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EVALUATION OF SCANNING EARTH SENSOR MECHANISM
ON ENGINEERING TEST SATELLITE IV

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ABSTRACT

This paper describes the results of the analysis and the evaluation of flight data obtained from the horizon sensor test project conducted jointly by National Aerospace Laboratory and National Space Development Agency of Japan and manufactured by Matsushita Research Institute, Tokyo, Inc.

The rotary mechanism of the scanning earth sensor composed of direct drive motor and bearings using solid lubricant is operated satisfactorily.

The transmitted flight data from Japanese Engineering Test Satellite IV have been evaluated in comparison with the design value and the rotary mechanism is forecasted to be used for a practical satellite.

INTRODUCTION

A scanning earth sensor (called HOST as abbreviation of HOrizon Sensor with Turning head) was originally designed as a roll/pitch attitude sensor of three-axis stabilized spacecraft. The HOST is one of the experimental equipments mounted on the Engineering Test Satellite IV (ETS-IV or 'Kiku 3') which was launched on February 11, 1981 from Tanegashima Space Center of National Space Development Agency of Japan into a transfer orbit with initial apogee and perigee heights of 36000 km and 223 km respectively and with inclination angle of 28.5 degrees.

In comparison with other earth sensors such as the radiation balance type and edge-track type, this conical scanning earth sensor is considered to be one of the main practical earth sensors for low and middle altitude because of its wide acquisition range and little influence to attitude change of spacecraft, but it is difficult to design its rotating mechanism, control its quality, and assure its reliability in general.

The ETS-IV spacecraft is spin-stabilized with nominal spin rate of 60 rpm and the nominal spin axis direction is perpendicular to the earth equatorial plane. The HOST has been tested not only as a horizon crossing indicator for spinning spacecraft, but also as a scanning earth sensor with the scanning axis parallel to the spinning axis.

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The experimental items of the HOST are as follows.

1. Performance change of rotating mechanism at space environment
2. Characteristic change of infrared optoelectronics in a space environment
3. Data acquisition at infrared input energy
4. Function and performance of attitude angle measurement by the HOST

The HOST has been operated during the primary mission term and the extended mission terms.

This paper describes the rotating mechanism of this HOST and the data analysis and evaluation of the flight experiments in the operating duration.

DESCRIPTION OF THE HOST

The HOST consists of three major components which are two rotary heads (HD1, HD2; Figure 1) and one electronic package. Each rotary head is mounted to both sides of the ETS-IV perpendicular to its spin axis direction. HD1 is on the spacecraft spin axis but HD2 is offset from its spin axis by 0.9 meters. For this reason, HD2 is affected by a centrifugal force of approximately 3.5 G towards the radial direction.

Each rotary head consists of an antireflection coated Ge lens, a pyroelectric infrared detector with an optical bandpass filter, a signal pre-amplifier and a motor for a rotating metal mirror. This rotary mechanism is composed of bearings using solid lubricant (Rulon C) and three phase direct drive motor (DD motor) using phase locked loop (PLL) control. The rotor magnet material of the DD motor is an anisotropic strontium ferrite.

The horizon crossing period of the instantaneous field of view (IFOV) is determined by detecting infrared radiation from the 14 to 16 μm CO_2 band using a narrow IFOV (about 1.4 degrees) conical scan with a cone angle of 120 degrees and rotating rate of 60 rpm. Pitch and roll angles are measured by using two conical scanning rotary heads.

The motors of either head can be turned on and off separately. When the motor is on, the total scanning speed is approximately (60+60) rpm at nominal spin rate and when it is off, it reduces to about 60 rpm, which is spacecraft spin rate.

The dimension and the weight of each rotary head are 160 mm x 230 mm, 3.2 kg respectively.

ROTARY MECHANISM

Figure 3 shows the structure of the HOST rotary head. The scanning mirror and the hollow shaft are driven by a three phase DD motor with a quartz stabilized PLL control which is to be at a constant rotation speed.

Bearing mechanism

A bearing mechanism has a preload structure to inner ring as shown in Figure 2 and has two angular ball bearings using a solid lubricant (Rulon C) retainer. This mechanism's merits are that it is small, easy to assemble and provides a wide distance of work points between two bearings. In order to minimize the precession caused by the HOST head rotation, clearance fit around two bearings was to be as small as possible.

Lubrication

An angular contact ball bearing is adopted and polymer composites having self lubrication are used with a retainer (Table 1). Lubrication is performed when a lubricant is transferred to a ball surface from a retainer by rotating bearings and is then transferred to a raceway of inner and outer rings from the ball surface. The most powerful reason why oil is not used is because the infrared optical system would be contaminated by the oil evaporation and adhesion. The reason why solid lubricant is used is because it is less volatile and less influenced by the large temperature changes and radioactivity of a space environment; this is important because of the HOST's rotating parts which are exposed. MoS₂ is a good lubricant in vacuum, but the ground test data in the air indicates it is not good because of weakness to moisture. Rulon C is a composite type lubricant of fiber reinforced PTFE (teflon) containing lead oxide (Pb₃O₄) and has been used in the Apollo Project of NASA.

This solid lubricant is characterized as follows.

1. Less contamination to the infrared optical system by means of low vapor pressure
2. Radiation resistivity
3. Fitness for use on the ground in the air
4. Comparative high load resistivity

GROUND TEST

An Engineering Model (EM), Protoflight Model (PM) and Flight Model (FM) of the HOST have been developed in turn, and the test levels of PM and FM are Qualified Test level (QT) and Acceptance Test level (AT) respectively (Table 2). Both HD1 and HD2 of the HOST-FM have been operated 20 hours in air and 110 hours in vacuum in the test at the factory, the acceptance test for each head and the inspection at the launching site.

It is confirmed that the measured data were of no difference between in the air and in vacuum of 10^{-5} Pa.

At higher temperature, the average motor torque will be larger, but the torque fluctuation will still be the same level. At larger acceleration, both the average motor torque and the torque fluctuation have larger values (Table 3). Stability of the operation is comparatively good for a short term (several tens of hours), but variations of the average motor torque and the phase jitter are 2.5×10^{-6} N·m, ± 0.076 deg. p-p ($\pm 1.2 \times 10^{-6}$ N·m when converted to torque), respectively, for a long term (several months).

OPERATING TEST ON THE SPACECRAFT

The operating test periods of the rotary mechanism on the ETS-IV are as follows.

1. Mission term (February 1981 ~ May 1981)
 - Continuous operating test (several tens of hours)
 - Function test
2. Extended mission term (May 1981 ~ February 1982)
 - Continuous operating test (several hundreds of hours)
 - Eclipse test
3. Extended mission term (second) (February 1982 ~ August 1982)
 - Continuous operating test (several thousands of hours)
 - Test in maneuvers of the spacecraft

The accumulated operating hours amount to about 4,500 hours for HD1, and about 4,000 hours for HD2 till August 1982. The orbital total hours including nonoperating time amount to about 18 months. The test is continuing.

DATA ACQUISITION

The data acquisition from the ETS-IV spacecraft is transmitted to the ground station by the PCM telemetry. The data of the motor coil current and jitter output are acquired once about 2 seconds and once about 32 seconds respectively. The variation within a short time can not be therefore observed.

Average motor torque:

The HD1 has been operated through about 4,500 hours in the temperature range from -34°C to 20°C and its average motor torque is stable at the value of

$4 \sim 8 \times 10^{-6}$ N·m (including iron loss). The HD2 has been operated through about 4,000 hours in the temperature range from -32°C to 25°C and its average motor torque varied from 1.10×10^{-5} to 2.65×10^{-5} N·m but these performance values were well within the limit value of 5×10^{-5} N·m (Figure 4). As HD2 is under stationary acceleration of about 3.5 G, its average motor torque is considered to be increased especially at high temperature in addition to the acceleration.

Motor torque fluctuation

The motor torque fluctuations for HD1 in the period of 20 ~ 30 min. were observed a few times at the beginning of this test schedule, but these phenomena were small and stabilized during the extended mission term. The fluctuations of the motor coil current are coincident with the data from the jitter (AC component) (Figure 5). There were no periodic motor torque fluctuations for HD2. A slight increase of its motor torque fluctuation was found at the middle of this test schedule, but this fluctuation was stable from that time on. The variations of these data are shown in Figure 5.

ANALYSIS AND EVALUATION OF BEARINGS

Table 4 shows the evaluation results of the average motor torque and the motor torque fluctuation including the ground test data. The iron loss is excepted from the average motor torque. The data of the motor torque fluctuation are obtained from the motor coil current output (AC component).

The average motor torque for HD1 varied once or twice from the ground test data, and the periodic variations were observed in the motor torque fluctuation for HD1 which was not found in the ground test data. The average motor torque and the motor torque fluctuation for HD2 are the proper values based on the ground test data.

Concerning the bearings using solid lubricant, temperature and acceleration factors make these characteristics change mainly in the ground test and loading test on the spacecraft. Adhesion that is doubtful especially in high vacuum ($10^{-6} \sim 10^{-11}$ Pa), is not a dominant factor to the solid lubrication in case of slow revolution and light load such as the HOST, but mechanical scratch on the raceway is considered to be a dominant factor mainly due to friction.

As for the motor torque fluctuation, ripple variations occurred, then subsided. This was not abnormal and was observed during the function test of the same type of bearings in the HOST. For the cases which used solid lubrication, the motor torque could be attributed to the fine differences in the adhesive state of the lubricant, mechanical contact state, mechanical accuracy, and surface roughness. Therefore, it is necessary to understand the lubrication properties and to choose the lubrication wisely.

Regarding the motor revolution accuracy, the phase jitter has a slightly large value of about 0.8 deg.p-p (max.) in contrast with the nominal value of 0.2 deg.p-p.

Encoding necessary for obtaining the chord width is the time measurement because the ETS-IV is a spinning spacecraft. This requirement is not essential if an optical encoder is adopted for practical use.

There were two unexpected events that occurred to the motors of HD1 and HD2. First, both HD1 and HD2 were stopped rotating three times by means of operating the current limiter for hours in the continuous operating test. Second, the motors were not driven in the long period eclipse test when HD1 and HD2 were exposed to low temperature below the designed value. In both cases, the motors of HD1 and HD2 were recovered and normally operating after these events. These events were unaccountable by means of no data acquisition when the events were occurred.

Long period eclipse test

A long period eclipse test has been performed during the extended mission term to investigate the characteristics of the rotary mechanism at the large temperature change. This test has been also performed to investigate the temperature change rate dependence of the rotary mechanism by continuously rotating the motor for the eclipse of 90 min. period over maximum eclipse time on the geostationary orbit (about 72 min.). It is shown that HD1 is hardly affected by the temperature change rate of 21°C/hr. and HD2 has large values of the average motor torque of $1.3 \sim 2.2 \times 10^{-5}$ N·m and the motor torque fluctuation of 1.3×10^{-5} N·m by the temperature change rate of 13°C/hr., but a PLL cycle slip does not occur for HD2.

Test in maneuvers of the spacecraft

Maneuvers of the spacecraft have been carried out for the purpose of the interference test by the Sun to the infrared optoelectronics. The motor for HD1 was operating in these maneuvers and the characteristics were observed in case of vibrations. The motor characteristics did not change and had a good operation before/in/after the maneuvers.

EVALUATION OF OTHER LUBRICATION

The long life study of the HOST (HOST-LL) was performed in addition to the lubrication results of the HOST. Several sorts of retainers were attached to the same type bearings of the HOST (a part of bearings have a raceway of inner and outer ring and balls sputtered with MoS₂) and a life test was performed with a revolution of 2,000 rpm and preload of 5 kg in high vacuum ($10^{-6} \sim 10^{-7}$ Pa) and atmospheric pressure. The results show that the bearings using Rulon E have a small average friction torque and are good for the life test over 1,000 hours. Rulon E is composed of PTFE and MoS₂. The bearings assembled along with a Rulon E retainer and a raceway of inner and outer ring and balls sputtered by MoS₂ (0.5 \sim 1.0 μ m) are

stable at small friction torque ($4 \sim 5 \times 10^{-6}$ N·m) and small friction loss of retainer. So these bearings exceed the target total revolution of 1.6×10^8 , which is equivalent to the life of the HOST-LL over 5 years.

It is concluded that about one-third of the HOST's average friction torque will occur, given the structure of the HOST-LL and a preload of 2 kg (Table 1).

The friction torque contains dispersive fluctuation and ripple fluctuation and so on. These fluctuation sources are mainly considered to be retainers from the test described above (Figure 6). It is necessary to investigate the following items more clearly.

1. Shape and size of retainers
2. Processing of retainers
3. Uneven materials of retainers
4. Roughness and shape of raceway and balls

It is also necessary to investigate bearings sufficiently for the limit value and design life.

CONCLUSION

Some problems are left unsolved for now, but the rotary mechanism system of the HOST has reached the expected goal through the mission term and the extended mission term. It is shown that the rotary mechanism system using solid lubricant is adequate for space applications.

REFERENCES

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2. Y. Wakabayashi et al. AIAA Guidance and Control Conference, San Diego (1982)

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Table 1. Bearings specifications and structure of the HOST and the HOST-LL

	Items	HOST	HOST-LL
Structure	Method of preload	Preload to inner ring	Preload to outer ring
	Preload	1.5 kg	2 kg
	Clearance fit (between axis and inner ring)	25 μm	5 μm
	Clearance fit (between housing and outer ring)	10 μm	5 μm
Bearings	Grouping	Angular contact ball bearings using solid state lubricant retainer	
	Design	7204C base	
	Ball materials	SUS 440C	SUS 440C
	Retainer materials	Rulon C	Rulon E + MoS ₂
	Inner radius	35 mm	35 mm
	Contact angle	15°	15°
	The number of balls	15	12

Table 2. Test level of the HOST rotary head

	Vibration test		Thermal test in vacuum	Acceleration
	Sine wave	Random		
EM	5.3 G _{o-p} max.	13.1 Grms 60 s.	-20 ~ +50 °C	0 ~ 10 G
PM (QT)	5.3 G _{o-p} max.	19.6 Grms 90 s.	-30 ~ +50 °C	0 ~ 5 G
FM (AT)	—	13.1 Grms 60 s.	-20 ~ +40 °C	0 ~ 5 G

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Table 3. Ground test results for the HOST-FM

Test	Condition	Average motor torque ^{a)}		Torque fluctuation ^{b)}	
		HD1 ^{c)}	HD2 ^{d)}	HD1 ^{c)}	HD2 ^{d)}
Temperature	-21 °C	1.75	5.25	2.4	7.8
	+19 °C	2.5	6.0	1.8	3.0
	+36 °C	3.0	12.5	1.2	2.4
Acceleration ^{e)}	1 G		2.5 ~ 3.0 ^{c)}		1.2 ^{c)}
	3.5 G		18 ~ 23.5 ^{f)}		9.6 ~ 15.6 ^{f)}

- unit ; $\times 10^{-6}$ N·m
- a) The data with the exception of iron loss (2×10^{-6} N·m)
- b) The data from the HOST jitter output
- c) Thrust direction (1 G / earth gravity)
- d) Radial direction (1 G / earth gravity)
- e) Room temperature in the air
- f) Radial direction

Table 4. Evaluation data for the HOST bearings

	Average motor torque ^{a)}		Torque fluctuation	
	HD1	HD2 ^{b)}	HD1	HD2 ^{b)}
Ground test	1.8 ~ 3.0	18.0 ~ 23.5	1.0 ~ 3.0	10.0 ~ 14.0
Mission term	2.0 ~ 3.0	9.0 ~ 15.0	2.0 ~ 12.0	2.0 ~ 6.0
Long period test	3.0 ~ 3.5	13.0 ~ 18.0	2.0 ~ 7.0	6.0 ~ 9.0
Eclipse test	3.0	13.0 ~ 22.0	5.0	13.0
Long term	3.0 ~ 6.0	14.0 ~ 25.0		

- unit ; $\times 10^{-6}$ N·m
- a) The data with the exception of iron loss (2×10^{-6} N·m)
- b) Measured value at the stationary acceleration (3.5 G)

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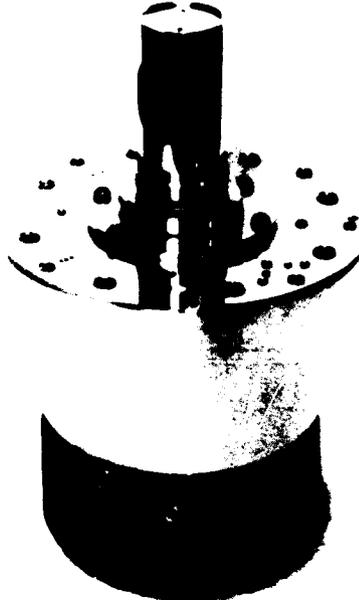


Figure 1. Rotary head of the HOST

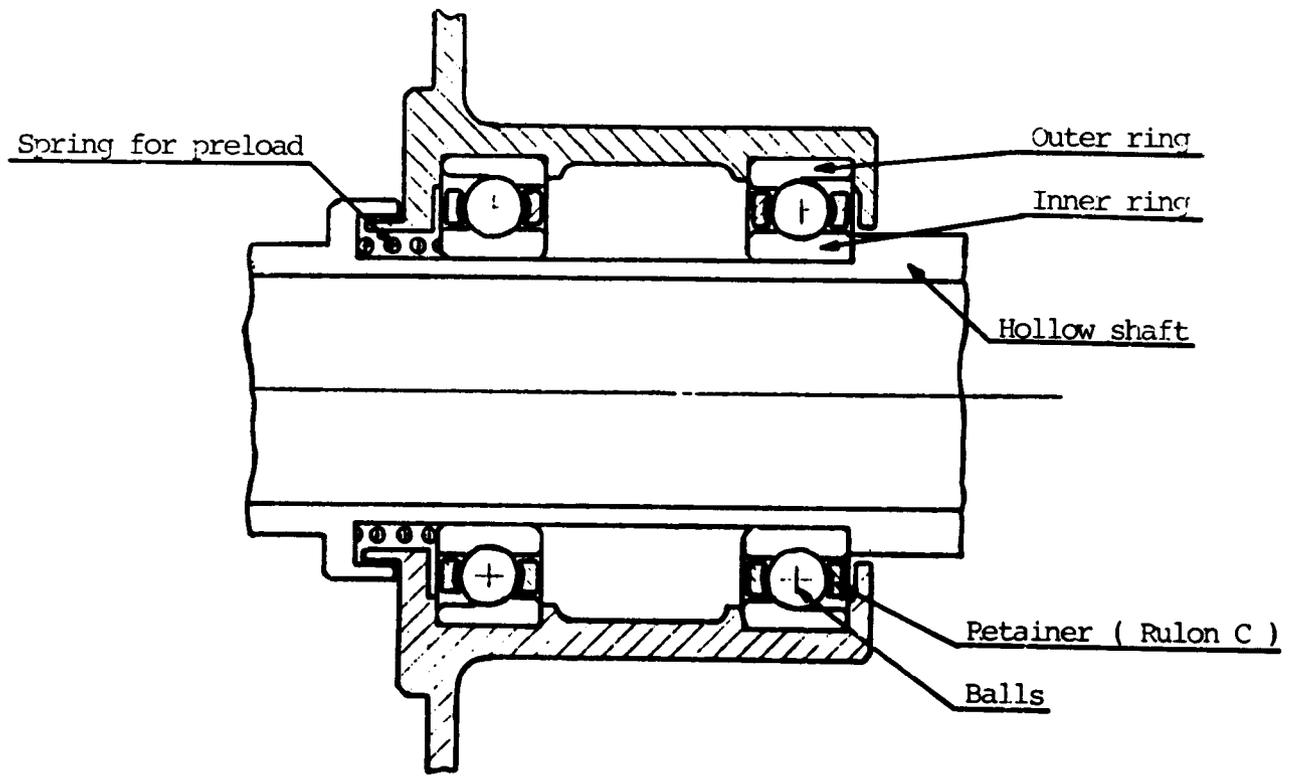
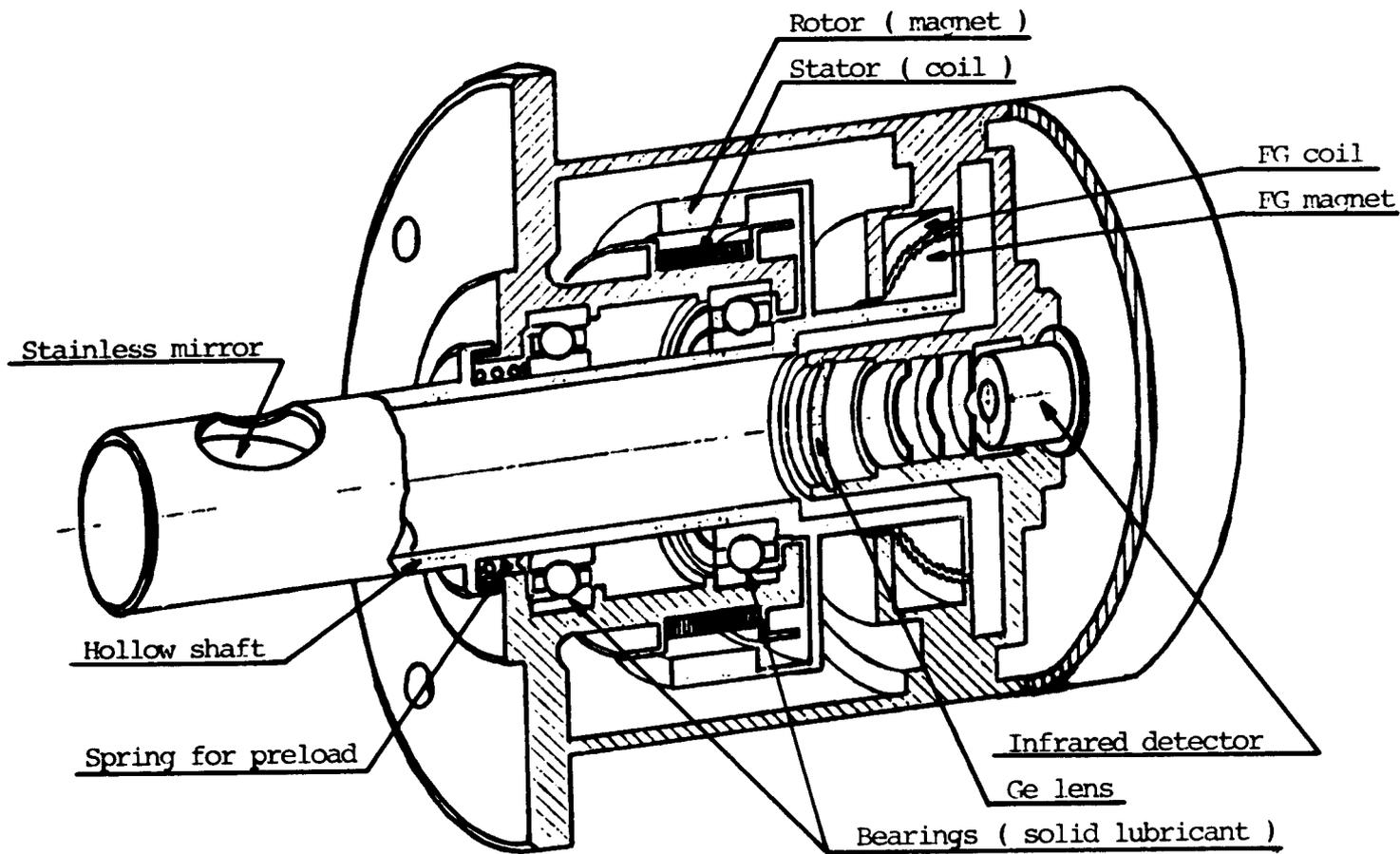


Figure 2. Method of preload



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Figure 3. Structure of the HOST rotary head

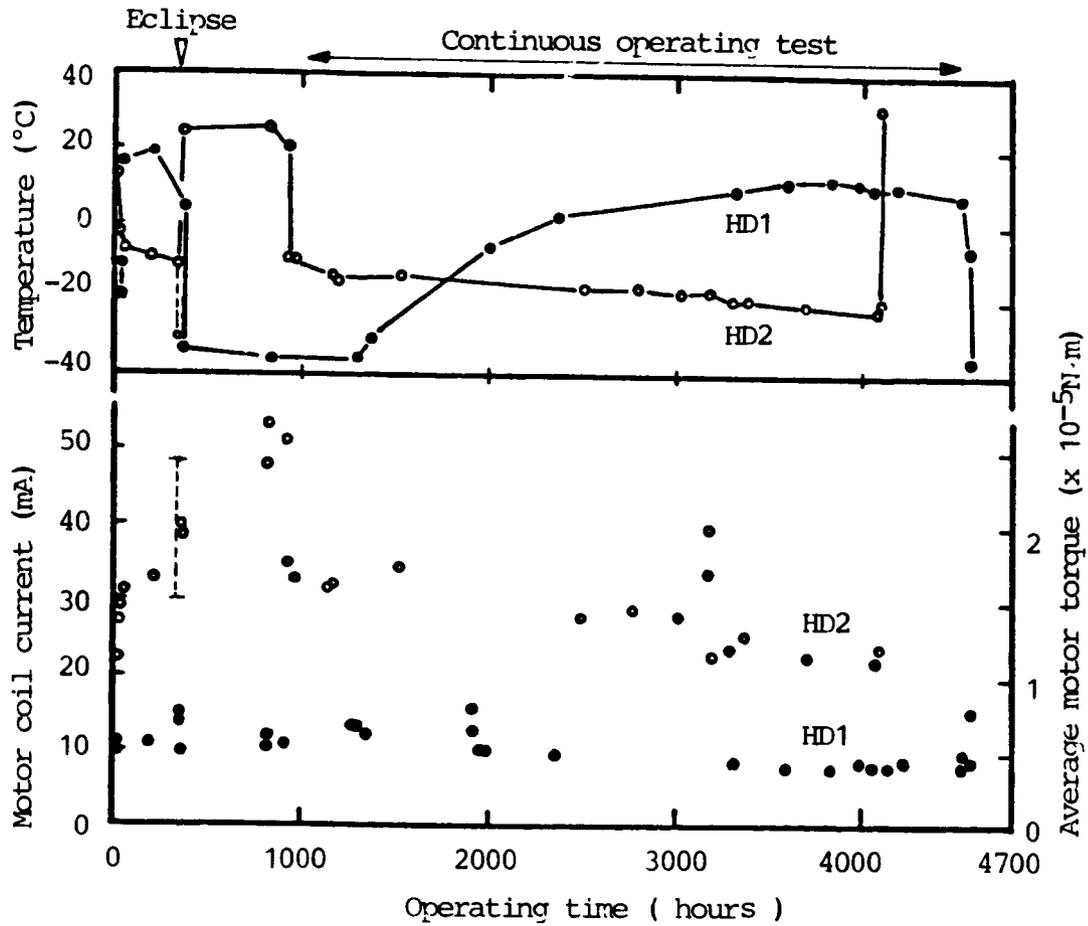


Figure 4. Changes of the average motor torque

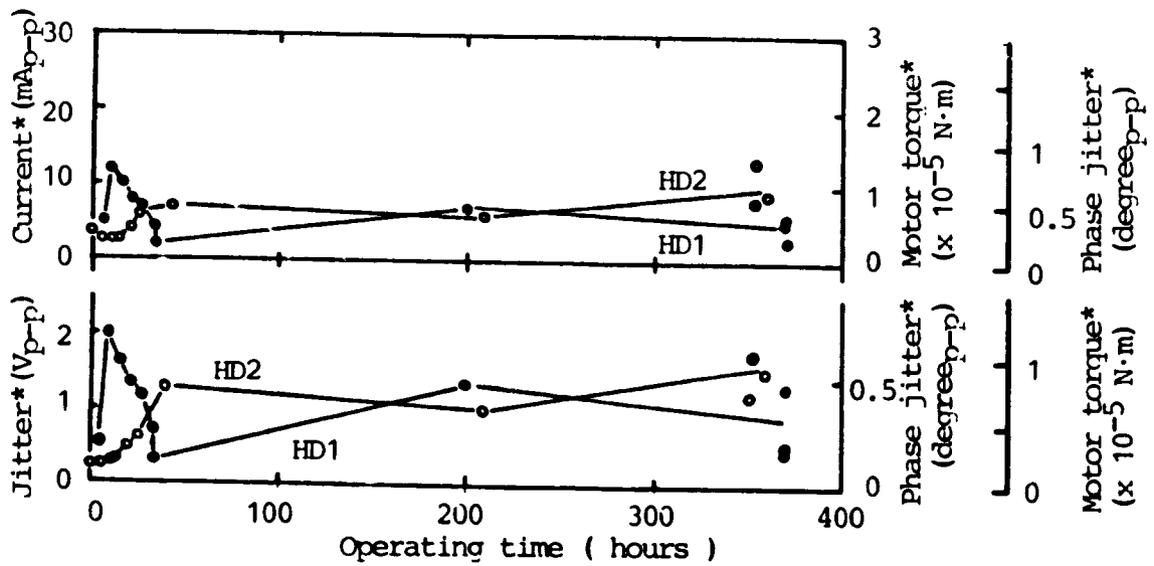


Figure 5. Changes of the motor torque fluctuation
(* mark shows the data of fluctuation)

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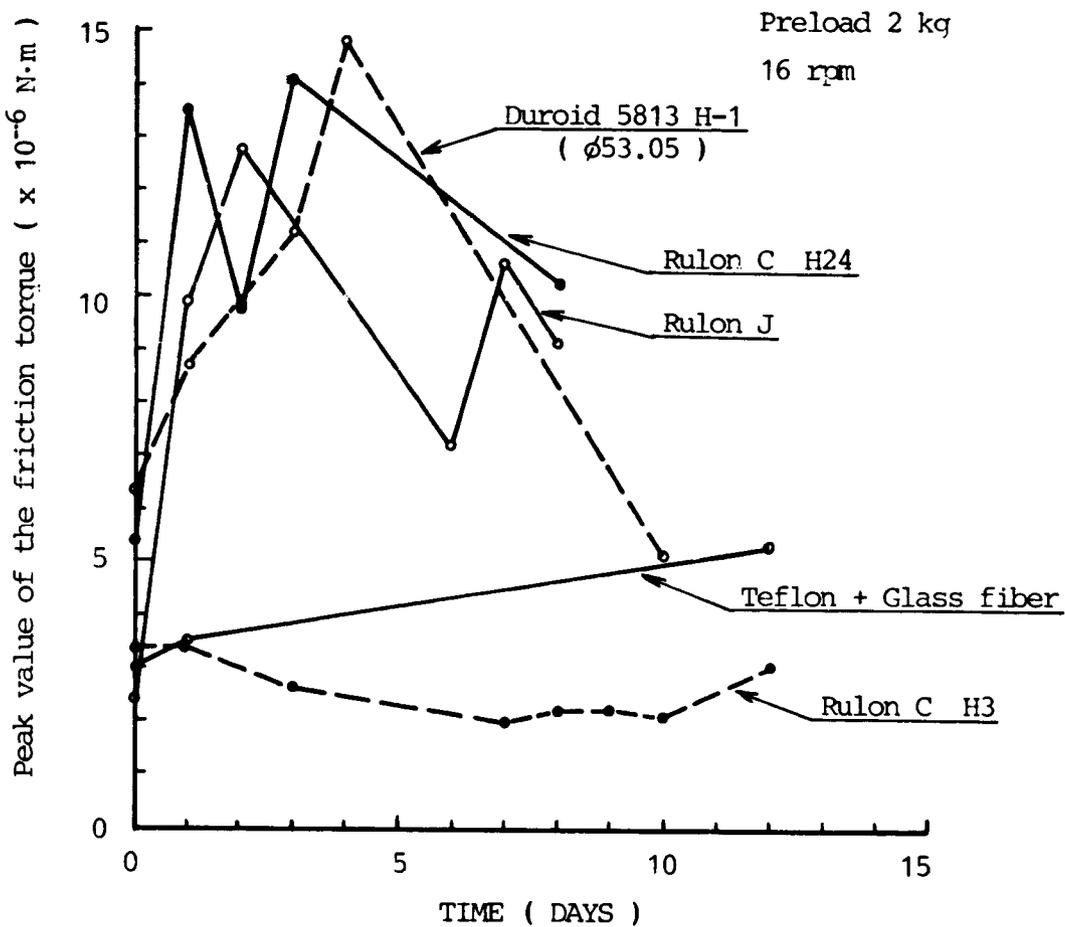


Figure 6. Bearing test of all sorts of retainers
(Equivalent parts of the HOST bearings)