DEVELOPMENT OF STRAIN WAVE GEARING FOR SPACE APPLICATIONS

Keiji Ueura(1), Yoshihide Kiyosawa(1), Jun'ichi Kurogi(1), Satoru Kanai(1), Hiroshi Miyaba(2), Kazuaki Maniwa(2), Mineo Suzuki(2) & Shingo Obara(2)

(1)Harmonic Drive Systems, Inc.
1856-1 Hotakamaki, Azumino-shi, Nagano 399-8305, JAPAN
Telephone: (81) 263-83-6917/ Fax: (81) 263-83-6804
E-mail: keiji.ueura@hds.co.jp

(2)Japan Aerospace Exploration Agency (JAXA)
Tsukuba Space Center, 2-1-1 Sengen, Tsukuba-shi, Ibaraki 305-8505, JAPAN
Telephone: (81) 29-868-2320 / Fax: (81) 29-868-2978
E-mail: maniwa.kazuaki@jaxa.jp

ABSTRACT

Strain wave gearing (SWG), also known as harmonic drive gear, has been used in many space applications which require lightweight and compact mechanical components. Especially, dry lubricated type SWGs have been used for Japanese satellites and have established many actual flight results. Recently, emphasis has been shifting from the dry lubricated type to the grease lubricated type, which can yield cost savings and longer life. However, the lifetime of the grease-lubricated type under space flight conditions has still not been verified enough.

In 2003, development of the grease lubricated type SWG for space flight applications was begun. In this paper, we describe results of the development and research on lubrication mechanism for the SWG under vacuum.

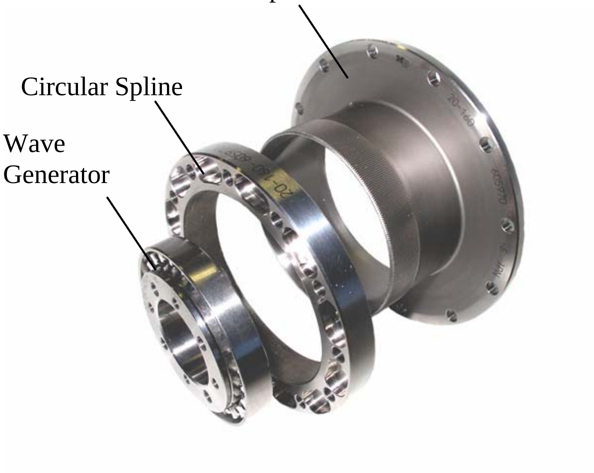

Figure 1. SHF type strain wave gearing

1. INTRODUCTION

In 2003, SWG was selected as a high-priority component to be developed by JAXA under activity of the JAXA Committee on Space Component Technology [1]. JAXA selected Harmonic Drive Systems, Inc. for the development of SWG for space applications. It was developed to achieve longer useful life and lighter weight of components than those of existing dry lubricated type SWGs.

In parallel to the development, basic research on lubrication mechanisms for the SWG was carried out by JAXA in cooperation with Tokyo Metropolitan Institute of Technology [2].

2. STRAIN WAVE GEARING

The SWG principle is unique in transmitting high torque through an elastically deformable component. The gear has just three concentric elements:

- The Circular Spline (CS) is a rigid ring with internal teeth, engaging the teeth of the Flexspline across the major axis of the Wave Generator.
- The Flexspline (FS) is a non-rigid, thin cylindrical steel cup with external teeth on a slightly smaller pitch diameter than the CS.
- The Wave Generator (WG) is a thin raced ball bearing fitted onto an elliptical plug serving as a high-efficiency torque converter.

These three basic components function in the following manner:

1. The FS has a slightly smaller diameter than the CS and usually has two fewer teeth than the CS. The elliptical shape of the WG causes the teeth of the FS to engage the CS at two regions at opposite ends of the major axis of the ellipse.
2. As the WG (input) rotates, the zone of tooth engagement travels with the major axis of the ellipse.
3. For each 180° clockwise movement of the WG, the FS (output) moves counterclockwise by one tooth relative to the CS (fixed).
4. Each complete clockwise rotation of the WG results in the FS moving counterclockwise by two teeth

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from its previous position relative to the CS.

The reduction ratio is therefore not a function of the relative sizes of the toothed components, as is the case for spur gears or planetary gears, but simply of the number of teeth.

$$i = \frac{n_{fs}}{n_{cs} - n_{fs}}$$

In that equation,

i = reduction ratio (input speed/output speed)
n_{cs} = number of CS teeth
n_{fs} = number of FS teeth

3. REQUIREMENTS

Tab. 1 shows requirements of the SWG for this development.

4. SPECIFICATIONS OF SWG

Considering that the major application of the SWG for space applications is a paddle drive mechanism and an antenna pointing mechanism, the SHF-type SWG with a hollow shaft shape was selected as a product for development (Fig. 1 and Fig. 3). Made of stainless steel to prevent rust (Tab. 2), its size is 20 (the tooth pitch circle diameter is 2 inches) which is currently the most used for space applications. Its gear ratio is 160:1, which is the largest ratio among standard ratios was selected because it is generally operated at very low speed in space applications. The SWG model number is “SHF-20-160-2A-GR-SP”.

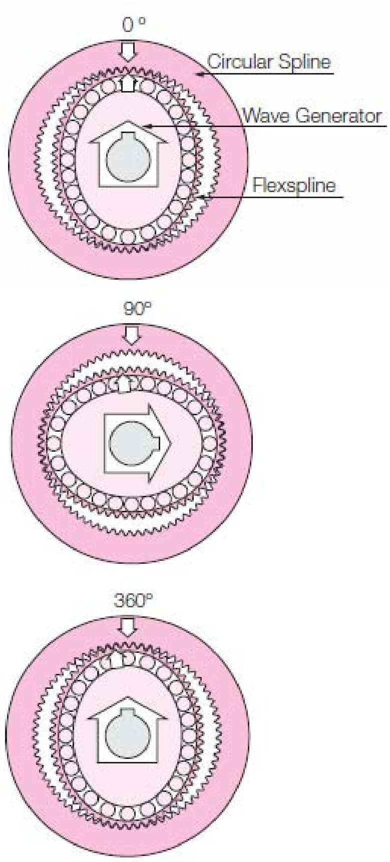


Figure 2. Principle of operation

Table 1. Requirements of SWG for this development

Characteristics	Requirement
Transmission accuracy	<30 arc-sec.
Spring rate	>1.38 × 10^4 N·m/rad at 7 N·m of load torque
No-load starting torque	< 3.6 cN·m Temperature: room temperature
Efficiency	> 50 % Lubrication: grease Temperature: room temperature Input speed: 50 r/min Load torque: 10 N·m
Gear ratio	160:1
Limit for momentary peak torque	92 N·m
Vibration resistance	Random: X, Y, Z axis 5 to 2000 Hz, 21Grms, 180 s Sinusoidal: X, Z axis 10 to 100 Hz, 25G
Thermal vacuum cycle resistance	Temperature: higher side of thermal cycle +80+5/-0 °C lower side of thermal cycle -10+0/-5 °C Vacuum pressure: less than 10^{-4} Pa Cycle number: 8 cycles
Life (Total output rotation)	Ground test: >10,000 rev. On orbit: >1,000,000 rev.
Lubrication	Multiply alkylated cyclopentane (MAC) grease

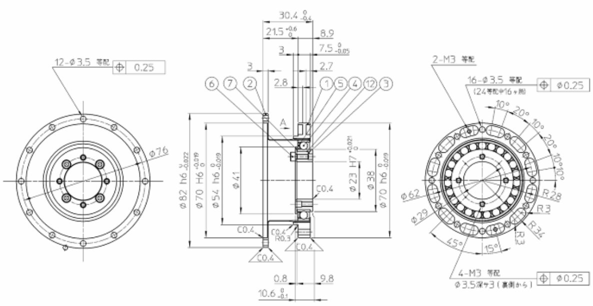


Figure 3. Configuration of the SWG

Table 2. SWG materials

Part	Material
Circular Spline	SUS630 stainless steel
Flexspline	15-5PH stainless steel
Wave Generator Plug	SUS630 stainless steel
Wave Generator bearing	SUS440C stainless steel
Wave Generator bearing separator	Phenolic resin
Retainer stopper	SUS304L stainless steel
Cap screw	SUSXM7 stainless steel

Table 3. Grease application part and quantity

Grease application part	Quantity [g]
Races and balls of WB	0.1 +/-5%
Outside of outer race of WG	0.2 +/-5%
Inside of FS	0.2 +/-5%
Tooth of FS	0.3 +/-5%
Tooth of CS	0.3 +/-5%

The teeth of CS and FS, between FS inside and WG outside and between races and balls of WG bearing (WB), are lubricated by multiply alkylated cyclopentane (MAC) grease. The WB separator is made of cotton-based phenolic resin; it is impregnated with MAC oil in vacuum. The grease application part and the quantity are presented in Tab. 3.

5. VALIDITY OF THE ACCELERATED TEST

It is very difficult to perform the life test using identical conditions to those encountered in actual space flight applications because SWG is usually operated at a quite low speed in space flight applications: more than 10 years would be needed to confirm its life.Consequently, we must verify its life using the accelerated test.

To verify the validity of the accelerated test in speed, we confirmed the effects of the input speed against the life by differences of wear between some kinds of input speed after running the test in atmospheric conditions. Four input speeds were selected for the test: 5, 50, 100, and 500 r/min. After running tests of input total revolutions of 1×10^6, a difference in the wear conditions between those of the contacted area of the FS inside surface and the WG outer race were apparent.

Fig. 4 shows the surface profile of the FS inside wall at each input speed. For 5 r/min, slight wear is apparent on the whole contacted area with WG outer race. In the other input speed, the wear is concentrated on the contacted part with both shoulders of the WG outer race. In an actual space flight application, SWG is usually operated at very low input speeds such as several revolutions per minute to tens of revolutions per minute. Although we were unable to perform the life test at 5 r/min because of the test duration, we chose 100 r/min as

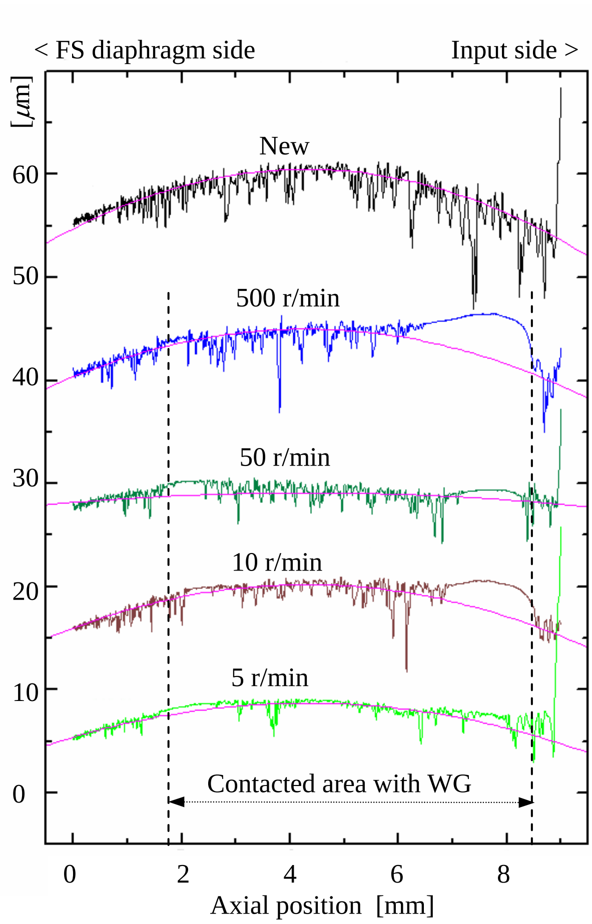


Figure 4. Surface profile of FS inside wall after running test in atmosphere

a valid input speed for the life test because the wear mode at 10 r/min to 500 r/min is similar.

6. QUALIFICATION TEST

Following the engineering model (EM) test, qualification model (QM) test was performed to verify whether the SWG satisfied requirements. The QM test condition was decided considering the EM test; it is indicated in Tab. 4.

6.1. Initial performance test

The QM unit was assembled into a test jig which was made for this development; it was assembled in the test jig all through the QM test. To check the initial performance the transmission accuracy, spring rate, no-load starting torque, and efficiency were measured. The test results are presented in Tab. 5.

6.2 Vibration test

A vibration test, thermal vacuum test, and life test were

Table 4. QM test condition

Test	Item and condition
Initial performance test	Transmission accuracy Spring rate No-load starting torque Efficiency
Vibration test	Random vibration: X, Y, Z axis 5 to 2000 Hz, 21Grms, 180 s Sinusoidal vibration: X, Z axis 10 to 100 Hz, 25G, 2 oct/min
Thermal vacuum test	Temperature: higher side of thermal cycle +80 +5/-0 °C, 1 h lower side of thermal cycle -10 +0/-5 °C, 1 h Vacuum pressure: less than 10^{-4} Pa Cycle number: 8 cycles
Life test	Load torque: +/-14 Nm (sinusoidal) Input speed: 100 r/min (continuous) Temperature: room temperature Vacuum pressure: less than 10^{-4} Pa

Table 5. Initial performance test result

	Specification	Actual value
Transmission accuracy [arc-sec.]	< 30	CW: 23 CCW:25
Spring rate K1 [$\times 10^4$ N·m/rad]	> 1.40	1.79
No-load starting torque [cN·m]	< 3.40	CW: 1.28 CCW:1.72
Efficiency [%]	> 50	CW: 71.4 CCW: 67.1

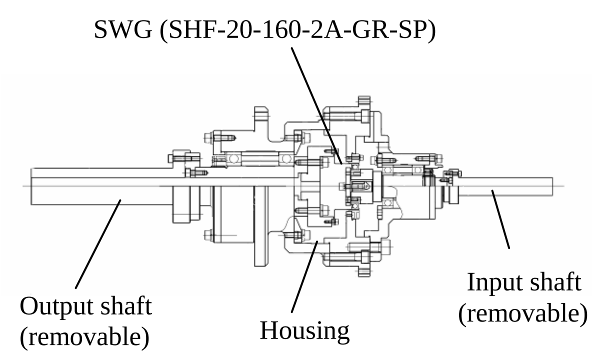
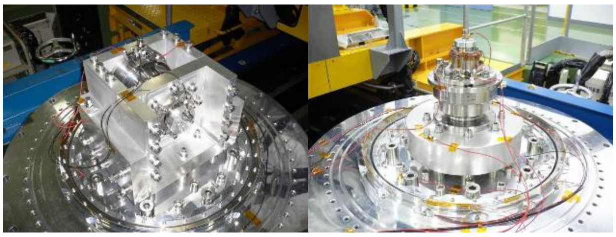


Figure 5. Test jig

carried out at the test facility of JAXA Tsukuba Space Center (TSC).

The QM unit was loaded with vibration according to the test conditions indicated in Tab. 4. The effect of vibration on the SWG peformance was estimated through comparison of the performance data, starting torque, and



(a) X-axis and Y-axis *(b)* Z-axis

Figure 6. Vibration test jig and equipment

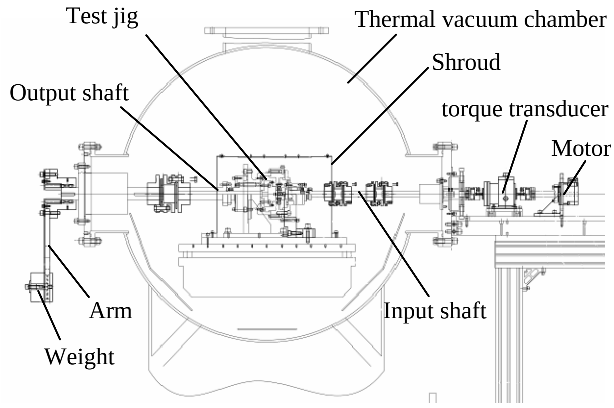


Figure 7. Thermal vacuum test equipment

efficiency before and after the test; no considerable difference between the data before and after testing was found.

6.3. Thermal vacuum test

The thermal vacuum test was performed to evaluate the effects of thermal vacuum environment. After the vibration test, the SWG and test jig were placed in the thermal vacuum chamber. That assembly was exposed to a thermal vacuum environment according to the test condition shown in Tab. 4. The effect of thermal vacuum environment on the SWG peformance was estimated through comparison of its performance data before and after the test; no considerable difference between the data was apparent.

6.4. Life test

Following thermal vacuum testing, a life test was carried out. A sinusoidal torque was loaded using an arm and weight on the output side. During the life test, the input torque was recorded at 0, 90, 180, and 270 deg at the output arm. The end of life was defined as the input torque increasing 50 %. The test conditions are as indicated in Tab. 4. The input torque of the SWG fluctuated at the early stage of the life test; it was stable after that. The input torque began to rise from the vicinity beyond 33,000 output revolutions and it increased 50 % to the initial value in 34,996 output revolutions. Then the test was stopped. Fig. 8 shows the

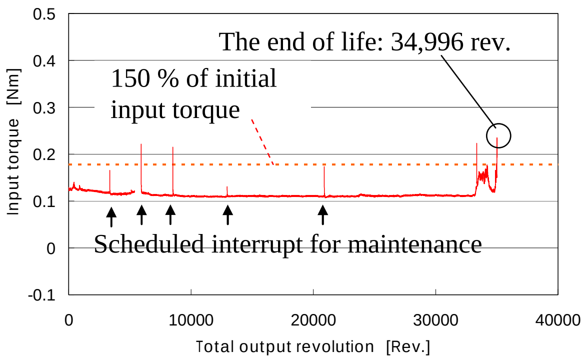
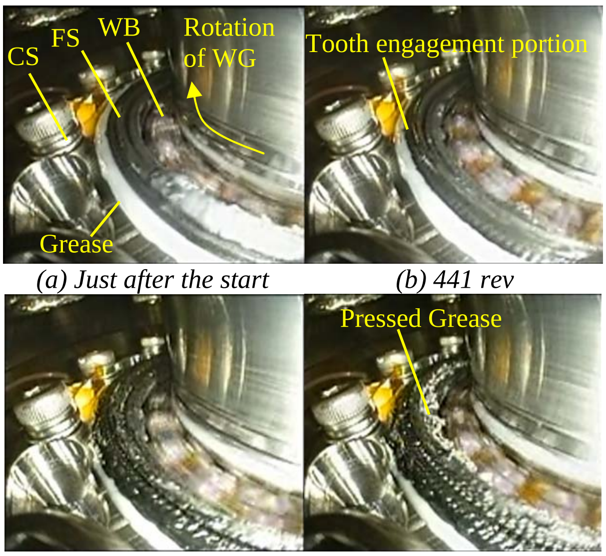


Figure 8. Input torque during life test
(at 90 degree of the arm angle)



(a) Just after the start *(b) 441 rev*

(c) Approx. 33,200 rev *(d) the end of life*

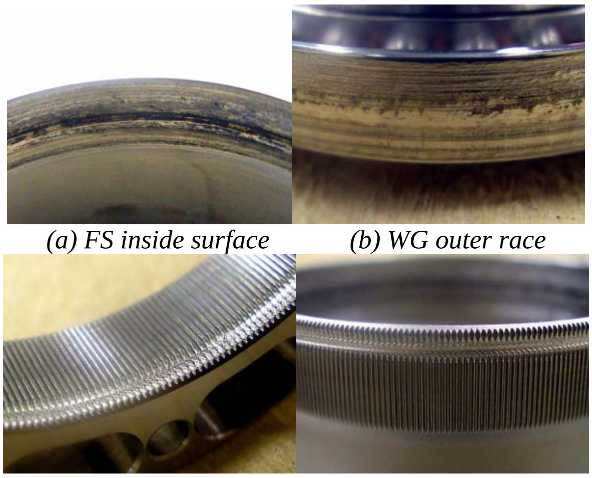
Figure 9. Inside of the test jig observed by fiberscope

input torque of 90 deg of the arm angle (maximum torque in the sinusoidal load cycle) during the life test. Some peaks of the input torque that are on the graph were by the restart when stopping for maintenance of equipment, and it was not used for judgment of the life.

Fig. 9 shows conditions of the input side tooth end and WB in the test jig observed using a fiberscope. Wear conditions of each rubbing surface of the QM unit after the test are shown in Fig. 10.

Remarkable wear is visible on each rubbing surface of the QM unit. The FS and WG were worn intensely on the input side and the wear reaches 60 μm at a deep part. The input sides of the tooth of the CS and FS were also worn away such that a tooth disappears.

Interior observations using a fiberscope after the increase in the input torque revealed that the grease between the WG and the FS was pressed out, and the protruding grease was darkened. Apparently, metal powder which was formed by wear of the rubbing surfaces mixed in the grease. It was observed that an end of the FS tooth was protruding periodically from an end face of the CS. This protrusion occurred because the FS was deformed elastically by axial force between the WG and the FS. The axial force depends largely on the lubricating condition and the applied load torque. It is considered from the surface damage of the WG and the FS shown in Fig.10, that the lubricating condition between them deteriorated during operation and very high axial force was loaded on the WG and the FS. It seems that lubrication of WG/FS interface is a crucial factor governing the life of SWG.



(a) FS inside surface *(b) WG outer race*

(c) CS teeth *(d) FS teeth*

Figure 10. Condition of rubbing surface after life test

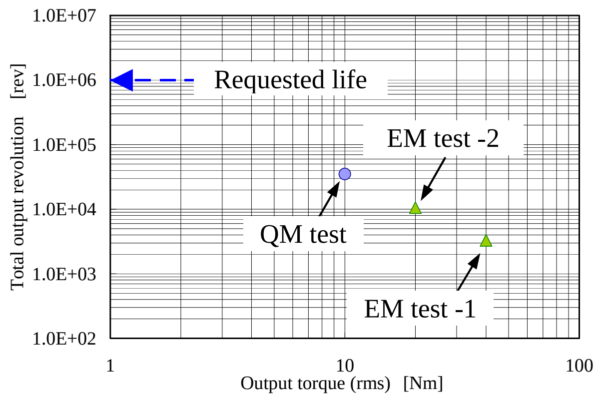


Figure 11. Results of EM and QM life tests

Fig.11 presents the results of the QM life test and EM life tests carried out before QM testing. The load torque of EM life test was a continuous load and the input speed was 500 r/min, which differs from those of the QM life test. The vibration test and the thermal vacuum test were also carried out before the life test in EM test -1 and EM test -2. The data shows that the requested life for the SWG can be achieved in some torque region under vacuum.

7. LUBRICATION MECHANISM OF SWG

Referring to the authors' experiences, the in-vacuum lives shown in Fig. 11 were remarkably short compared to the case of general use in atmosphere conditions. Most SWG operated in atmosphere reaches its life because of a rolling fatigue of WB or a worn-out of FS tooth. For the SWG tested in vacuum, however, the damage at the WG/FS interface was most remarkable. In this section, the effect of the environmental pressure on the lubricating conditions of SWG was investigated. The cause of the shortened life in vacuum operations is discussed.

7.1. Experimental apparatus

The lubricating condition of SWG was characterized by the lubricant film formation between moving mechanical parts of SWG. For this work, the contact electric resistance technique was applied. The experimental apparatus is shown in Fig. 12 [3]. A test SWG was assembled inside the test jig. The load torque to the output shaft was applied by the rotating arm placed outside the vacuum chamber. Output voltages for monitoring the lubricating conditions were derived to the outside the chamber through the rotating shafts and two slip-rings. The environmental pressure in the vacuum chamber was changed between 3×10^{-3} Pa and 10^{5} Pa by laboratory air purging. The SWG and its lubricant used in the experiment were the same as those in the development test.

Figs. 13 (a) and 13 (b) show the circuit for contact resistance measurements. The WG, FS, and CS were electrically isolated and the contact electric resistances were measured at three moving combinations: between inner and outer races of WB, between the WG outside surface and the FS inside surface, and between the FS teeth and CS teeth. By the measurement of voltages V_{io}, V_{of}, and V_{fc}, the degree of surface separation at each moving interface is separable into three regimes from the voltage- resistance relationship in Fig. 13 (c); (1) 0 mV, continues metallic contact (boundary lubrication); (2) 0 - 49.5 mV, partial metallic contact (mixed lubrication); and (3) 49.5 mV, complete separation (hydrodynamic lubrication).

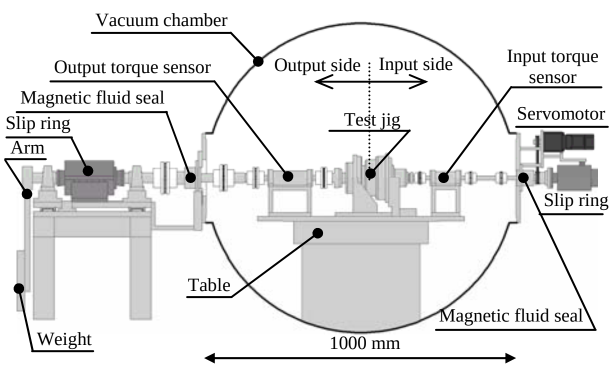
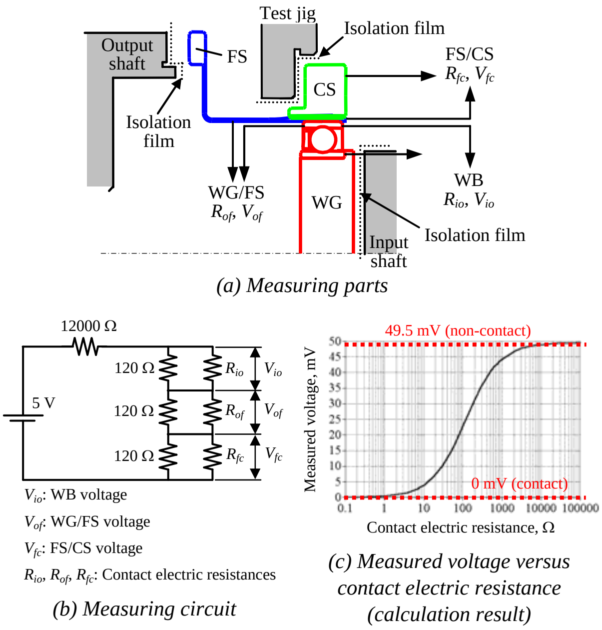


Figure 12. Schematic of experimental apparatus



(a) Measuring parts

(b) Measuring circuit

(c) Measured voltage versus contact electric resistance (calculation result)

Figure 13. Measuring method of contact electric resistances in SWG

7.2. Experimental results

Fig. 14 shows the typical measured voltage in vacuum (3×10^{-3} Pa) and in atmosphere for the case at an input rotational speed of 100 r/min and a load torque of 13 N·m. For all the interfaces, the voltage measured in vacuum (Fig. 14 (a)) was lower than that measured in atmosphere (Fig. 14 (b)), which means that the metal-to-metal contact occurred more easily in vacuum operation. The most drastic change depending on the environment pressure was observed at the WG/FS interface.

Fig. 15 depicts the output voltage as a function of environmental pressure and input rotational speed. The average, minimum and maximum voltages during one rotation of output shaft are plotted. Features in respective interfaces are as follows.

(1) Inner/outer-races of WB

The WB operates in an almost mixed lubrication regime. The environmental pressure slightly affects the lubricating condition. The fraction of metal-to-metal contact decreases as the input rotational speed and the environmental pressure increase.

(2) WG/FS

The lubricating condition at this interface is the most sensitive to the environmental pressure among three contacting combinations. At pressures of less than about

5×10^2 Pa the WG/FS interface works constantly under a boundary lubrication. Above this pressure, the lubricating condition moves to a mixed lubrication regime when increasing the input rotational speed.

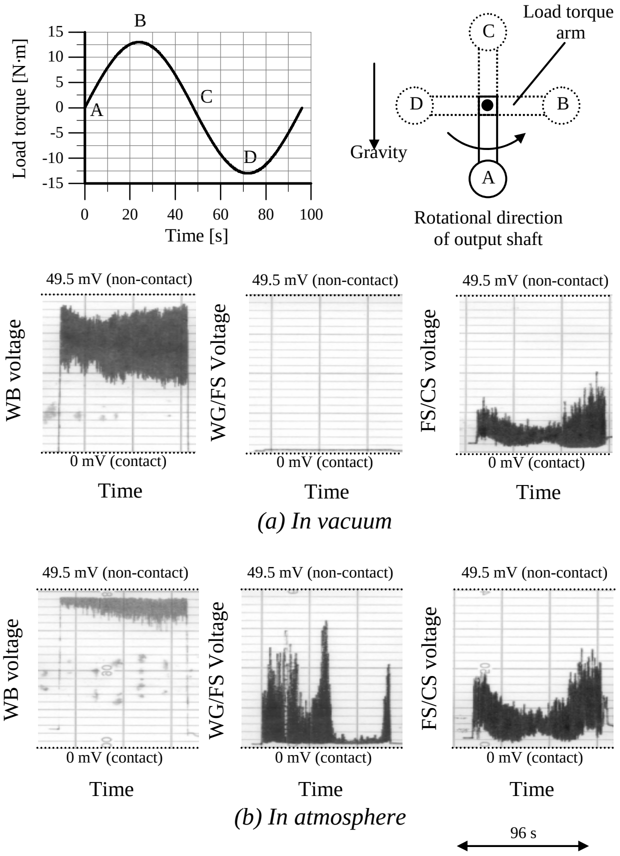


Figure 14. Lubricating conditions at input rotational speed of 100 r/min and load torque of 13 N·m

(3) FS/CS

The contact between FS/CS teeth is under a mixed lubrication. The fraction of metal-to-metal contact decreases slightly as the input rotational speed and the environmental pressure increase.

7.3. Numerical analysis

To clarify the lubricant film behavior at the WG/FS clearance, where the lubricating condition changed most drastically depending on the environment, a mixed lubrication analysis was conducted [4]. As shown in Fig. 16, the separation of WG/FS was calculated in consideration of elastic deformation of the WG and the FS. The metal-to-metal contact and oil film pressures were calculated using the Greenwood-Williamson model [5] and the average flow model [6], respectively. Selected operating conditions for numerical analysis

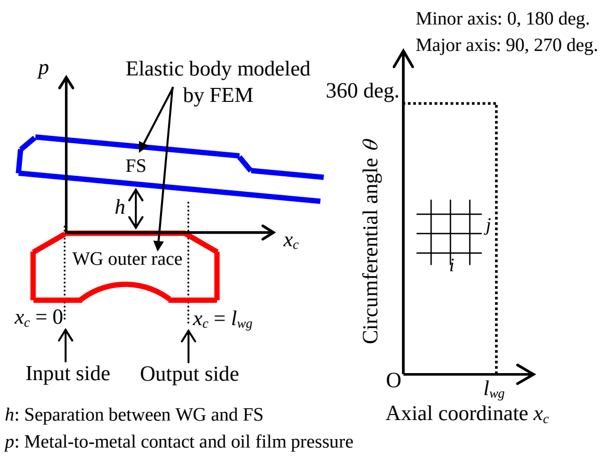
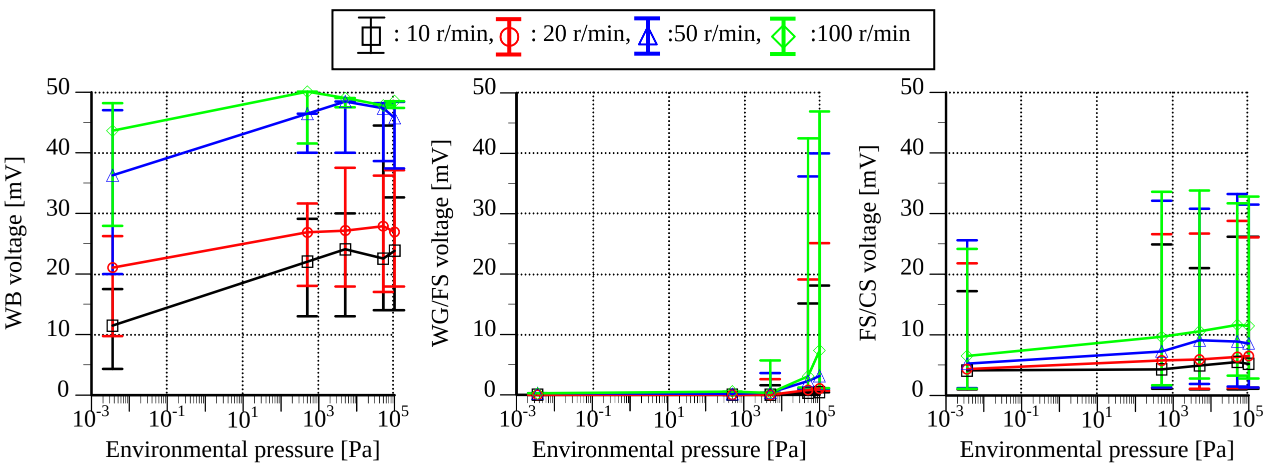
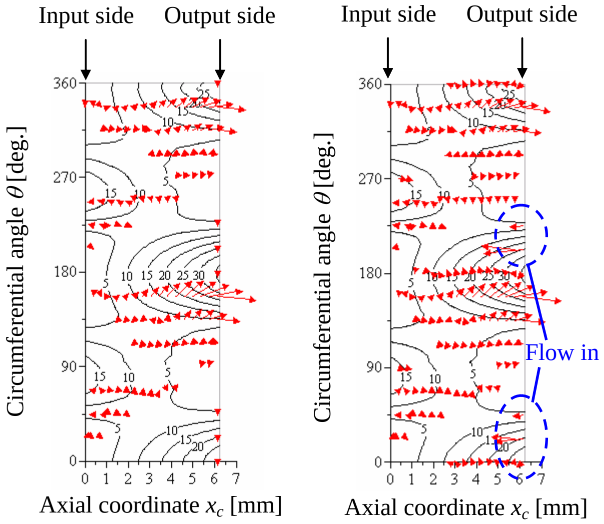


Figure 16. Mixed lubrication analysis model



(a) WB *(b) WG/FS* *(c) FS/CS*

Figure 15. Effects of environmental pressure and input rotational speed on the lubricating conditions at load torque of 13 N·m (0 mV: contact, 49.5 mV: non-contact)



(a) In vacuum (0 Pa) *(b) In atmosphere (1.013×10^5 Pa)*

Figure 17. Distribution of oil film thickness and flow vector (unit of contour line: μm)

show the input rotational speed of 100 r/min, a load torque of 13 N·m, and a viscosity of 0.157 Pa·s (= viscosity of MAC at 20 °C). The boundary conditions around the calculation region are set to vacuum (0 Pa) or atmosphere (1.013×10^5 Pa).

Fig. 17 shows the distributions of the oil flow vector and oil film thickness in the WG/FS clearance. For the in-vacuum operation depicted in Fig. 17 (a) the oil moves mainly in the axial direction and flows out at the "output side" boundary. For the in-atmosphere operation in Fig. 17 (b) the distribution of the flow vector is almost the same as that of the case for vacuum, but the inflow of oil is observed at the "output side" boundary.

The drastic change in the lubricating conditions of the WG/FS interface in atmosphere and in vacuum, in addition to the remarkable life shortening of SWG in vacuum are probably caused by the following mechanism: For in-atmosphere operation, the oil amount inside the WG/FS clearance is preserved by flowing-in by the ambient pressure and flowing-out by the squeeze motion between the WG and FS; in contrast, for in-vacuum operation, the lubricant flows out only, which might lead to lubricant starvation.

8. CONCLUSIONS

Qualification testing of the SHF-type SWG ended in 2006. At present, the additional life tests in vacuum are being performed for verification of reliability. The SWG development is scheduled for completion in 2007.

Basic research through application of the contact electric resistance technique and the mixed lubrication analysis clarified that, for all contacting surfaces, the lubricating conditions become severe in vacuum operations; especially, lubrication at the WG/FS interface is crucial for the long operation life of SWG.

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