion error caused by eccentricity error rotating with wave generator;

e_{3f}——Error factors that rotate with the wave generator, such as fit clearance or runout;

θ_{3f}——The angle between the eccentricity error vector and the OY axis.

3.5 Comprehensive expression of motion error generated by each error source

The motion errors caused by the manufacturing and assembly errors of the various parts of the harmonic gear transmission can be divided into four categories: (1) The motion errors of the frequencies generated by the eccentric error vectors of the rigid wheels with eccentric errors, including the machining of the rigid wheels Error, the fixed eccentric error vector between the rigid wheel and the flexible wheel, the fixed eccentric error vector in the wave generator component; (2) The eccentric error vector generated by the flexible wheel that rotates with the flexible wheel generates frequency Movement error; (3) The frequency movement error produced by the eccentric error vector rotating with the wave generator in the wave generator component; (4) The frequency movement error produced by the small period error formed by the rigid and flexible wheel processing errors. Therefore, the comprehensive formula for the motion error of the harmonic gear transmission is

$$\Delta = \frac{\sum e_{1f} \sin\left(2\frac{z_G}{z_R}\omega_b t + \varphi_{1f}\right)}{\cos\alpha_n} + \frac{\sum e_{2f} \sin\left(2\omega_b t + \varphi_{2f}\right)}{\cos\alpha_n} + \frac{\sum e_{3f} \sin\left(2\omega_b t + \varphi_{3f}\right)}{\cos\alpha_n} + \frac{\sum f_{ff}' \sin\left(2 z_G \omega_b t\right)}{2}$$

Where, Δ——Total motion error;

e_{1f}——Corresponding to the eccentric vector value of the flexible wheel;

e_{2f}——Corresponding to the eccentric vector value of the flexible wheel;

e_{3f}——The eccentric vector value that rotates with the wave generator;

f_{ff}'——Rigid and flexible tangential comprehensive error vector value;

φ_{1f}——The initial phase angle of the eccentric vector of the rigid wheel;

φ_{2f}——The initial phase angle of the eccentric vector of the flexible wheel;

φ_{3f}——The initial phase angle of the eccentric vector of the wave generator;

z_G——Teeth number of rigid wheel;

z_R——Teeth number of flexible wheel;

ω_b——The angular velocity of the wave generator;

t——time.

4 Test and results of factors affecting transmission accuracy of harmonic drive mechanism

The assembly state of the harmonic drive mechanism is shown in Fig. 3. The rigid wheel is fixed, the wave generator is input, and the flexible wheel is output. The relative position of the rigid and flexible wheel is fixed. The relative position X of the flexible wheel and the wave generator is determined by the spacer adjustment. When the relative position of the rigid and flexible wheels is fixed, the relative position X of the flexible wheel and the wave generator determines the meshing position of the harmonic gear. In order to study the influence caused by the meshing position of the harmonic gear, two thickness pads are processed Sheet, so that the relative positions of the flexible wheel and the wave generator are 0.75mm and 0.84mm, respectively.

The test object is a 40-type harmonic drive component, the lubrication method uses space lubricating grease, and the transmission ratio is 100. There are two assembly states: 1) Normal state: the relative position of the flexible wheel and the wave generator are 0.75mm respectively; 2) The specific state: the relative position of the flexible wheel and the wave generator is 0.84mm respectively. Test conditions: 1) Speed range 20~1500r/min; 2) Load torque range 5~15N·m; 3) Temperature range -75~125℃. The test results are shown in Fig. 4.

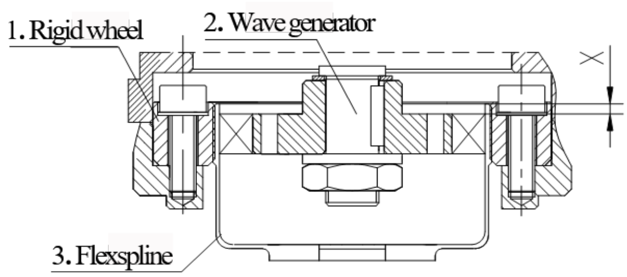
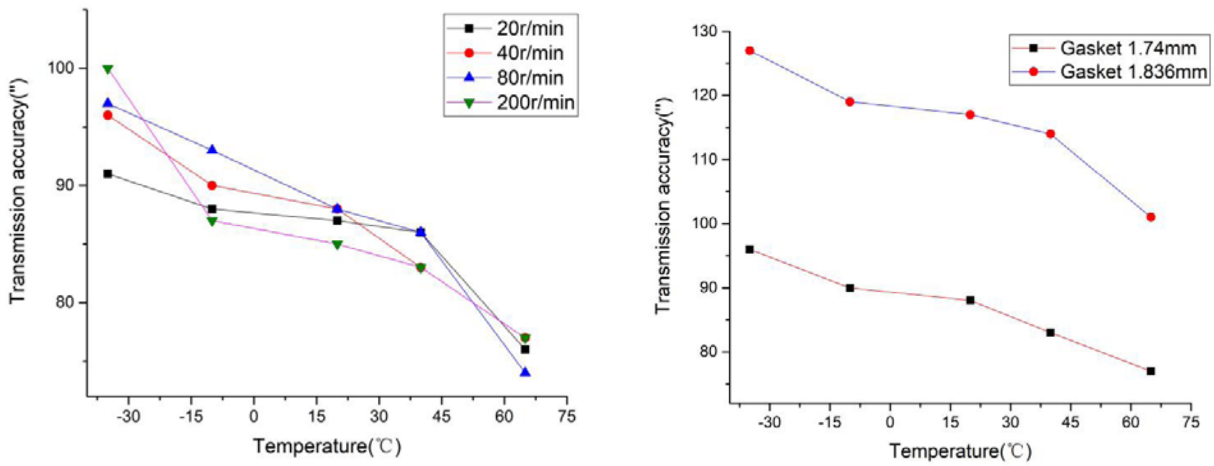


Fig.3 Schematic diagram of the assembly of the three major parts of the harmonic reducer



a) Transmission accuracy of harmonic drive components at different speeds and temperatures

b) Transmission accuracy of harmonic drive mechanism under different gap states

Fig.4 Transmission accuracy test of harmonic drive mechanism

According to the test plan, the transmission accuracy of the harmonic drive components in the two states was tested, and the transmission accuracy at different speeds and different temperatures was obtained. From Fig.4, comparing the transmission accuracy curves under different conditions, different speeds, and different temperatures, it can be found that:

(1) The transmission error of the harmonic reducer decreases with increasing temperature. The transmission error is 97" at -35℃, and 77" at 65℃. The transmission accuracy is greatly affected by temperature. The test results are consistent with the above mechanism analysis. It can be determined that the harmonic radial clearance is greatly affected by temperature;

(2) The transmission error of the harmonic reducer has nothing to do with the speed. The transmission accuracy curve shows that the relationship between transmission error and speed is irregular, and the transmission error values at the same temperature and different speeds are concentrated. Under the condition of excluding measurement errors, it can be considered as the transmission error value at the same temperature and different speeds. Consistent, so it can be considered that the transmission error and speed of the harmonic reducer are not significant;

(3) Assembly quality has a significant impact on the accuracy of harmonic drive. When the relative position difference between the flexible wheel and the wave generator is only 0.096mm, the difference of the harmonic drive error between the two states is about 35", so the assembly process must be strictly controlled during the product development stage.

5 Conclusions

(1) Through the analysis of the mechanism of influencing factors of transmission accuracy of the harmonic drive mechanism, it is found that the assembly error has a great influence on the transmission accuracy of harmonic drive mechanism, which can cause the accuracy of the harmonic drive mechanism to decrease, increase the stress, and increase the wear. Performance degradation and other failure modes.

(2) The transmission accuracy of the harmonic drive mechanism decreases with increasing temperature, and the speed has little effect on the transmission accuracy of the harmonic drive mechanism.

Reference

[1] KIM S Y, CASTET J F, SALEH J H. Spacecraft electrical power

subsystem: Failure behavior, reliability, and multi-state failure analyses[J]. Reliability Engineering and System Safety, 2012, 98: 55-65.

[2] Liu S, Wang Q. Studying contact stress fields caused by surface tractions with a discrete convolution and fast fourier transform algorithm[J]. Journal of Tribology, 2002, 124(1) : 36-45.

[3] PAN Bo, ZHANG Donghua, SHI Wenhua, et al. Modeling and analysis on pointing accuracy of antenna in satellite[J]. Spacecraft Engineering, 2011, 20(5): 49-54.

[4] CASTET J F, SALEH J H. Beyond reliability, multi-state failure analysis of satellite subsystems : A statistical approach[J]. Reliability Engineering and System Safety, 2010, 95: 311-322.

[5] WAYER J K, CASTET J F, SALEH J H. Spacecraft attitude control subsystem : Reliability , multi-state analyses, and comparative failure behavior in LEO and GEO[J]. Acta Astronautica, 2013, 85: 83-92.

[6] ZHANG Huibo. Pointing accuracy analysis of the two-axes-postion mechanism for satellite antenna[D]. Harbin: Harbin Institute of Technology, 2011.

[7] DENG Sier. Frictional torque characteristic of angular contact ball bearings[J]. Journal of Mechanical Engineering, 2011, 47(5): 114-120.

[8] Michael R, Johnson, Russ Gehling, Ray Head. Life Test Failure of Harmonic Gears in a Two-Axis Gimbal for the Mars Reconnaissance Orbiter Spacecraft[C]. Proceedings of the 38th Aerospace Mechanisms Symposium, Langley Research Center, 2006.

[9] Li Jun-Yang, Wang Jia-Xu, et al. Accelerated life testing of harmonic driver in space lubrication[J]. Journal of Engineering Tribology, 2015, 29(12): 1491-1502.