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ABSTRACT

The severest lubrication portion in a swashplate compressor is a sliding surface between a swashplate and a shoe. It is important to measure the shoe behavior to clarify the lubricating condition between them. In this study, a model experimental apparatus which simulates a relative motion of the swashplate and the shoe is used to measure the shoe behavior. The shoe behavior is measured by observing optical interference fringes formed in an oil film between the swashplate and the shoe. It is found that an inclination of the shoe changes steeply at the instant that load on the shoe becomes zero while shearing force acts on an piston-side surface of the shoe by precession of a piston. This unstable shoe behavior probably causes metal contact between the swashplate and the shoe which occurs at the beginning of a suction process in a practically operating compressor.

1. INTRODUCTION

Swashplate compressors are favorably used for automotive air conditioning systems. The sliding contact between a swashplate and a shoe is one of the severest lubricating portions in the swashplate compressor. Metal contact between them sometimes causes lubrication failure. It is, therefore, important to clarify the lubricating condition between the swashplate and the shoe.

Several studies (Chappell, *et al.*, 2000, Hotta, *et al.*, 2004, Yanagisawa, *et al.*, 2004 and Suzuki, *et al.*, 2008) have been done to monitor the lubricating condition between the swashplate and the shoe by an electric resistance method (Kohno, 1998 and Tanaka, *et al.*, 2000) in which the swashplate and the shoe were used as electrodes and the electric resistance between them was measured. In our previous studies (Yanagisawa *et al.*, 2004 and Suzuki *et al.*, 2008), it was shown that the lubricating condition becomes worse when pressure load increases. Concerning rotational speed, the lubricating condition becomes better with increasing the rotational speed up to 5000 rpm, whereas it becomes worse when the rotational speed surpasses 7000 rpm. The metal contact between the swashplate and the shoe mainly occurs in a compression process and a discharge process due to pressure force acting on a piston. Besides that, the metal contact also occurs at the beginning of a suction process although the load on the shoe becomes zero at the moment. Although the reason why the metal contact occurs even when the load is zero is thought to be that the shoe behavior becomes unstable when the contact force is unloaded, the shoe behavior at the beginning of the suction process is not clear yet.

In this study, a model experimental apparatus which simulates a relative motion of the swashplate and the shoe is used to measure the shoe behavior. The relative motion is achieved with a sliding motion of a rotating disk, an orbital precession of the piston, and a periodical load by a piezo actuator. The rotating disk is made of glass. The shoe behavior is measured by observing optical interference fringes formed in an oil film between the glass plate and the shoe. The shoe behavior at the instance that the load on the shoe becomes zero is examined with the model experimental apparatus.

2. CONTACT CONDITION BETWEEN SWASHPLATE AND SHOE

Contact condition between the swashplate and the shoe was monitored under a practical operating condition by applying the electric resistance method (Suzuki, *et al.*, 2008). Figure 1 shows a schematic view of an experimental swashplate compressor. It has 7 cylinders with a suction volume of 160 cm^3/rev and is for automotive air conditioning use. In order to monitor the contact condition between the swashplate and the shoe, the electric resistance method that employs swashplate and shoe as electrodes is applied. Since the swashplate and the shoe must be insulated electrically except for the relevant contact point, the anti-piston-side surface of the swashplate and the piston circumference are coated with PTFE resin. The connection to an electric circuit with the reciprocating piston is ensured by a brush and a terminal.

Figure 2 shows the output of the contact signal between the swashplate and the shoe at the piston of A and D in Fig. 1 against rotational angle whose zero is at the top dead center. Rotational speed is 3000 rpm, refrigerant is HFC134a, the suction pressure is 0.2 MPa[gauge] and the discharge pressure is 1.0 MPa[gauge]. The output of 0 V means that there is no contact between the swashplate and the shoe, and 2 V means that the shoe has the metal contact with the swashplate completely. As shown in this figure, the metal contact between the swashplate and shoe mainly occurs in a discharge process (270-360 °) and a re-expansion process (360-60 °) due to the pressure force acting on the piston. The metal contact also occurs at the beginning of a suction process (90-120 °) although the load on the shoe becomes zero at the moment. The metal contact at the beginning of the suction process was observed almost of all experimental conditions (Yanagisawa *et al.*, 2004 and Suzuki *et al.*, 2008).

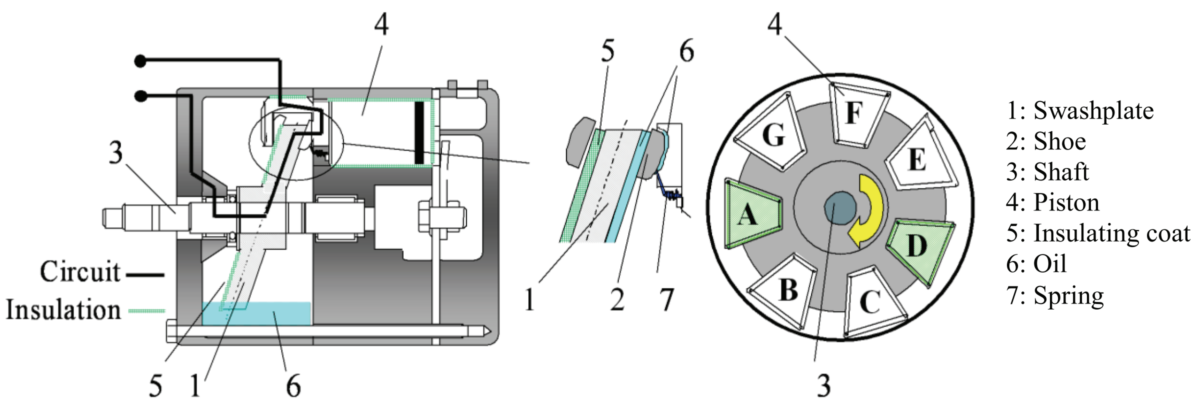

Figure 1 Schematic view of swashplate compressor

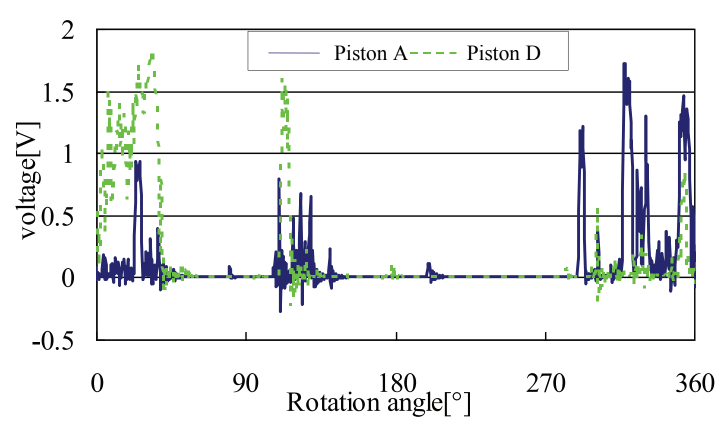

Figure 2 Contact signal in one revolution

3. EXPERIMENT

Figure 3 shows a schematic view of the model experimental apparatus, which simulate the relative motion of swashplate and shoe. It consists of the shoe, the rotating glass plate, and the piston with the orbital precession. The shoe behavior is measured by observing interference fringes (Akei and Mizuhara, 1996, Hotta, *et al.*, 2004) formed in the oil film between the plate and the shoe. The glass plate is connected to an induction motor to rotate it at arbitrary rotating speed. The shoe which is put on the glass plate is thrust by the piston. The piezo actuator is installed in the piston and applies the periodical load on the shoe. A load cell is equipped in the piston to measure the load acting on the shoe. An adjust bolt in the piston is used to set a clearance between the rotating plate and the shoe to be 20 μm. The piston has an inclination of 20 ° against vertical axes at the center of the shoe. The piston is held in a piston holder with bearings. The piston holder rotates by another motor, and the piston has the orbital precession around the vertical axes. In a practically operating compressor, when pressure in the cylinder becomes equal to suction pressure and the load on the piston becomes zero during the suction process, the swashplate and the piston tend to be separated off within a swashplate-shoe clearance by inertia force acting on the piston at the beginning of the suction process. It causes a negative squeeze force on the piston-side shoe surface which pulls the shoe apart from the swashplate. At the experimental setup, springs attached to the piston pull upward the piston so that the piston moves upward when the load becomes zero to simulate the negative squeeze force acting on the shoe.

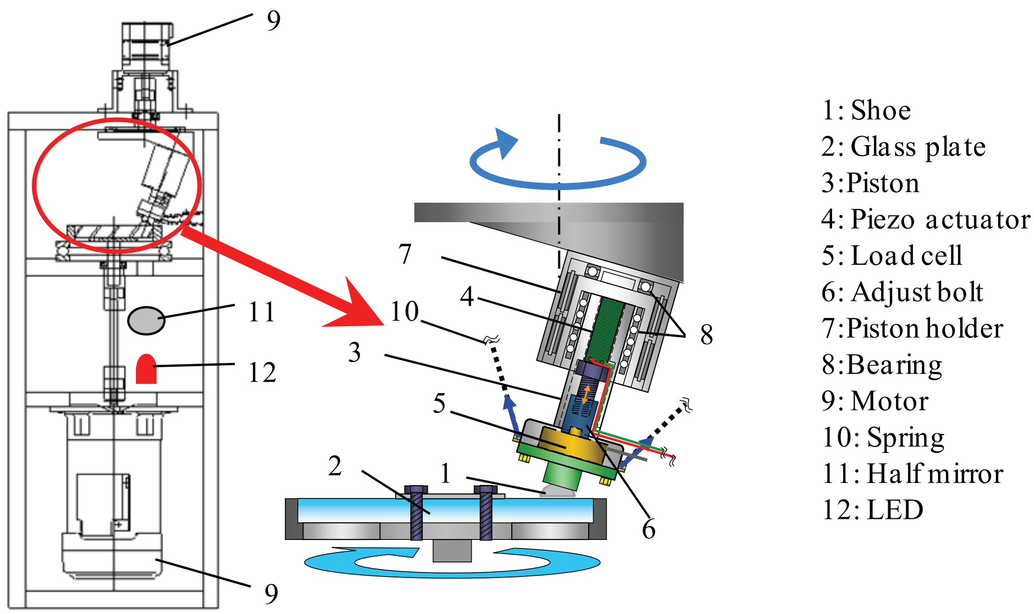

Figure 3 Schematic view of model experimental apparatus

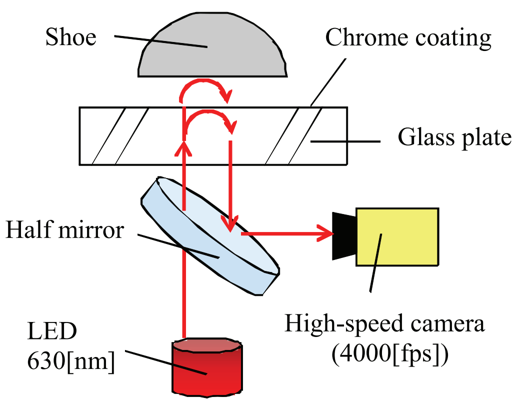

Figure 4 Optical system

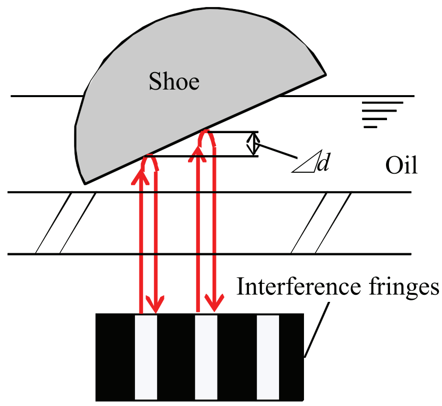

Figure 5 Interval of fringes

Oil is supplied on the glass plate and the clearance between the plate and the shoe is filled by the oil. In this study, a shoe whose bottom has slightly convex shape is used.

The interference fringes formed in the oil film between the glass plate and the shoe is observed by an optical system shown in Fig. 4. LED having wavelength of 630 nm is used as a light source, and is mounted beneath the glass plate. Incident light from the LED goes through a half mirror to the glass plate. A contact surface of the glass plate with the shoe has a half-reflection coating (Chrome coating with reflection rate of 50%), and a part of the light is reflected by the half-reflection coating. The other part of the light is reflected by the shoe surface. These two reflected lights interfere, and the interference fringes are formed according to the clearance between the plate and the shoe. The interference fringes are observed through the half mirror and are recorded by a high speed camera. Difference of clearances between the plate and the shoe corresponding to an interval of the fringes, Δd in Fig. 5, is expressed by Eq. (1).

$$\Delta d = \lambda'/2 = \lambda/(2n) \tag{1}$$

where, λ and λ' are wave length of the light in air and the oil respectively, and n is refractive index of the oil.

In order to make the lubricating condition in the model experiment equivalent to that under the actual condition, Sommerfeld number, S, which is non-dimensional number used to evaluate the lubricating condition is set to be the same with each other. Sommerfeld number is defined by Eq. (2).

$$S = v \cdot \mu / f_w \tag{2}$$

where, μ is viscosity of oil, v is sliding speed, and f_w is the contact force per unit length expressed as follows for the actual compressor.

$$f_w = P_{cy} \cdot A / (D_{shoe} \cdot \cos\alpha) \tag{3}$$

In Eq. (3), P_{cy} is pressure acting on the piston in a cylinder, A is cross-sectional area of the piston, D_{shoe} is diameter of the shoe, and α is a swashplate angle. When shaft rotational speed is 5000 rpm, discharge pressure is 1.5 MPa[gauge], and suction pressure is 0.2 MPa[gauge] in the actually operating compressor, Sommerfeld number is $1.5\text{x}10^{-5}$. Since the piezo actuator used in the model experiment can generate the force of 90 N, sliding speed of the glass plate is decided to be 2.62 m/s ($\approx$ 500 rpm), and turbine oil of VG32 is used. Sommerfeld number in the model experiment under this condition is $1.9\text{x}10^{-5}$. The rotational speed of the orbital precession of the piston is 500 rpm.

Table 1 Experimental conditions of model experiment

Oil	Turbine oil (VG32)
Refractive index of oil at 20 °C	1.462
Sliding speed [m/s]	2.62
Rotational speed [rpm]	500
Load frequency [Hz]	8.3 (≒500[rpm])
Maximum load [N]	0～90
Sommerfeld number (model experiment)	1.9×10^{-5}
Sommerfeld number (actual compressor @5000rpm)	1.6×10^{-5}

Table 2 Test conditions of model experiment

Test	Load	Precession of piston
Test 1	Steady load	No
Test 2	Periodical load	No
Test 3	No-load	Yes
Test 4	Periodical load	Yes

Frequency of the periodical load generated by the piezo actuator is synchronized with the rotation of the orbital precession of the piston. The experimental condition of the model experiment is summarized in Table 1. The shoe behavior is observed by the high speed camera with 4000 fps. Since the frequency of the periodical load and the rotation of the orbital precession of the piston can be controlled independently, the experiments are done under four different conditions to identify the factor which causes the metal contact between the swashplate and the shoe at the beginning of the suction process explained above. The test conditions of the experiment are shown in Table 2.

4. RESULTS AND DISCUSSION

4.1 Shoe behavior under steady load (Test 1)

Steady load (40 N) is applied on the shoe without the precession of the piston in Test 1. Under the condition of Test 1, stable interference fringe is observed and is shown in Fig. 6. Center of fringes shows a point where the oil film is thinnest, and the interval between fringes shows the inclination of the shoe, i.e. narrow interval means steep inclination of the shoe. Therefore, the behavior of the shoe is decided by the position of the center and the interval of the fringes. As shown in Fig. 6, the center of the fringes is located at trailing side of the sliding shoe, and a steady oil film having wedge shape is found to be formed between the glass plate and the shoe. In addition, the position of the minimum oil film thickness and the inclination of the shoe do not change when the direction of piston is changed in Test 1.

4.2 Shoe behavior under periodical load (Test 2)

In Test 2, periodical load is applied on the shoe by the piezo actuator without the precession of the piston. Figure 7 shows variation of the load versus time and the interference fringes observed at several points. The center of the fringes is located at the trailing side of the sliding shoe, and the wedge shape oil film is confirmed even under the periodical load. Since the shoe is pushed against the glass plate when the load is applied to the shoe, the inclination of the shoe becomes small. Therefore, the center of the fringes move toward the center of the shoe and the interval of the fringes becomes wider. On the other hand, when the load becomes zero, the center of the fringes move toward the edge of the shoe and the interval of the fringes becomes narrow. It means that the inclination of the shoe becomes large when the load becomes zero. This movement is caused by the negative squeeze force acting on the piston-side surface of the shoe. The negative squeeze force pulls the shoe up by the upward motion of the piston, which results in the large inclination of the shoe.

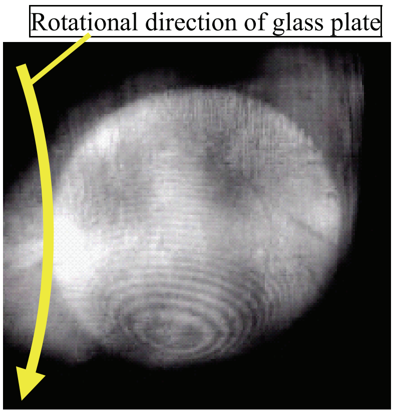

Figure 6 Experimental result in Test1

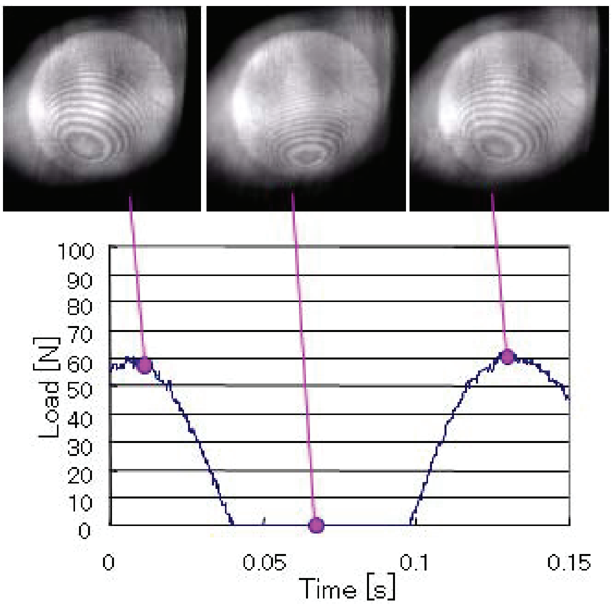

Figure 7 Experimental result in Test 2

4.3 Shoe behavior with precession of piston (Test 3)

Under the condition in Test 3, the piston has the orbital precession. In this case, if the steady load is applied, the load tends to fluctuate because of a waving motion of the plate surface, backrush of the bearing which supports the assembly for the precession of the piston, and a misalignment of the precession axes. Therefore, the load is not applied on the shoe in Test 3, and consequently, only the shearing force is applied on the piston-side surface of the shoe by the orbital precession of the piston. The results in Test 3 are shown in Fig. 8.

Number shown in figures indicates a sequence of pictures. An arrow shows the piston direction, and a geometric relationship between the piston direction and the rotational direction at the picture 1 corresponds that at the bottom dead center in the actual compressor. Similarly, the picture 2 corresponds to the compression process, the picture 3 corresponds to the top dead center and the picture 4 corresponds to the suction process. Although the center of the fringes is located at the trailing side of the sliding shoe and it is found that the wedge shape oil film is formed in all pictures, the inclination of the shoe slightly changes according to the direction of the precession of the piston. In picture 1, the direction of the piston precession moves toward an opposite direction against the sliding direction, and the shearing force acting on the piston-side surface of the shoe causes the moment which tends to make the inclination of the shoe small. Since the inclination of the shoe reduces, the center of the fringes moves toward the center of the shoe and the interval of fringes becomes wider. In contrast, the center of the fringes moves toward the edge of the shoe and the interval of the fringes becomes narrow in picture 3, which means that the inclination of the shoe increases.

4.4 Shoe behavior under periodical load with precession of piston (Test 4)

Figure 9 shows the shoe behavior which is simulated by the model experiment under the periodical load with the orbital precession of the piston. Variation of the periodical load is shown in a graph against time. The interference fringes corresponding to several points on the time history of the load are shown. In this case, the center of the fringes is located at the trailing side of the sliding shoe when the load is applied to the shoe. However, it is found that the position of the minimum oil film thickness and the inclination of the shoe have an abrupt change when the load on the shoe becomes zero. This behavior is caused by the negative squeeze force and the shearing force acting on the piston-side surface of the shoe by the upward motion and the orbital precession of the piston. It results in the unstable shoe behavior and probably causes the metal contact between the swashplate and the shoe which occurs at

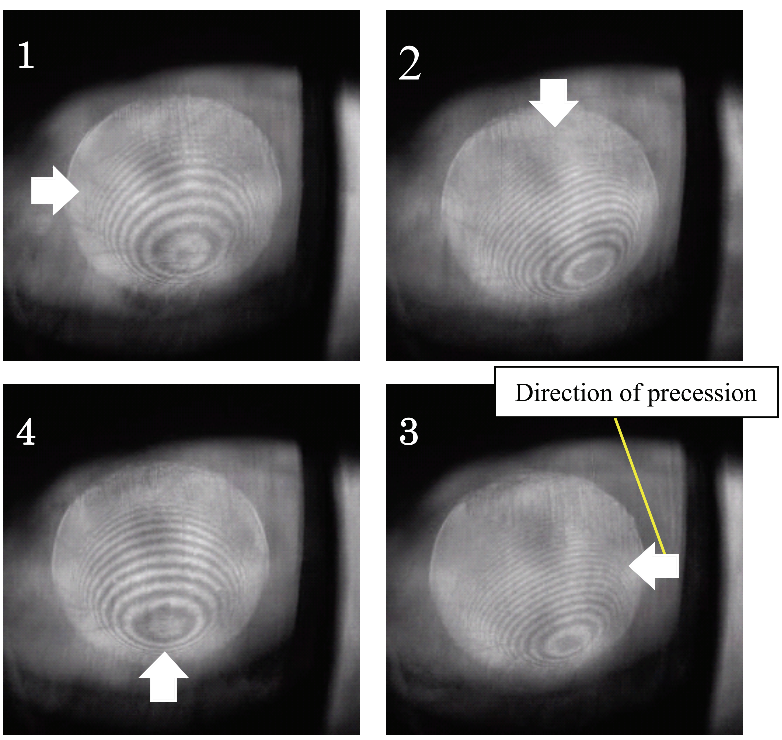

Figure 8 Experimental result in Test 3

the beginning of suction process in the practically operating compressor.

4. CONCLUSION

Metal contact between a shoe and a swashplate in a swashplate compressor for automotive air conditioning use was detected by an electric resistance method not only in a compression process but also at the beginning of a suction process in our previous study. In order to clarify the factor which affects shoe behavior, a model experimental apparatus which simulates a relative motion of swashplate and shoe is used in this study. The shoe behavior is measured by observing optical interference fringes formed in an oil film between the swashplate and the shoe. It is found that a wedge shape oil film is formed steadily when a steady load is applied without an orbital precession of a piston. When the load on the shoe becomes zero and the piton moves upward under a periodical load condition, inclination of the shoe increases by a negative squeeze force pulling the shoe up. In case that the piston has the orbital precession without applying the load, the inclination of the shoe changes by shearing force acting on a piston-side surface of the shoe which causes a turning moment on the shoe. Although the inclination of the shoe slightly changes under these conditions, the wedge shape oil film is formed steadily. On the other hand, under the condition that the periodical load is applied with the orbital precession of the piston, the inclination of the shoe and a position of minimum oil film change steeply at the instant that the load on the shoe becomes zero. This behavior is caused by the negative squeeze force and the shearing force acting on the piston-side surface of the shoe by the upward motion and the orbital precession of the piston. It results in the unstable shoe behavior. It probably causes the metal contact between the swashplate and the shoe which occurs at the beginning of the suction process in a practically operating compressor.

In the future, the model experiment apparatus developed in this study will be used to evaluate the oil film formation with shoes having different shape.

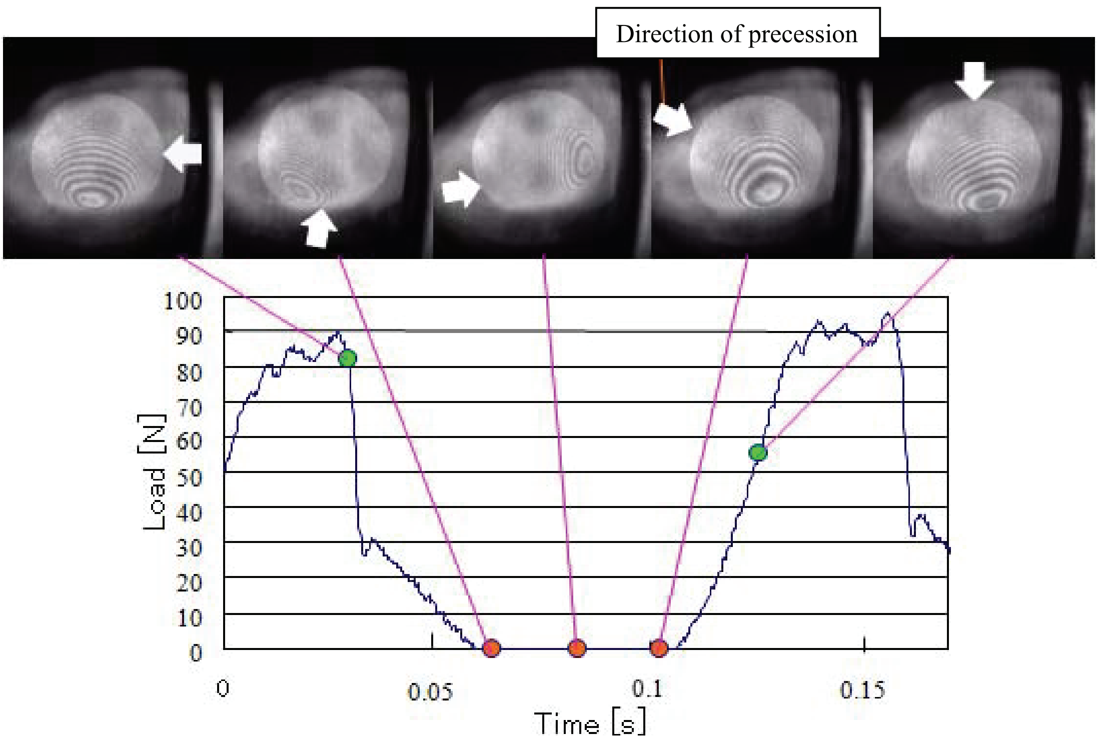

Figure 9 Experimental result of experiment in Test 4

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