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Experimental study on transmission performance of harmonic drive under multifactor interaction

Guangwu Zhou*, Zhenhua Zhang, and Hua Zhang

School of Aeronautics and Astronautics, Sichuan University, Chengdu 610065, PR China

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Abstract. In space environment and complex working conditions, the harmonic drive is prone to performance degradation. The traditional performance analysis method cannot reveal the interaction among the factors. In this paper, a mathematical model of multifactor interaction analysis is built to analyze transmission performance of efficiency, stiffness, and starting torque in various temperature, vacuum, speed and torque. And the high performance gear transmission platform is independently designed and developed. The experimental research and mechanism analysis are carried out on the starting torque, stiffness and efficiency of the harmonic drive. Research shows that the multifactor interaction has an important impact on the transmission performance of harmonic drive. The approach provides some guidance for the application of harmonic drive in space.

Keywords: Mechanical drives / speed reducers / gears / harmonic drive / transmission performance

1 Introduction

Harmonic drive is composed of three core components, i.e., flexspline, circular spline and wave generator, which utilizes an elastic periodic deformation generated by the flexspline to realize power transmission [1]. It has the advantages of large transmission ratio, compact structure, light weight, many meshing teeth, strong loading capacity, high transmission accuracy, and low noise etc., and it is widely applied in the aerospace, industrial robots, medical devices and other fields [2].

Harmonic drive is an important deployment and moving part of space vehicle equipment. It was invented firstly for space applications by Professor C.W. Musser [3] in 1953. Since then, NASA and ESA applied harmonic drive in spacecraft such as the lunar rover, Mars probe, and Hubble telescope.

In space environment of changeable temperature, ionizing radiation, and vacuum, harmonic drive often produces degradation and failure in working condition, the transmission performance of harmonic drive has attracted a great number of researches. Johnson et al. [4] studied the harmonic drive of directing mechanism in Mars Reconnaissance Satellite and analyzed the lifespan and reliability by increasing the output stiffness of the drive through the type of lubricant and the size of the flexspline. Schmidt et al. [5] took the harmonic drive in the pointing mechanism of Kompsat-3 antenna as the research object, and selected PTFE-based grease in the thermal vacuum life test to study the wear of the flexspline and circular spline and transmission efficiency. Schafer et al. [6] adopted different PTFE-based greases for thermal vacuum contrast experiments to examine the changing rules of the transmission performance such as efficiency, starting torque and stiffness through input speed, load, and temperature during operation. Maniwa et al. [7–9] analyzed the flow field distribution and oil film pressure of flexspline and flexible bearings in the atmosphere and vacuum via the mixed lubrication analysis model with micro convex contact to study the wear and life of harmonic drive. Li [10–12] designed experiments adopted interactive orthogonal design to analyze the effects of different temperature, load, lubrication method, rotational speed, and their interactions on the harmonic drive transmission efficiency. Li [13] proposed a new accelerated life test method for the performance of harmonic drive, and the speed and load are selected as the acceleration stresses of the test by a mixed lubrication analysis.

Simply univariate analysis cannot reveal the interaction among the environmental and working factors. Orthogonal experimental study of Li et al. [10] has strict requirements on the experimental design of parameters. However the actual test could not choose the suitable orthogonal table. In addition, the orthogonal experimental design cannot reveal the interactions among speed, vacuum, torque and temperature. To explore the transmission performance of harmonic drive under the

* e-mail: gwzhou@scu.edu.cn

multifactor interaction in space environment, a mathematical model for multifactor analysis was established in this paper to qualitatively and quantitatively analyze the effects of various factors and interactions on the transmission performance.

2 Design of experimental apparatus

2.1 Harmonic drive mechanism

One of the three components of the harmonic drive is fixed, an input, an output, and the three constitutes a planetary transmission mechanism. The wave number of the harmonic drive is the difference between the teeth of the circular spline and the flexspline. The cam-typed wave generator forces the flexspline to deform through the flexible bearing, so that the nearby tooth in the major axis of the flexspline mesh with the circular spline, and the minor axis tooth completely disengage the circular spline, in the area between the major axis and the minor axis, the two gears are in transitional state of half-engaged or half-disengaged. The above can be seen in Figure 1.

Each tooth of the flexspline is periodically deformed by the wave generator. The teeth of the flexspline continue to engage and disengage with the circular spline, from engage to disengage, from disengage to engage, states cycle back and forth. Due to the difference in the number of teeth, each time the wave generator rotates one revolution, the flexspline rotates the angular displacement of two teeth with respect to the circular spline, the drive achieves the purpose of deceleration.

In this paper, the harmonic drive adopts SHF25-120-2UH model, it is shown in Figure 2. The flexspline of the harmonic drive is fixed, the wave generator is used as the input component, and the circular spline is taken as the output component. Transmission ratio is 121, and rated torque is 67 N m.

2.2 Experimental apparatus

A newly designed high performance gear transmission test platform is applied in present research, an overall view of the experimental application is shown in Figure 2a. The platform includes space environment equipment, harmonic drive test benches and measurement systems. The space environment device simulates the temperature and vacuum environment in the universe's cold black environment. The vacuum degree can be precisely controlled in a range from 10^{-4} Pa to atmospheric pressure, the temperature of harmonic drive body can be changed from −60 °C to 120 °C, and harmonic drive transmission test bench simulates harmonic drive working conditions, as it is shown in Figure 2b. The picture shows that the transmission test bench is on the space environment. The experiment of the harmonic drive in a high temperature environment is carried out by heating the resistor on the mounting plate of the reducer. Each sensor, motor and reducer mounting plate is insulated by a thermal pad. The servo motor in input end can reach to 8.4 N m, and the torque loading motor in output end could get 82 N m. The platform communication system conducts the communication of the experimental process and the detection of data. The transmission performance test method of the harmonic drive refers to the GB/T 30819-2014 standard.

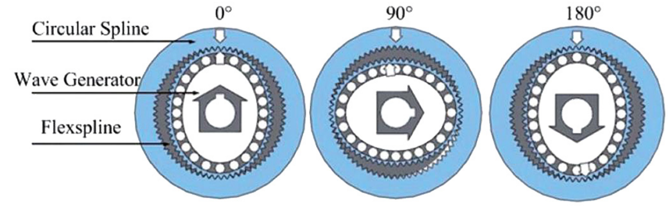

Fig. 1. Drive principle of harmonic drive [13].

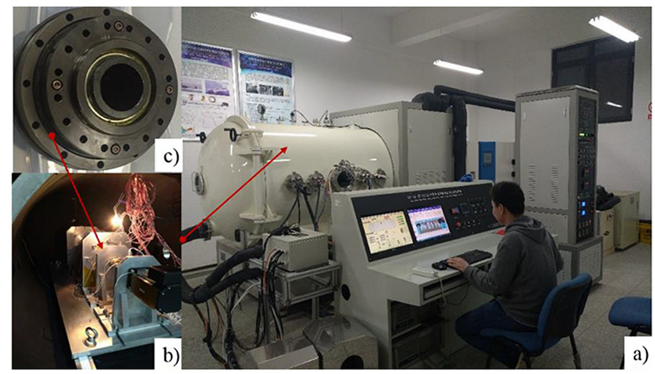

Fig. 2. Experimental apparatus. (a) Overall view of experimental apparatus. (b) Transmission platform inside the vacuum tank. (c) SHF 25-120-2UH harmonic drive.

3 Mathematical model

Variance analysis model is established to study the effects caused by setting factors. In the transmission performance test experiment, the torsional stiffness and the starting torque experiment have two indicators of temperature and vacuum. The accuracy and efficiency experiments include four factors, i.e., temperature, vacuum degree, load and speed, therefore, bivariate and four-variables analysis of variance are needed respectively.

Multivariate analysis of variance is that the sum of the squares of the total dispersion is decomposed into the sum of squared deviations of the factors and the sum of squared errors. A linear statistical model is constructed and make test hypotheses. According to the *F*-value, it can judge whether factors and their interactions were significant on dependent variables, and the significance level was generally selected for 0.01. For the sake of convenience, parameters that is not made clear in the passage are defined in Nomenclature.

Taking the transmission efficiency analysis as example, temperature, vacuum, speed and torque are the four factors. Total deviation S_T can be calculated by:

$$S_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{n} X_{ijklm}^2 - n\overline{X}^2. \quad (1)$$

Sum of square of single factor A can be inferred by (2), and the sum of square of B, C, and D also can be deduced by (2).

$$S_A = bcdn\sum_{i=1}^{a}(\overline{X}_{i\bullet\bullet\bullet\bullet} - \overline{X})^2 = \frac{a}{n}\sum_{i=1}^{a}X_{i\bullet\bullet\bullet\bullet}^2 - n\overline{X}^2. \quad (2)$$

Sum of square of the interaction between two variables is figured out by (3)

$$S_{AB} = \frac{1}{cdn}\sum_{i=1}^{a}\sum_{j=1}^{b}X_{ij\bullet\bullet\bullet}^2 - n\overline{X}^2 - S_A - S_B. \quad (3)$$

The interaction among three variables and four variables can be done in the same manner which are shown in (4) and (5).

$$S_{ABC} = \frac{1}{dn}\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}X_{ijk\bullet\bullet}^2 - n\overline{X}^2 - S_{AB} - S_{AC} - S_{BC} - S_A - S_B - S_C. \quad (4)$$

$$S_{ABCD} = \frac{1}{n}\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}X_{ijkl\bullet}^2 - n\overline{X}^2 - S_{ABC} - S_{BCD} - S_{ACD} - S_{AB} - S_{AC} - S_{BC} - S_{AD} - S_{CD} - S_{BD} - S_A - S_B - S_C - S_D. \quad (5)$$

Error sum of squares and degree of freedom f are used to derive mean square M and F-statistics, the formulas are given as follows:

$$MS = \frac{S}{f} \quad (6)$$

$$F = \frac{MS}{MS_E} \quad (7)$$

Whether the factor has effect on efficiency can be concluded by comparing F to $F0.01$. Then correlation coefficient r can be obtained to study the magnitude of effect.

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}}. \quad (8)$$

More calculation process can be seen in references [14–16].

4 Analysis of transmission performance

4.1 Multifactor crossover transmission efficiency experimental study

The Harmonic drive efficiency is the ratio of output power to input power or the products of torque and speed. The test data of efficiency has 480 groups, and each group is obtained in different working conditions.

Vacuum and temperature are fixed to study the effect on variable load and speed in Figure 3. With the increase of torque, efficiency goes up. When the speed accelerates, the efficiency cuts down. Moreover, the lines in two adjacent points are almost in parallel. Torque and speed are set constantly to explore the rules on changeable vacuum and temperature in Figure 4, along with the rise of temperature, the efficiency declines. The influence of vacuum on efficiency cannot reveal clearly. Therefore, variance analysis and correlation analysis are used to make sure the tendency and size in Table 1 and Figure 5, respectively.

A multivariate analysis of variance was performed on the experimental data of each factor and its interactions. The analysis of variance table was obtained as shown in the Table 1. Significant P values were all less than 0.01, indicating that all factors have a significant effect on efficiency (confidence $p = 99\%$), meanwhile, F ratio: $D > B > C > A > B\times D > C\times D > A\times B > B\times C > A\times D > A\times B\times D > B\times C\times D > A\times C > A\times B\times C > A\times C\times D > A\times B\times C\times D$. Therefore, the influence on the efficiency caused by these factors is arranged as the F ratio order.

It can be seen in Table 1 that single-factor variables have the greatest impact on efficiency, with the torque most, followed by temperature, speed and vacuum. The influence of two factors on the efficiency is secondary, although the effect of vacuum is less than the speed, but the interaction of "vacuum and temperature" is greater than the interaction of "temperature and speed", indicating that there is a stronger promotion or weaker suppression between vacuum and temperature. In addition, the interaction "vacuum × temperature × torque" is greater than the interaction "temperature × speed × torque", indicating that the former has a stronger interaction or weaker inhibition than the latter on efficiency. The bivariate interaction of "vacuum × speed" is less than the three-factor interaction "vacuum × temperature × torque" and "temperature × speed × torque", and the four-variable interaction "vacuum × temperature × speed × torque" has the least influence on efficiency.

It can be concluded from Figure 5 that torque has the most significantly positive relationship with efficiency. The correlation coefficient is 0.909, and it gets close to linear increasing. The rising torque will make meshing more fully, which can enhance efficiency. Because of the error, the influence on efficiency made by vacuum is too little to analyze in detail, so it is not taken into discussion in the essay.

The velocity gradient of grease will go up when the rotational speed increases, the shear force generated by the motion of harmonic drive will elevate, which makes resistance rise and efficiency down. In addition, in the spatial environment, the grease will be squeezed out more easily due to the increasing velocity, the effect of lubrication will be cut down, which can also bring down the efficiency. As shown in Figure 3, the efficiency of the harmonic drive decreases as the rotational speed increases.

The rising temperature can bring the viscosity of grease down and cut down the shear force produced by gear operation, so it can add the efficiency up. Besides, the

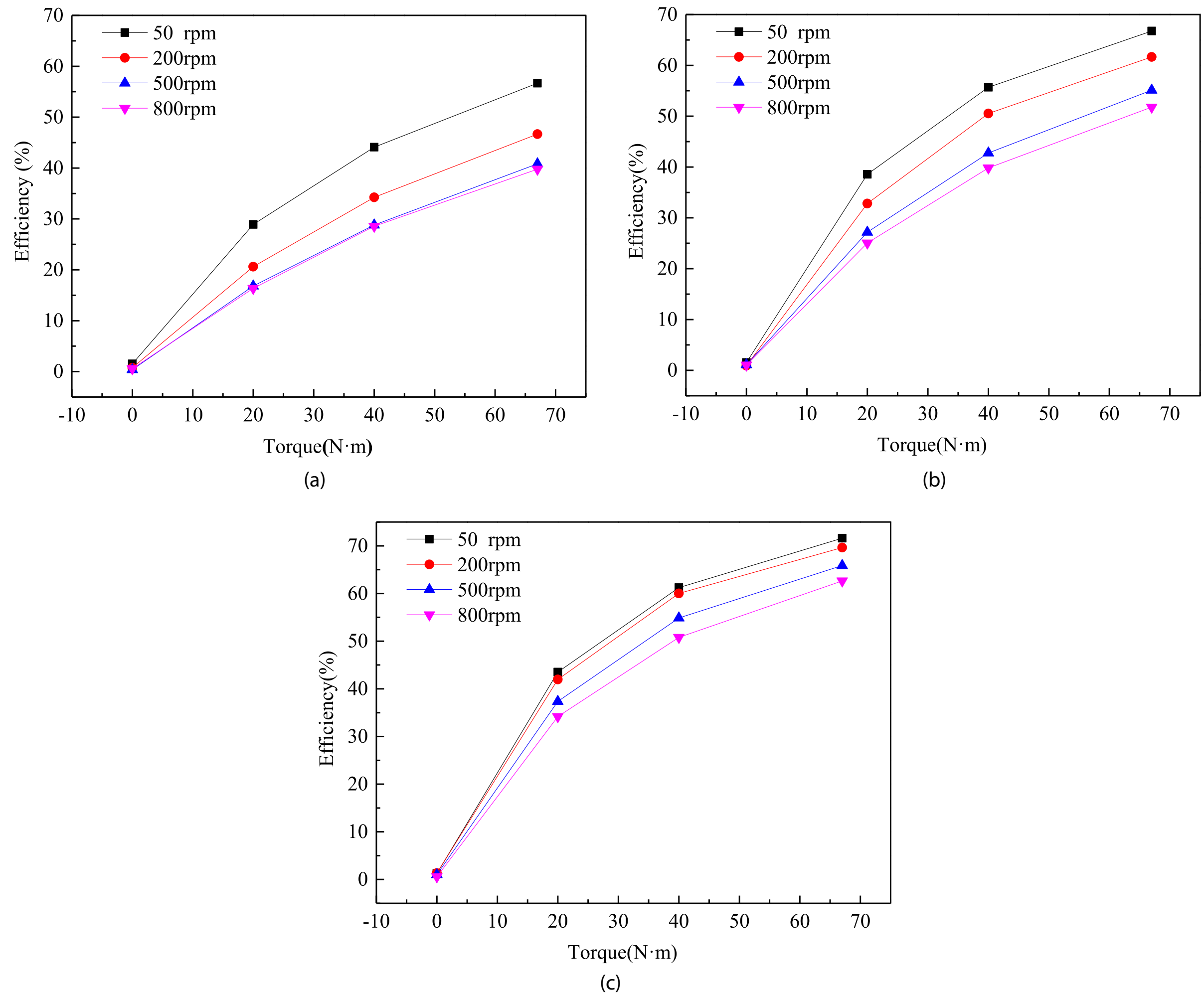

Fig. 3. Efficiency curves in different speed and torque. (a) Vacuum = 0.001 Pa, temperature = –20 °C; (b) vacuum = 0.01 Pa, temperature = 20 °C; (c) vacuum = 20,000 Pa, temperature = 60 °C.

elasticity modulus of flexspline will decrease as the temperature increase, the energy that produces the elastic deformation of flexspline can be reduced [17], and the deformation transfers the power in the transmission. Therefore, the efficiency rises.

4.2 Multifactor crossover stiffness experimental study

Torsional stiffness is the ability that resist the elastic deformation caused by torque, test curve of stiffness is as Figure 6, and the experimental data of torsional stiffness is shown in Figure 7.

From Table 2, it can be shown that the value of significance P of three factors are all less than 0.01. So, vacuum, temperature and their interaction all have influences on the torsional stiffness. Meanwhile, the temperature has the greatest effect, followed by interaction and vacuum.

It can be concluded in Figure 7 that vacuum and temperature have influence on torsional stiffness. The torsional stiffness decreases with increasing temperature. According to the correlation analysis of torsional stiffness, the correlation coefficients between vacuum, temperature and efficiency are −0.011 and −0.744 respectively. Therefore, vacuum and temperature are correlated with efficiency in a negative way, temperature has more significant effect, and the influence produced by vacuum can be neglected due to minimal numbers.

As the temperature rises, the elastic modulus decreases [18,19]. In the view of dislocations, when the temperature reduces, the Cottrell atmosphere enhances the pinning effect of dislocations, the movement of dislocations is blocked, and the degree of deformation resistance increases macroscopically. As a result, the torsional stiffness will increase. From the point of material structure, the material of flexspline is 40CrNiMo, its main component is tempered sorbite that is made up of ferrite and granular carbide. As an interstitial solid solution, tempered sorbite separates out granular carbide with the decreasing temperature. Volume shrinkage produced by temperature reduction cuts down the lattice constant of iron, and precipitates more carbide, which can enhance the solid solution strengthening effect and increase the torsional stiffness.

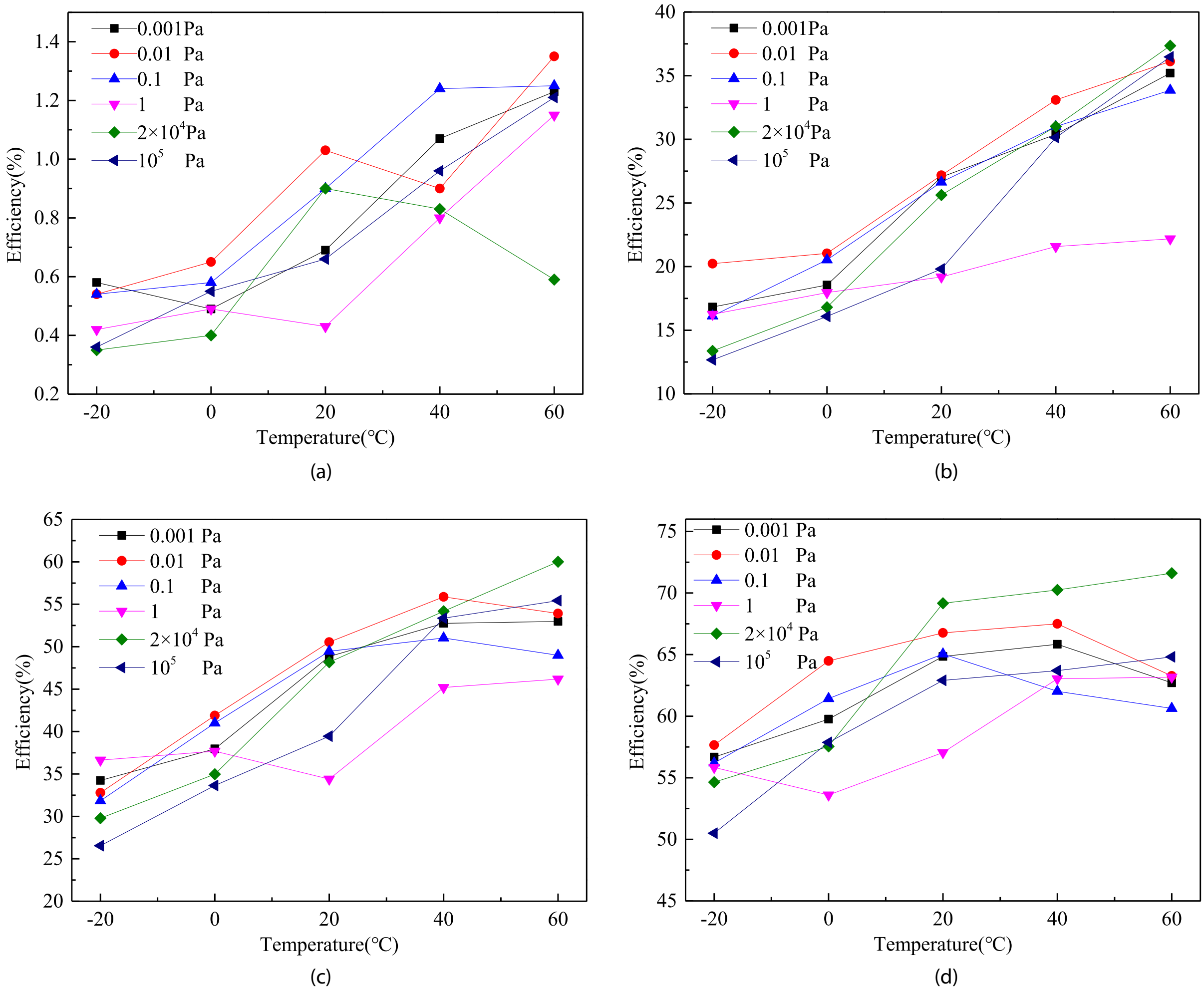

Fig. 4. Efficiency curves in different temperature and vacuum. (a) Torque 0 N m, speed 800 rpm; (b) torque 20 N m, speed 500 rpm; (c) torque 40 N m, speed 200 rpm; (d) torque 67 N m, speed 50 rpm.

Table 1. Variance analysis table of efficiency considering interaction.

Source	Sum of squares	DoF	Mean square	*F* ratio	Significance *P*
A (Vacuum)	0.200	5	0.040	1100.5	1.28e–25
B (Temperature)	1.059	4	0.265	7278.6	5.45e–34
C (Speed)	0.595	3	0.198	5454.2	9.89e–32
D (Torque)	16.882	3	5.627	154751.4	1.05e–47
$A \times B$	0.219	20	0.011	301.2	2.41e–22
$A \times C$	0.008	15	5.5e–4	15.1	3.03e–8
$A \times D$	0.071	15	4.7e–3	129.5	6.53e–18
$B \times C$	0.073	12	0.006	167.4	1.00e–18
$B \times D$	0.312	12	0.026	716.0	1.30e–25
$C \times D$	0.164	9	0.018	500.5	2.54e–23
$A \times B \times C$	0.020	60	3.3e–4	9.1	2.35e–7
$A \times B \times D$	0.070	55	1.28e–3	35.1	2.85e–13
$A \times C \times D$	0.006	45	1.33e–4	3.7	8.5e–4
$B \times C \times D$	0.029	36	8.05e–4	22.1	7.39e–11
$A \times B \times C \times D$	0.021	163	1.3e–4	3.6	4.9e–4
Error	8e–4	22	3.636e–5	–	–
Sum T	21.710	479	–	–	–

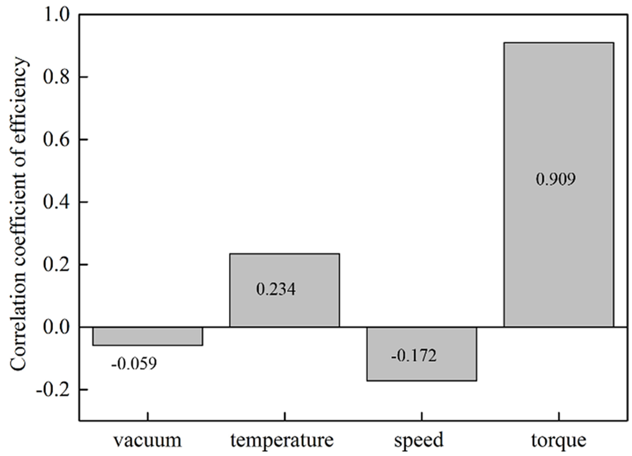

Fig. 5. Correlation coefficient of efficiency.

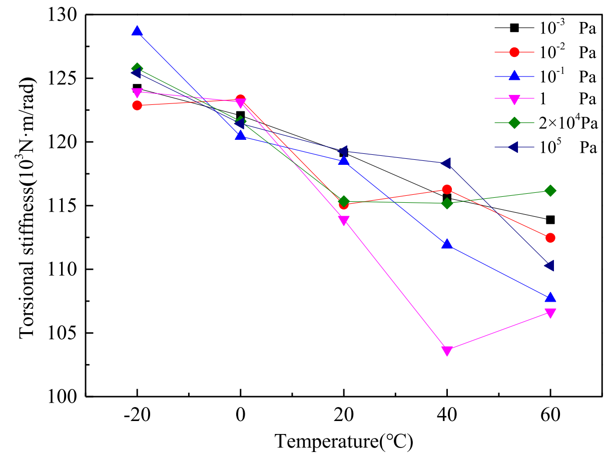

Fig. 7. Torsional stiffness curve.

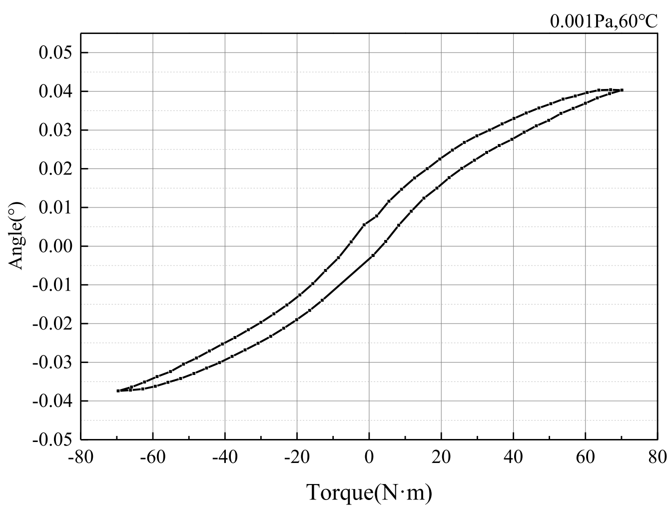

Fig. 6. Test curve of stiffness.

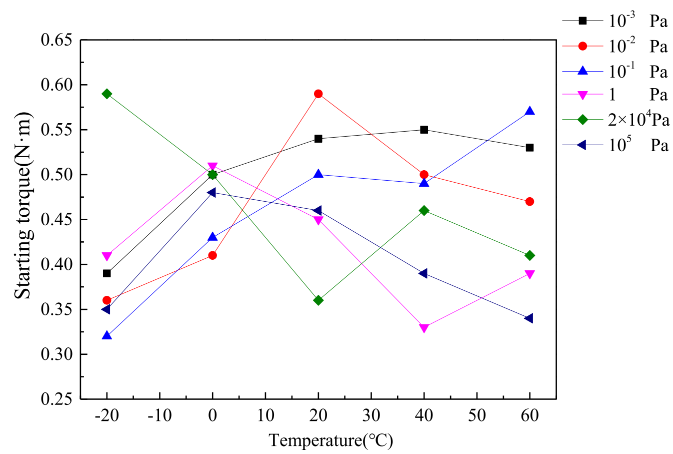

Fig. 8. Starting torque in different temperature and vacuum.

Table 2. Variance analysis table of torsion stiffness considering interaction.

Source	Sum of squares	DoF	Mean square	F ratio	Significance P
A (Vacuum)	6.47e8	5	1.29e8	10.4	1.37e–8
B (Temperature)	5.03e9	4	1.26e9	101.3	1.32e–41
Interaction $A \times B$	1.367	20	6.83e7	5.5	2.31e–10
Error E	1.86e9	150	1.24e7	–	–
Sum T	8.91e9	179	–	–	–

4.3 Multifactor crossover starting torque experimental study

Starting torque is the minimum torque that drive the harmonic drive to overcome friction and operate, it selects the maximum as test data in five repeated experiments. Test data can be observed in Figure 8, it cannot tell direct rule of starting torque with the variation of temperature and vacuum. Mathematical analysis of significance and correlation are needed to draw some conclusions. These can be shown in Tables 3 and 4.

The results can be obtained from Table 3, vacuum, temperature and interaction all have noticeable influence on starting torque, vacuum has the most significant effect on starting torque, followed by temperature and interaction. As shown in Table 4, the correlation coefficient

Table 3. Variance analysis table of starting torque considering interaction.

Source	Sum of squares	DoF	Mean square	F ratio	Significance P
A (Vacuum)	0.089996	4	0.0225	8.96	2.94e–7
B (Temperature)	0.122867	5	0.0246	8.21	7e–6
Interaction $A \times B$	0.369116	20	0.0185	6.73	–
Error E	0.32904	120	0.0027	–	–
Sum T	0.911019	149	–	–	–

Table 4. Correlation analysis table of starting torque.

Source	Correlation analysis	Starting torque
A (Vacuum)	Pearson correlation	–0.334
	Covariance	–0.045
B (Temperature)	Pearson correlation	0.173
	Covariance	0.019

between vacuum and starting torque can reach −0.334, which indicates that intensity of pressure has a negative effect on starting torque. The correlation coefficient between temperature and starting torque is 0.173, which shows that starting torque decreases as temperature rises. During operation, grease is extruded to form negative pressure, the intensity of pressure in the atmosphere can make up the reduced grease, while in vacuum it cannot gain compensation, which will influence the effect of lubrication, and the idea is hold by Ueura [20]. Further, the protective film of the rubbing surface can be instantaneously regenerated under atmospheric pressure, however, the protective film cannot be regenerated in a vacuum, and no protective film is liable to cause adhesive wear. Therefore, the vacuum rises can make the drive lubricate better, and lower starting torque. The viscosity of the grease decreased when the temperature increased, which will make the grease drain easily, reduce lubrication performance and increase starting torque.

5 Conclusion

- The high performance gear transmission platform is independently designed and developed. The test bench can simulate vacuum and temperature environment and has high test accuracy.
- A mathematical model is established to analyze the interaction among the factors of harmonic drive and an experimental method of the model is designed.
- The influencing factors of the transmission performance of the harmonic drive under multifactor interaction are analyzed. The results show that the single factor has the greatest impact and the interaction also has an important impact.

Nomenclature

A	vacuum (Pa)
a	level number of A, $i = 1,2,...,a$
B	temperature (°C)
b	level number of B, $j = 1,2,...,b$
C	speed (rpm)
c	level number of C, $j = 1,2,...,c$
D	torque (N m)
d	level number of D, $j = 1,2,...,d$
MS_A	mean square value of S_A
F	the ratio of mean square of factors to mean square of error
n	times of repetition, m = 1,2,...,n
S_T	total deviation
S_A	the sum of square of A
S_{AB}	the sum of square of interaction between A and B
S_{ABC}	the sum of square of interaction among A, B and C
S_{ABCD}	the sum of square of interaction among A, B, C and D
$\overline{X}$	the average value of the test data
$\overline{X}_{i\bullet\bullet\bullet\bullet}$	$\sum_{j=1}^{b}\sum_{k=1}^{c}\sum_{l=1}^{d}\sum_{m=1}^{n} x_{ijklm}$
$\overline{X}_{ijkl\bullet}$	$\sum_{m=1}^{n} x_{ijklm}$
DoF	degree of freedom

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