PERFORMANCE AND TESTING OF HARMONIC DRIVE GEARS LUBRICATED WITH TWO TYPES OF LUBRICATION:LIQUID-LUBRICATED H-DLC-COATING AND SOLID MoS_2

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ABSTRACT

A series of performance testing regarding some harmonic drive gears with two types of lubrication had been carried out respectively in order to confirm the performance degradation of liquid-lubricated gears and the reliability of solid-lubricated ones. Accelerated life test under four kinds of output torque stress were adopted to evaluate the gears which were treated with PFPE-lubricated H-DLC-coating and to verify whether they could meet the requirement of long lifetime service. Several extreme environment simulation testing and life testing were designed to verify the feasibility and reliability of gears which were lubricated with sputtering MoS_2 composite films and to confirm that they could be applied in extream environment such as broader range of temperature from - 60 ℃ to +80℃ simultaneous with high output torque(30Nm).

1. INTRODUCTION

1.1 Harmonic drive gears lubricated with PFPE grease-lubricated W-C:H Coatings

Harmonic drive gears are used in a wide range of spacecraft mechanisms[1],[2], and a fundamental requirement is to guarantee their reliability and performance for long time service in space. Advanced lubrication technology and valid accelerated test procedure for the components are the preconditions that should be imposed before their application in space so as to quantify their performance degradation and confirm their failure mechanism[3]. The paper described the degradation of transmisson performance of this kind of moving parts under various accelerated load stresses accompanying with a low rotational input speed which created a similar lubrication regime for each interface between flexspline and their counterfaces like in flight[4], and the data obtained through these accelerated tests could be summarized as a specific method to estimate the reliability and life of harmonic drive gears. The work completed in this paper made a beneficial complement for the research fields of space tribology.

1.2 Harmonic drive gears lubricated with sputtering MoS_2 films

Generally, solid lubricated harmonic reducer can be used in broader range, but may not be advised to use in long life missions[5-7]. This study described a kind of solid lubricated harmonic reducer used in space deploy device. The parameters of this harmonic reducer were as follows: model number was HD50-100, reduction ratio was 100:1. The material of circular spline was 40Cr, and that of flexspline material was 40CrNiMoA. The operation conditions of this reducer was that storage temperature in space was from -180 ℃ to +130 ℃, and working temperature was from -60℃ to +80℃. The operation parameters were crucial, and the output torque was 30N·m with a input speed 3 rpm and swing angle of input axis -120°～+120°. The solution of solid lubrication was selected for bearings, flexspline and circular spline of the harmonic reducer for short working life, wide temperature range applications. The inner and outer races of bearings were lubricated with MoS_2 film, and bearing cages were made of PTFE-based self-lubricating polymers. All parts of flexspline and circular spline were also coated with MoS_2 film. In this study, in order to verify whether the harmonic reducer is able to meet the use requirements, the extreme temperature storage test, thermal vacuum test and atmospheric life test(100h) were designed and conducted for its performance evaluation[8-9].

2. SECTION 1 EXPERIMENT AND RESULT OF HARMONIC DRIVE GEARS LUBRICATED WITH PFPE GREASE-LUBRICATED H-DLC-COATINGS

2.1. Accelerated stress tests for harmonic drive gears

With the aid of specific test device, twelve harmonic drive gears whose inner fexspline diameter is 60mm and reduction ratio is 200:1, were divided into four groups to estimate their performance degradation and life under four kinds of output torque stress respectively in vacuum. Lode-torque from 5N.m to 30N were put on the output axises by means of Magnetic torque generator. Their performance including transmission accuracy, backlash and transmission efficiency was tested regularly during these life tests, and each life test was stopped at a given condition that its efficiency declined below 50% noticeably.

The interface between each flexspline and its wave generator is their shortcoming, and is likely worn in initial course of life test[10],[11]. So every surface of circular spline and flexspline were deposited with W-C:H-Coatings prior to being lubricated by a space grease named Braycote 601 , a grease containing Z25 oil and PTFE. Previous study on this

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subject[12] necessitates diverse stresses life tests, and the following accelerated life tests conditions and efficiency test condition are shown in table1 and table2.

Table1 Accelerated life tests conditions

Experimental item and condition			Environmental condition
Number of experimental samples	Outpu torque	State of input rotation axis	
3（No. 1～No. 3）	5N.m	The axes rotated at a speed of 15r/min clockwise and anticlockwise by turns, and reversed per 13.5min.	Vacuum pressure:10^{-4}Pa Experimental temperature: 25℃±5℃
3（No. 4～No. 6）	10N.m		
3（No. 7～No. 9）	20N.m		
3（No. 10～No. 12）	30N.m		

Table 2 Efficiency test condition

Test	Items and condition
Efficiency test	Output load torque: 20Nm
	Input speed: 100 r/min
	Temperature: room temperature(20–25℃)

Data extracted from the accelerated load torque stress tests can improve their practicality and be available for being analysed statistically, since all tests were conducted under a same input speed of 15r/min in vacuum,which conformed to the principle that the moving parts' lubrication failure mechanism must not be modified in comparison with that in flight[13]. Further more' the results of the accelerated life tests could help to analyse and quantify the variation of HD gears' reliability.

2.2. Evaluation method of performance degradation during accelerated life tests

The harmonic drive gears' efficiency, transmission accuracy and backlash were tested regularly so as to identify their performance degradation trends. Fig1 presented the one scene of accelerated life tests in vacuum simulator, and test method regarding efficiency, transmission accuracy and backlash was conducted through a specific facility as can be seen in Fig2.

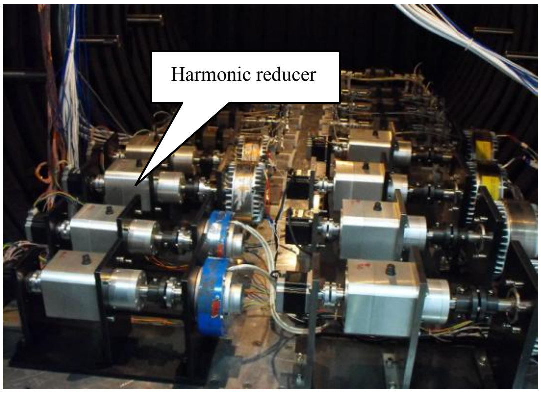
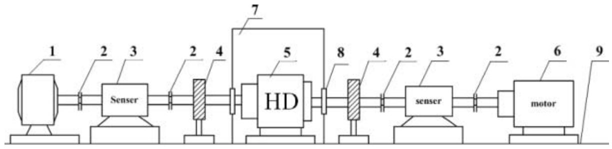


Fig 1. scene of accelerated tests for harmonic drive gears in vacuum

In order to calculate the efficiency through data abtained from torque sensors straightforwardly, calculating formula of transmission efficiency could be transformed into a simple one like the following, which made the test result more accurate.

$$\eta = \frac{M_1}{M_2 \cdot n} \times 100\% \qquad (1)$$

M_1: Gear output torque;
M_2: Gear input torque;
n: reduction ratio.



1— Magnetic torque generator；2—Coaxial directional coupler；3—torque sensor；4—goniometer；5—Harmonic drive gears(to be tested)；6—Motor；7—vacuum simulator；8—Hydromagnetic seal；9—Horizontal substrate

Fig2. Schematic diagram of performance test for harmonic drive gears

2.3. Measurement of Worn areas

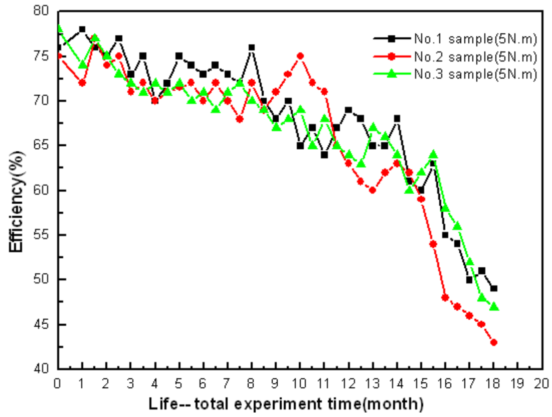
The 3D surface topography of inner surface of every Flexspline dis-assembled was measured after life test with Taylor Hobson laser rough instrument, which directly reflects the wear on worn surfaces.

2.4. FTIR analysis for remanent PFPE grease

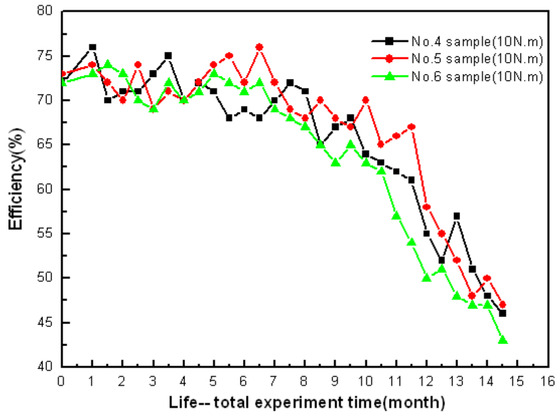
The remnants of PFPE grease on each worn surfaces were tested through FTIR to establish whether the structure of giant molecule of PFPE was destroyed, and whether there was new functional group after long periods of life test.

2.5 Result and discussion

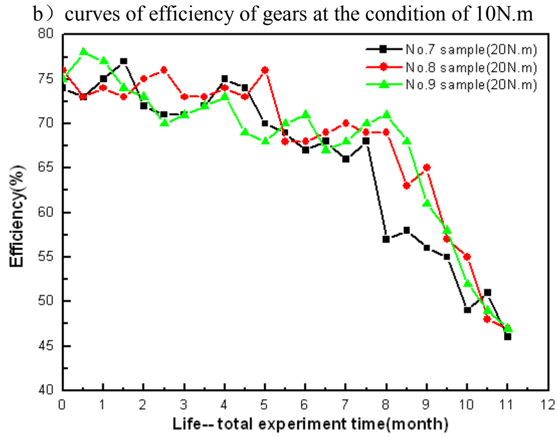
The trends of efficiency degradation under different output torque stresses from 5Nm to 30Nm were shown respectively in Fig3. Each life test was not stopped until their efficiency decreased significantly to under 50% , and total revolutions of corresponding input axis were calculated. As showen in Fig3, it presented different slope of efficiency degradation with a range of output torques of 5Nm, 10Nm, 20Nm and 30Nm. The total revolutions of input axes could add up to 1.2×10^7r and 9.0×10^6r averagely at the load stresses of 5Nm and 10Nm when their efficiency declined below 50% obviously. Correspondingly, It took about 18 monthes and 13.7 months to accomplish this two low accelerated load stress tests. Additionally, their efficiency levelled off relatively at a range of 75%±3% during the initial 13.5 months and 10.5 months, and hence declined at a rapid slope. However, the results at higher load stresses of 20Nm and 30Nm amounted to 7.1×10^6r and 6.0×10^6r, taking 11 monthes and 9.2 months respectively which were less than two previous groups of specimens. This was likely due to higher internal contact stress caused by higher load between inner surface and wave generator which resulted in more wear[14]. In comparison with efficiency degradation, the transmission accuracy and backlash of these specimens showed no tendency of degradation.



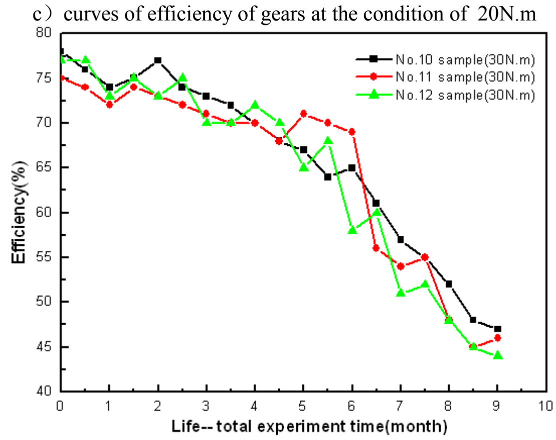
a）curves of efficiency of gears at the condition of 5N.m



b）curves of efficiency of gears at the condition of 10N.m



c）curves of efficiency of gears at the condition of 20N.m



d）curves of efficiency of gears at the condition of 30N.m

Fig3. curves of efficiency versus experimental time

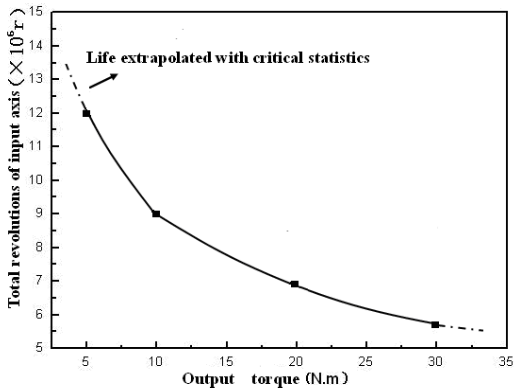
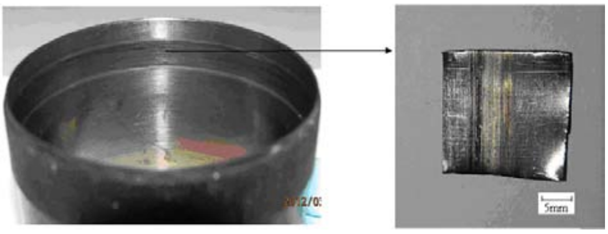
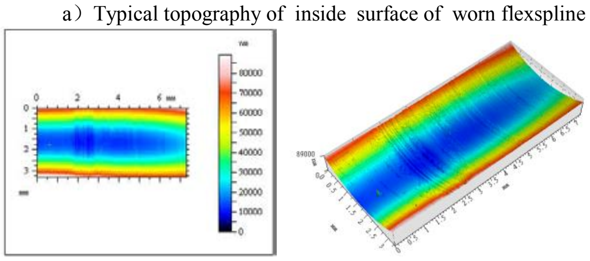


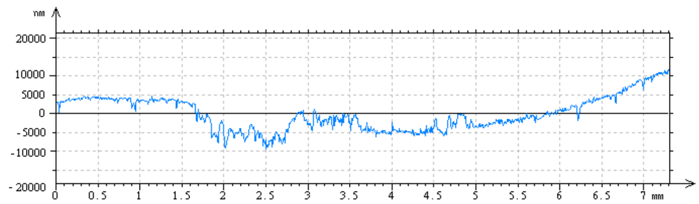
Fig4.Total revolutions of input axis versus output torque



a）Typical topography of inside surface of worn flexspline



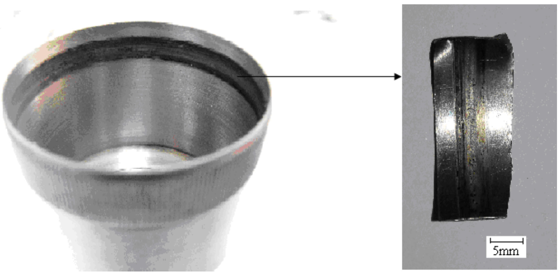
b）3D surface topography of inside surface of worn flexspliner



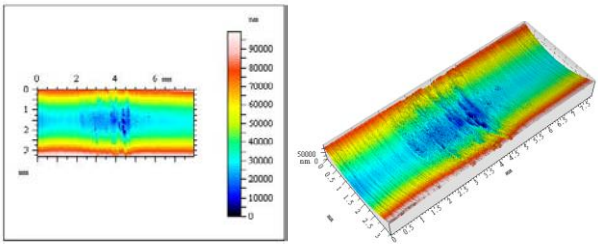
c）Typical scan curve of profile at worn zone

Fig5. Wear of inside surface of flexspliner (5N.m)

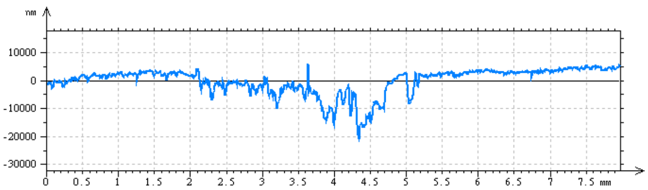
As shown in Fig3c, the efficiency at output torque of 20N.m degraded earlier than other two specimens' of lower stresses. The period of steady efficiency could only lasted 5.5 months and then the efficiency fell rapidly. Compared to trends mentioned above, sharp curves, without steady process throughout the experiments were displayed in Fig3d(30N.m). In addition, the operation of gearboxes became noticeably noisy when their efficiency declined to about 50%. It was evident that higher output torque had effects on specimens' life as it was summarized in Fig4. The operation life of gears decreased from 1.2×10^7r to 6.0×10^6r with increasing load from 5N.m to 30N.m. The extrapolated value of life was calculated through critical statistics which was based on experimental results.



a）Typical topography of inside surface of worn flexspline



b）3D surface topography of inside surface of worn flexspliner

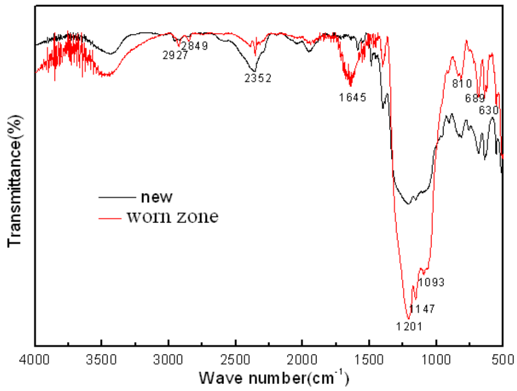


c）Typical scan curve of profile at worn zone

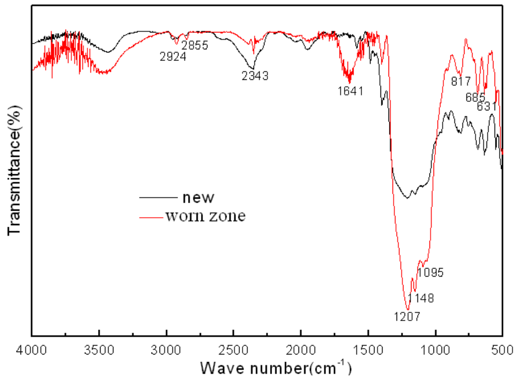
Fig6. Wear of inside surface of flexspliner (20N.m)

Fig5 and Fig6 revealed main wear areas which were located inside surface of flexspliner. The wear depth of specimens under the load torque of 5N.m ranged from 8.5μ m to 11.5μ m averagely and the results of 20N were from 12.8μ m to16.5μ m. It was clear that the degree of wear was sensitive to contact stress on inside surface of flexspline caused by higher output torque though the latter experioments took less time. As expected, increasing wear occurring the interfaces counteracted gears' torque output partially and resulted in a decreasing efficiency. Furthermore, higher load torque could reduced gears' life, which was proved in Fig3 and Fig4.

The remnants of grease sampled from worn areas were analysed by using Fourier Transform Infrared spectroscopy with an intention to establish whether there were new chemical bands in addition to those of PFPE. Two kinds of infrared absorption spectrum were showed in Fig7, which demonstrated similarly bonds at $1206cm^{-1}$(C-F), $1143cm^{-1}$(C-O-C), $1094cm^{-1}$ (C-O-C) that were derived from PFPE. Compared to unused PFPE grease, however, the absorption spectrum at $1645cm^{-1}$ was detected and confirmed 'C=O', which indicated that PFPE grease at worn areas was destroyed or oxidated partially. Further investigation will be conducted to describe the range of temperature variation on worn surface while the gears operate both smoothly and roughly, which will reveal the possibility that PFPE grease degrades at instantaneous high temperature due to the asperity of hard friction.



a）FTIR analysis of remnant grease on worn flexspline



b）FTIR analysis of remnant grease on teeth

Fig7. FTIR analysis of remnant grease

2.6 Conclusions of section 1

The PFPE grease–lubricated W-C:H-Coatings could afford HD gears(Type-60) a long running life which added up to more than 1.2×10^7 revolutions under a condition of 5N.m output torque which is actually higher than that in flight. Based on this result, a promising space application of grease lubrication combined with DLC films could be achieved.

The transmission efficiency of HD gears fluctuated at a small range of 75%±3% at a moderate load stress from 5Nm to 10Nm during their main experimental period which accounted for approximately 71% of the entire running lifetime, and compared to the stage when efficiency declined continuously at a rapid slope, the HD gears could operate smoothly at a relatively stable efficiency which indicated that less wear occurred before that inflexion. With an increasing output torques loaded on output axis of HD gears, their running life degraded noticeably, from which a conclusion could be drawn that wear rates of flexsplines tended to go up correspondingly.

The running life were reduced significantly with a increasing accelerated stress of output torques. It declined by 33% approximately from 1.2×10^7r(5N.m) to 9.0×10^6r (10N.m). Further more, its running life only accounted for 58% and 50% of the initial value under higher load conditions of 20N.m and 30N.m respectively.

The wear on surfaces of flexsplines played the leading role that reduced HD gears' efficiency , and that in teeth system FS/CS was negligible to some degree.

3. SECTION 2 EXPERIMENT AND RESULT OF HARMONIC DRIVE GEARS LUBRICATED WITH SOLID SPUTTERING MoS_2 FILMS

3.1 Extreme temperature storage test

Extreme temperature storage test was aim to confirm whether the harmonic reducer could start normally, and whether its performance would degrade when the harmonic reducer was in room temperature environment after storage in low or high temperature environments. Low temperature storage test was carried out in liquid nitrogen storage containers whose schematic diagram is shown in Fig8.

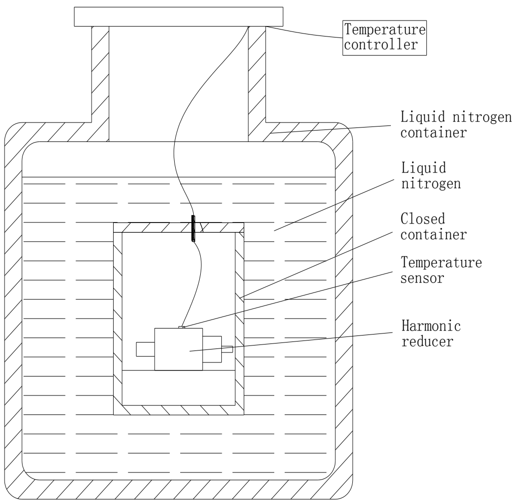


Fig 8 Low temperature storage test of harmonic reducer

During low temperature storage tests, the harmonic reducer in a smaller container was kept in liquid nitrogen environment in order to avoid the occurrence of frost which could have effect on the test results, further more, the smaller sealed container was kept a low vacuum by pre-pumping. The harmonic reducer was removed from the liquid nitrogen container after the low temperature storage test of 15 days, and its transmission efficiency, transmission accuracy and stiffness properties were measured at room temperature. After finishing these test, the harmonic reducer was put into liquid nitrogen container again to accomplish the following 2 cycles of temperature storage test with the temperature lower than -190 ℃. Likewise, its high temperature storage tests of 3 cycles were conducted in a chamber with the temperature of +130 ℃ and its transmission perormance were tested after it returned to normal temperature. The test results after each low and high temperature storage test were shown in Table3.

Table3 Results of low and high temperature storage test

Test stage		Start torque (N·m)	Efficiency (%)	accuracy (°)	Stiffness (N·m/°)
before test		0.05	72.5	0.032	276
Results of low temperature storage tests	after 1st cycle	0.06 (first time) 0.05(second time)	70.3	0.029	275
	after 2nd cycle	0.08(first time) 0.06(second time)	73.6	0.027	272
	after 3rd cycle	0.07(first time) 0.05(second time)	72.2	0.034	264
Results of high temperature storage tests	after 1st cycle	0.06	71.4	0.036	263
	after 2nd cycle	0.05	72.9	0.030	278
	after 3rd cycle	0.05	71.7	0.034	273

It was seen from table 3 that the start torque of the harmonic reducer increased slightly from 0.05N·m to 0.08N·m as the temperature return to room temperature from low temperature, however, at the second test after running in , it recovered to the initial level of before the storage test. Each internal clearance of the harmonic reducer became smaller due to thermal expansion and contraction at low temperature, and when it returned to the room temperature, its internal stress was not completely removed. It was the reason why the start friction torque increased at the first test, and reached to the initial level at the second time. On the other hand, its transmission performance did not decrease after high temperature storage test, and the transmission efficiency, transmission accuracy and stiffness of harmonic reducer before and after the storage tests did not change significantly with little difference due to its factors of test resolution and precision .

3.2 Thermal vacuum test

Thermal vacuum test was conducted to evaluate its performance in thermal vacuum environment. In the test, the transmission efficiency was measured as the key index and its schematic diagram of test device was shown in Fig 9.

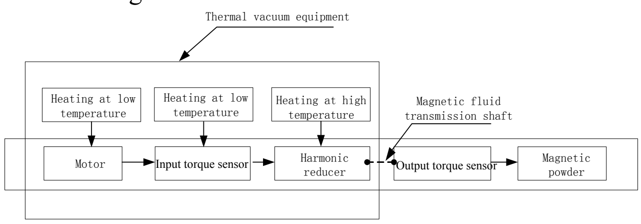


Fig.9 Schematic diagram of the thermal vacuum equipment

As shown in Fig 9, the motor and input torque sensor were used for driving of harmonic reducer and test of driving force respectively. The output torque sensor and a magnetic torque generator were used for realization of torque loading and testing. The drive motor, input torque sensor and harmonic reducer were installed in the vacuum chamber, and connected with the magnetic torque generator and output torque sensor by a magnetic fluid transmission shaft. In the low temperature test, in order to ensure the normal operation of driving motor and torque sensor in vacuum with a low temperature, the motor and torque sensor were heated by means of active temperature control device. During the high temperature test, heating device was adopted to heat the harmonic reducer only. Thermal vacuum test profile was shown in Fig 10.

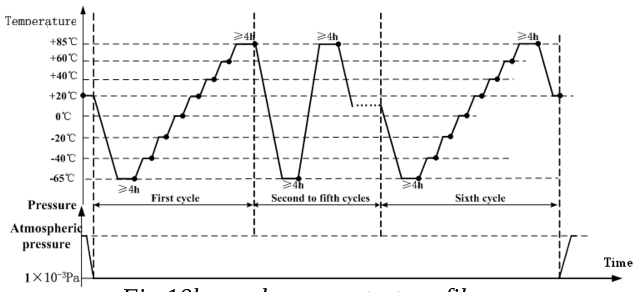


Fig 10hermal vacuum test profile of harmonic reducer

The thermal vacuum test were carried out for 6 cycles in all. The transmission efficiency was measured at the temperature of -65 ℃, -40 ℃, -20 ℃, 0 ℃, 20 ℃, 40 ℃, 60 ℃ and 85 ℃ in the first and sixth cycle. During other cycles, its transmission efficiency was measured at the end of high and low temperature stage. The test results were shown in Fig11 and Fig12.

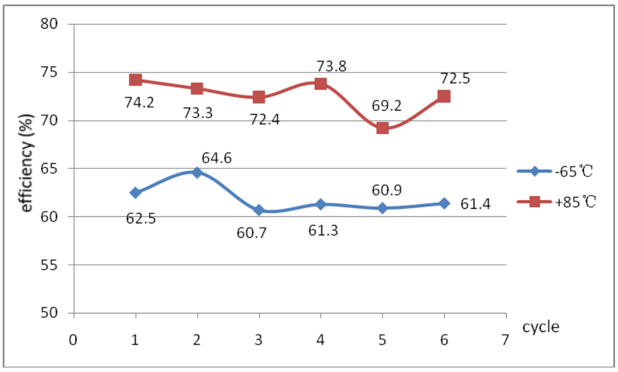


Figure 11 Transmission efficiency at high and low temperature during each cycle

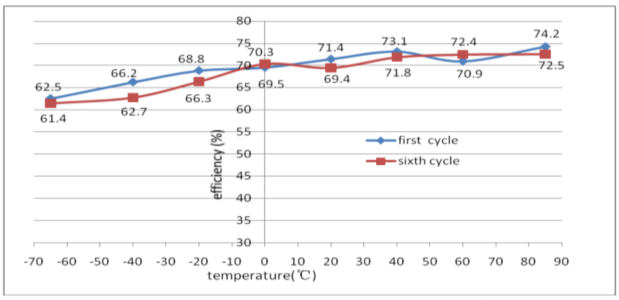


Figure 12 Transmission Efficiency from -65 ℃ to +85 ℃ during 1st cycle and 6th cycle

The Fig.11 presented a clear information that the transmission efficiency obtained at 85 ℃ was about 10% higher than that at -65℃ from first cycle to the sixth cycle. And as showed in Fig12, the transmission efficiency of harmonic reducer decreased gradually at a condition of decreasing temperature. It was obvious that the efficiency at high temperature was slightly higher than that at room and low temperature. The reason that efficiency decreased at low temperature could be explained by the fact that the increasing friction and wear occured due to smaller gaps which resulted from thermal expansion and contraction effect.

3.3 Atmospheric lifetime test

Life test in the atmosphere was carried out on the harmonic reducer performance tester (Fig13). Two torque sensors were used for the measurement of input and output torque. The motor (1#) was used to drive the harmonic reducer,and the motor (2#), HD gears(2#), and torsion bar were combined for creating load to the tested sample[15].

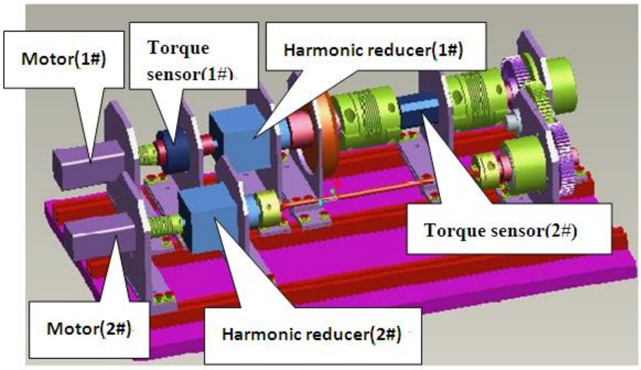


Fig13 Harmonic reducer performance tester

In the whole process of the test, transmission efficiency of harmonic reducer was measured every 10h. The results were showed in Table4.

Table 4 Transmission efficiency results of atmospheric lifetime test

Test time (h)	0	10	20	30	40	50	60	70	80	90	100
Transmission efficiency (%)	70.9	71.2	70.3	69.4	69.5	68.9	68.7	67.7	68.1	67.8	67.3

After atmospheric life test, its transmission efficiency, transmission accuracy and stiffness were measured and compared with those before the life test. The results were summarized in Table 5.

Table5 The results of harmonic reducer performance before and after the atmospheric life test

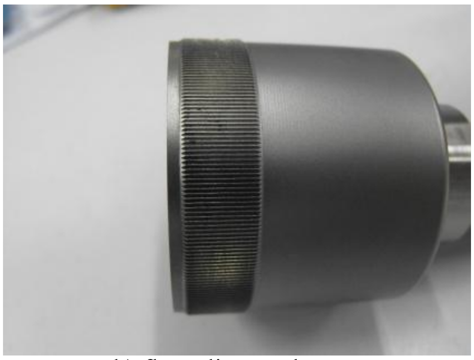
Test item	before test	after test	test conditions
Transmission efficiency (%)	70.9	67.3	load torque: 30 N·m, input speed :3rpm.
Transmission accuracy (°)	0.038	0.40	
Stiffness (N·m/°)	265	255	

It was summarized in Table 5 that, after 100h atmospheric life test, the efficiency decreased from 70.9% to 67.3%, the value of accuracy increased from 0.038 ° to 0.40° and the stiffness decreased from 265 N·m/° to 255 N·m/°. According to the Table 4 and Table 5, some interfaces of the HD gears showed wear caused by motion of moving parts. The transmission efficiency decreased as the increasing friction force due to the wear of moving parts, and the transmission precision got bad due to the increasing gap between the contact surfaces. Its stiffness decreased because of the reduced preload between the gearings due to the increasing gaps of some interfaces[16].

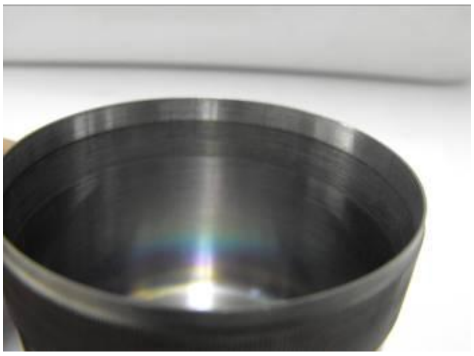
3.4 Topography analysis after all the tests

After completion of life test, the surface of the flexspline and circular spline, interface of wave generator-flexspline were checked. The surface topography were shown in Fig14.

a) circular spline teeth



b) flexspline teeth



c) innerface of wave generator-flexspline.

Fig14 Surface morphology of harmonic reducer after the tests

It could be seen that the circular spline teeth and flexspline teeth showed almost no wear after extreme temperature storage test, thermal vacuum test and atmospheric life test. Only slight wear was found at the innerface of wave generator-flexspline.

3.5 Conclusions of section 2

The performance of the harmonic reducer lubricated with solid MoS_2 did not decrease after high temperature and low temperature storage test .

The harmonic drive gears worked well in thermal vacuum environment, and its performance did not decrease after thermal vacuum test.

The transmission efficiency of the harmonic reducer decreased gradually as the temperature decreased, and it was more obvious at low temperature.

The performance of harmonic reducer decreased slightly after 100h atmospheric life test, but it was still in good condition to satisfy the space requirement.

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