Tribological Characteristics of Solid Lubricated Bearings used in ADEOS-II TCM

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ABSTRACT

Japanese satellite, Advanced Earth Observing Satellite-II (ADEOS-II, to be launched in 2002) has a flexible solar cell array paddle, made up of an extension mast and 50 flexible blankets with 55680 solar cells. To keep the tension applied to the blankets at a suitable level, a tension control mechanism (TCM) is mounted at the tip of the paddle.

With the purpose of proving the performance and the lifetime of ball bearings used in TCM, three kinds of oscillatory motion tests were performed. The test results demonstrated sufficient performance and lifetime of the bearings. The other result also indicated that very smooth oscillatory motion could be achieved by appropriate running-in of the bearings.

1. INTRODUCTION

ADEOS-II (Fig. 1) has a flexible solar cell array paddle, made up of an extension mast and 50 flexible blankets with 55680 solar cells.

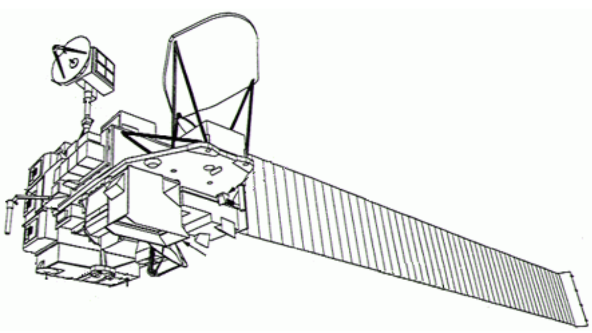

Fig. 1 ADEOS-II

Before the launch, the paddle is stowed in a small box with the size of about 3 m in width, 20 cm in length and 40 cm in depth, and is deployed to about 3 m in width and 24 m in length in the orbit. The paddle generates more than 5000W of electrical power.

This high-performance paddle was realized by its flexible structure. However, this structure requires special mechanisms to absorb the difference of thermal expansion between the paddle blankets and the mast. TCM (Fig. 2) is mounted at the tip of the paddle, and keeps the tension applied to the blankets at a suitable level and the shape of the paddle.

TCM has two toggle links, and changes its length with folding or extending them according to the thermal expansion or contraction of flexible solar cell arrays. A couple of solid-lubricated #7900 angular contact ball bearings are attached in each hinge of the toggle link. About 25 degrees of oscillatory motion is expected in one round flight on the orbit, and a life of totally 27000 cycles of oscillatory motion is required.

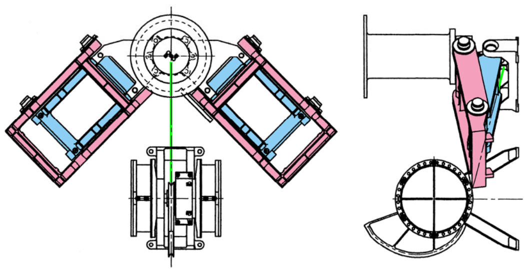

Fig. 2 Tension Control Mechanism (TCM)

With the purpose of proving the performance and the lifetime of the bearings used in TCM, three

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kinds of oscillatory motion tests were performed.

Firstly, the 25 degrees of oscillatory motion was applied to a couple of test bearings in 10^{-6} Pa ultrahigh vacuum (UHV), and frictional torque was measured. This environment pressure aimed the real operation environment of TCM, about 10^{-8} Pa at 800km in altitude [1].

Secondly, to investigate the effect of vacuum pressure in test environment, a similar oscillatory motion test in 10^{-3} Pa high vacuum (HV), simulating the test environment of TCM component, was performed. Some paper reported that the coefficient of friction (COF) of MoS_2 is responsive to test environment and shows pressure dependency in a certain vacuum level [2][3]. This second test was performed to ensure whether the bearing performance between UHV and HV is tribologicaly identical, and whether the TCM component test result obtained in HV, about 3~4 order higher pressure than real environment, is reasonable.

Finally, in order to reduce the torque peaks found in the results of former two tests, an evaluation test of running-in was carried out in UHV. Torque peaks have been sometimes observed in oscillatory motion test of solid-lubricated bearings [4]~[7], and caused some malfunctions of mechanical components [4][8]. In this test, continuous unidirectional rotation of 1500 revolutions at 2.4 rpm (2.5deg./sec.) was appended before the oscillatory motions, and its effect on the torque peak was evaluated.

2. TEST BEARINGS AND RIG

The balls and races of the test bearing are lubricated with a sputtered MoS_2 film, and the retainer is made of a PTFE based composite. Table 1 shows the specifications of the test bearing.

Table 1 Specifications of #7900 bearing

Outer diameter	22 mm
Inner diameter	10 mm
Width	12 mm
Number of balls	11
Initial contact angle	15 deg.
Precision	JIS P4 (equivalent to ABEC 7)

Figures 3 and 4 show the test rig of bearings used in this lifetime test. In Fig. 4, a couple of bearings are mounted within the bearing holder. An axial load is applied to the bearings with inserting a coil spring between them.

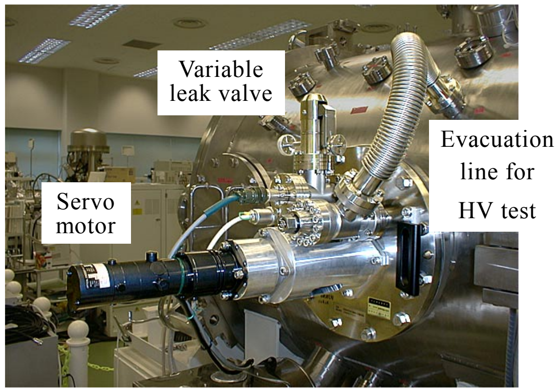

Fig. 3 Test rig (Outside of vacuum chamber)

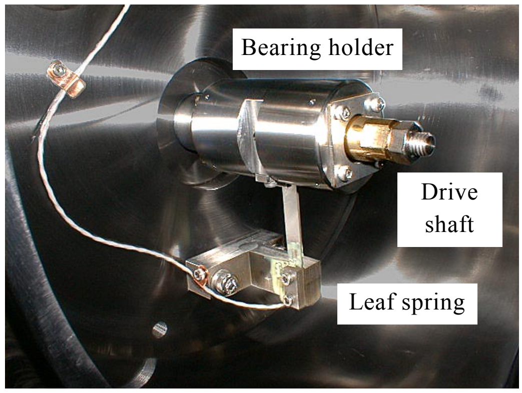

Fig. 4 Test rig (Inside of vacuum chamber)

In this lifetime test, the outer races of the test bearings were held and the inner races were driven by a DC servomotor. A leaf spring is connected to the bearing holder and the base plate of the rig, and the frictional torque of the test bearings is measured by strain gauges attached on the leaf spring. This test rig is mounted onto a vacuum chamber and evacuated down to 10^{-6} Pa with a turbo molecular pump and a cryopump.

HV of 10^{-3} Pa was attained by the following manners: The assemblies shown in Fig.4 were completely covered by a metal case. The inside of the case was evacuated through the evacuation line with a metal valve. Simultaneously, dry air was introduced through a variable leak valve. The vacuum level in the case was controlled by regulating the metal valve and the variable leak valve.

3. TEST CONDITION AND ENVIRONMENT

Tables 2 and 3 show the test parameters and the test environment of lifetime test. The coefficient of friction (COF) μ of each bearing in Table 2 is defined by following equation;

$$\mu = 2T / (dW),$$

where T is frictional torque of each bearing, d is an inner diameter of the test bearing, and W is an axial load.

The test bearings were not running-in before the oscillatory motion, simulating the flight model of TCM.

Table 2 Test conditions

Test mode	Oscillatory motion
Motion angle θ_0	25 deg (equivalent to TCM)
Angular velocity ω_0	2.5 deg/s (5 times as fast as TCM)
Axial load	240 N (generating equivalent contact stress to TCM)
Maximum contact stress	Ball and outer race : 1.53 GPa
	Ball and inner race : 1.62 GPa
The test completion criteria	54000 cycles (twice as the requirement of TCM)
	COF of each bearing > 0.05

Table 3 Test environments

UHV	Vacuum pressure	1.1×10^{-6} ~ 1.3×10^{-6} Pa
	Temperature	21.3～ 21.6 °C
HV	Vacuum pressure	9.3×10^{-4} ~ 1.0×10^{-3} Pa
	Temperature	22.7 ~ 22.9 °C

4. RESULT OF UHV TEST

Figure 5 shows the frictional torque curve at 54000 cycles of oscillatory motion in UHV. In Fig. 5, remarkable torque peaks are found at both ends of CW and CCW motion.

Figure 6 shows the traces of three characteristic values, μ_{s_min}, μ_{s_max}, and μ_p, defined in Fig. 7 and Table 4. Throughout the test, μ_{s_min} and μ_{s_max} show almost stable values, 0.005 and 0.008, respectively. Within first approximately 3000 cycles μ_p quickly increased from 0.008 to 0.02, and kept almost constant value in following 51000 cycles.

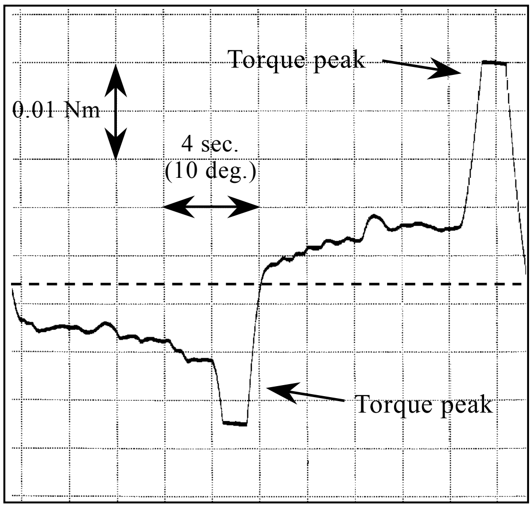

Fig. 5 Frictional torque curve (at 54000 cycles, tested in UHV)

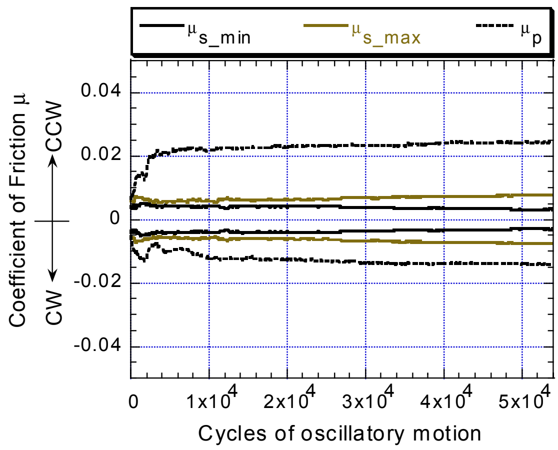

Fig. 6 COF traces vs. motion cycle (UHV)

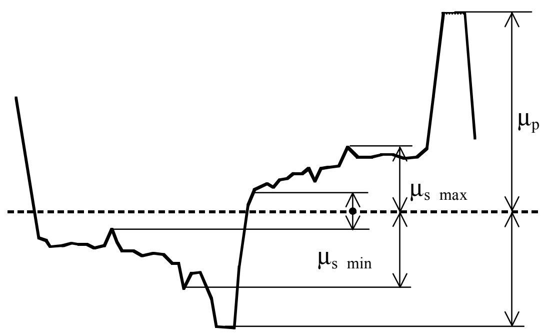

Fig. 7 Definitions of characteristic values of COF

Table 4 Definitions of μ_{s_min}, μ_{s_max}, and μ_p

μ_{s_min}	Minimum value of COF while bearings rotating
μ_{s_max}	Maximum value of COF while bearings rotating (except torque peaks)
μ_p	Value of COF at torque peak

During the lifetime test in UHV, the COFs of test bearings kept below the test completion criterion of 0.05. This shows that the test bearings have enough lifetime for TCM application in UHV environment.

5. RESULT OF HV TEST

Figure 8 shows the frictional torque measured in HV environment. The torque peaks with similar shape and magnitude to those in Fig. 5 are generated.

Figure 9 shows the traces of μ_{s_min}, μ_{s_max}, and μ_p versus cycles in HV. During the test, μ_{s_min} and μ_{s_max} had nearly stable values, 0.005 and 0.008, respectively. In first approximately 3000 cycles μ_p quickly rose from 0.008 to 0.024, and stayed on almost constant in following 51000 cycles.

During the test in HV, the COFs of test bearings kept below the test completion criterion of 0.05. This result indicates that the test bearings have also sufficient lifetime for TCM application in HV environment.

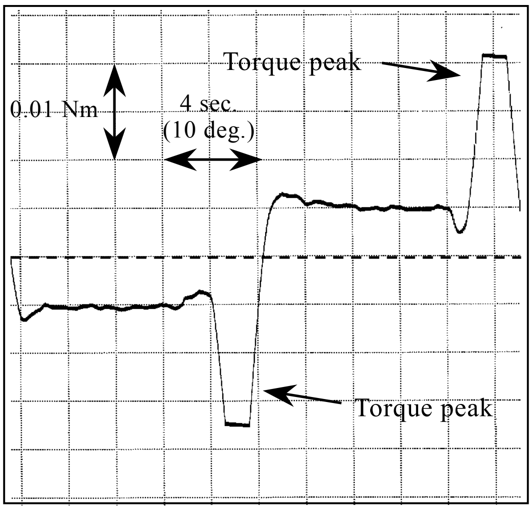

Fig. 8 Frictional torque curve
(at 54000 cycles, tested in HV)

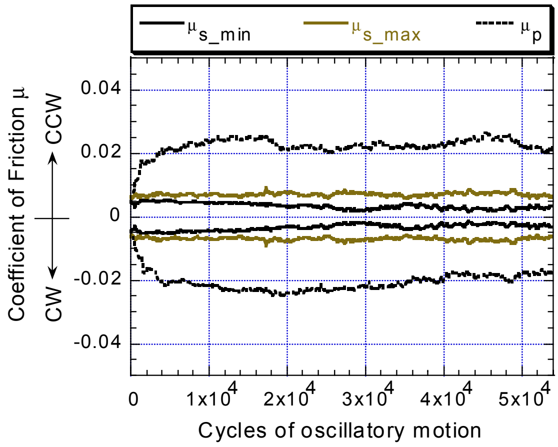

Fig. 9 COF traces vs. motion cycle (HV)

6. COMPARISON OF RESULTS

Figures 10 ~ 12 show the comparison of the characteristic-value-traces of COF measured in UHV and HV.

In Figs. 10 and 11 the traces of μ_{s_min} and μ_{s_max} measured in UHV is fairly overlapped with those measured in HV. This result indicates that the difference in environment pressure between UHV and HV did not affect the tribological performance of the bearings.

In Fig. 12, two traces of μ_p in CCW side are similar each other, whereas some difference are found in CW side. The reason of this difference has not been clear, but this may be caused by the slight difference in wear of sputtered MoS_2 film. The generation mechanism of the torque peak will be discussed in the following section.

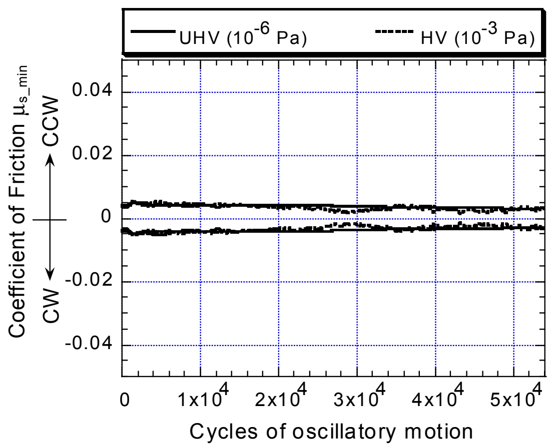

Fig. 10 Comparison of μ_{s_min}

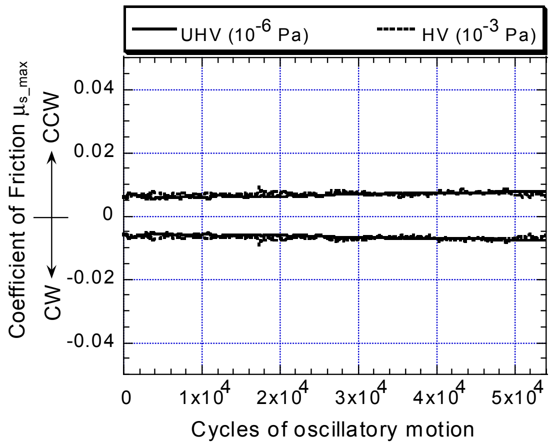

Fig. 11 Comparison of μ_{s_max}

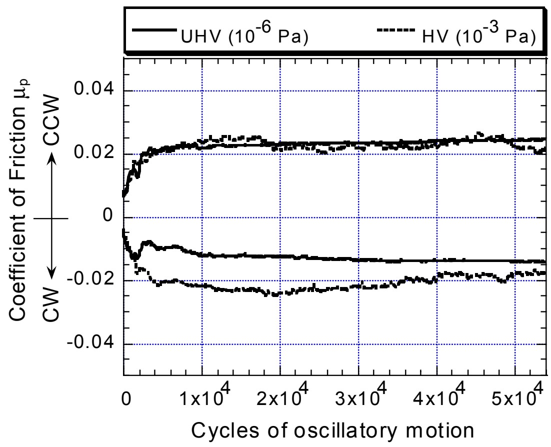

Fig. 12 Comparison of μ_p

7. REDUCTION OF TORQUE PEAK

During the oscillatory motion tests of the solid-lubricated bearings, the torque peaks were generated at both ends of CW and CCW motion as shown in Figs. 5 and 8.

After the oscillatory motion tests, the races, balls and retainers of the bearings were investigated with an optical microscope, SEM, EPMA and roundness-measuring device.

Figures 13 and 14 shows the roundness of inner and outer races after the test. On the surface of inner and outer races, 11 dents are clearly found.

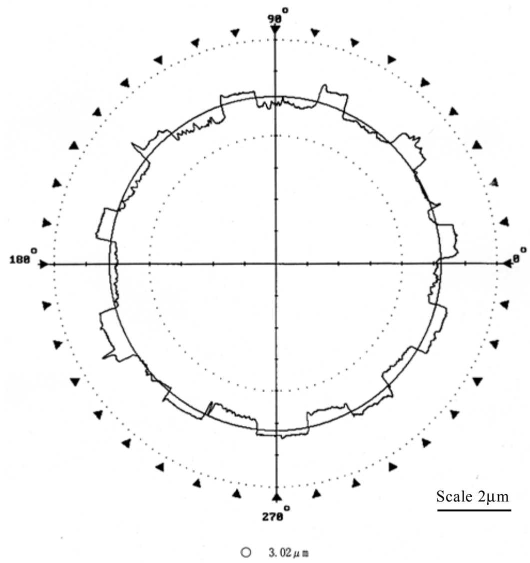

Fig. 13 Roundness of inner raceway
(tested in UHV)

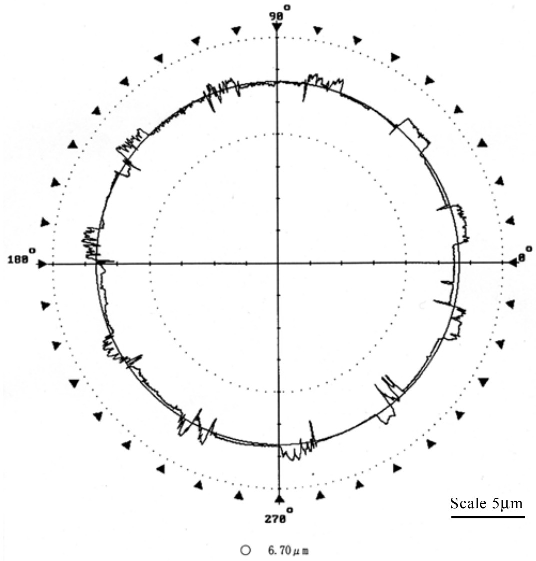

Fig. 14 Roundness of outer raceway
(tested in HV)

Their widths, about 10 degrees on the inner raceway and 15 degrees on the outer raceway, are well matched to the contact area numerically predicted from the bearing geometry and motion. Also, their depths about 1μm are almost the same as the initial thickness of the sputtered MoS_2 film. Therefore, these 11 dents are the wear areas of the pre-coated MoS_2 film due to the oscillatory motion.

Figure 15 shows the dent on a ball surface. A rectangular profile is seen on the surface. This dimension was identical to that of the dents on the inner and outer raceway.

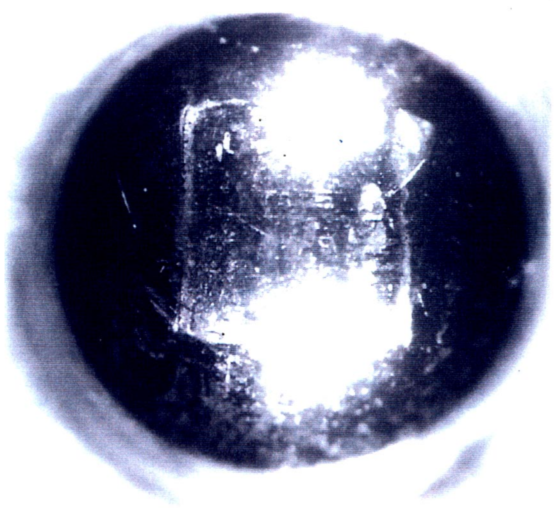

Fig. 15 Contact area on ball (tested in UHV)

According to these results, the torque peaks are considered to arise by the wear of the sputtered MoS_2 film and the build-up of the MoS_2 debris on the edge of the oscillatory motion area.

From this consideration and the fact that the torque peak became almost constant after about 3000 cycles of the oscillatory motion, shown in Fig. 12, it is expected that considerable MoS_2 film had been worn away within first approximately 3000 cycles. Also shown in Figs. 13 and 14, a remaining very thin MoS_2 film seems to support the long-term lubrication. They suggest that torque peaks may be reduced if the running-in equivalent to 3000 cycles of oscillatory motion is applied to the bearings before the test to reduce the unnecessary MoS_2 film. In order to confirm the effect of running-in to reduce the torque peaks, an evaluation test was carried out.

8. RESULT OF EVALUATION TEST

In the evaluation test, unidirectional rotating running-in was conducted before the oscillatory motion test of the bearings. Table 5 shows the conditions of running-in. The frequency of contact between a specific area on the inner or outer raceway and the ball during the unidirectional 1500 rotation is equivalent to that during the 3000 cycles of oscillatory motion.

Table 5 Conditions of running-in

Bearing motion	Unidirectional rotation
Angular velocity ω_0	2.5 deg/s
Axial load	240N
Number of rotation of the inner race	1500 rotations

Following the running-in, the lifetime test was performed in UHV under the conditions shown in Table 2. The environment of the running-in and the lifetime test is listed in Table 7.

Table 7 Test environments

Vacuum pressure	1.3×10^{-6} ~ 2.6×10^{-6} Pa
Temperature	21.9～ 23.7 °C

Figure 16 shows the comparison of μ_p traces. It is found that remarkable reduction of torque peaks was achieved, and running-in of 3000 rotations exerted no influence on the lifetime of the bearings. μ_p was reduced from 0.25 to 0.09 and this value was kept until 54000 cycles.

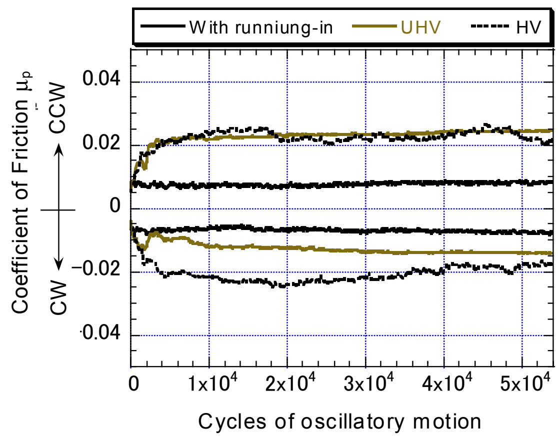

Fig. 16 Reduction of torque peak μ_p

Figures 17 and 18 show the roundness of the inner and the outer races after the test when the running-in was appended. The dents found in Figs. 13 and 14 are disappeared in Figs.17 and 18.

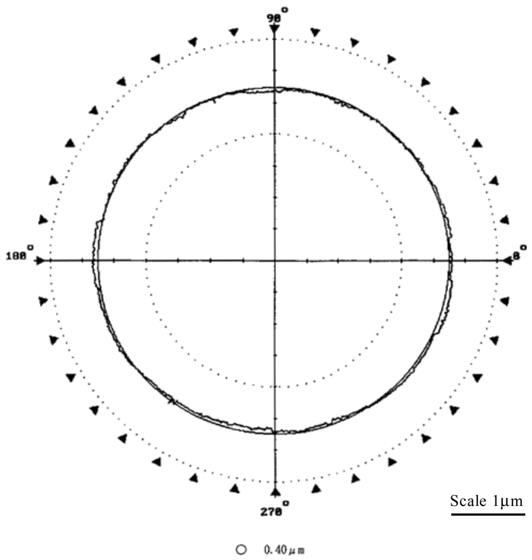

Fig. 17 Roundness of inner raceway
(with running-in)

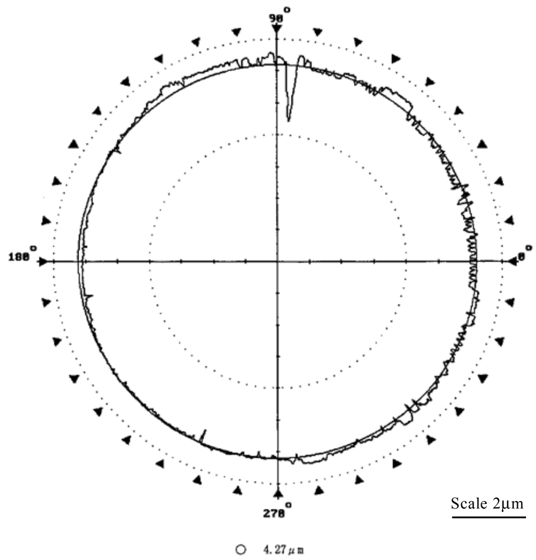

Fig. 18 Roundness of outer raceway
(with running-in)

9. CONCLUSIONS

From the results of lifetime tests of #7900 bearings, following conclusions were established.

(1) The #7900 bearings with a sputtered MoS_2 film exhibited very good performance at 10^{-6} Pa, indicating enough lifetime for TCM application.

(2) The frictional characteristic of the bearings in 10^{-3} Pa was almost identical with that in 10^{-6} Pa. From the tribological point of view, this result supports that the evaluation of TCM component in 10^{-3} Pa was reasonable and its result can be treated as equivalent to that in 10^{-6} Pa.

(3) Torque peaks appeared at the end of oscillatory motion due to wear of the pre-coated solid lubricant. Running-in process with continuous unidirectional rotation is very effective to reduce the torque peaks.

Following to the evaluation test reported here, some tests are proceeding to find more practical procedure of running-in.

10. ACKNOWLEDGEMENT

The authors express sincere thanks to Prof. Dr. Yoshitsugu Kimura of Kagawa University, and Mr. Kichiro Imagawa of NASDA for their useful suggestions on the planning of the tests.

Also appreciation is paid for Mr. Tetsuya Kikuchi and Mr. Kensuke Takahashi of Advanced Space Engineering Co., Ltd. for their effort on the proceeding of the tests.

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