A study of lube displacement under a flying head slider caused by slider-disk interaction

Takeshi Watanabe and David B. Bogy

Computer Mechanics Laboratory
Department of Mechanical Engineering
University of California, Berkeley, CA 94720

Abstract

Lube flow on a hard disk due to a flying head slider was studied using an Optical Surface Analyzer. The tests were performed using a pico (1.25×1.00mm) slider, and a regular modulation of lube thickness was observed, which was greater under the lower flying rail of the slider. The stronger modulation is thought to be due to the higher air bearing pressure under the lower rail. The frequency spectrum clearly showed some peaks, which were consistent with the natural frequency air bearing modes of the flying slider motion detected by an LDV. In addition, the flying slider attitude affected the lube thickness modulation.

Furthermore, we also found that the lube modulation tended to follow the disk surface topography within the rail tracks of the slider. We conclude that most lube accumulation areas were formed in "valleys" on the disk surface because the lube layer was pushed by air bearing shear flow.

From these experimental results, we conclude that the displacement of the lube layer depends strongly on both the disk topography and air bearing pressure due to the slider's flying motion. As long as the slider continues flying on the same track, both effects are active and the lube modulation continues to grown.

Keyword: Lube flow, Lube modulation, Air bearing pressure, Disk topography, Air bearing shear flow, slider-disk interaction, Optical surface analyzer

1.Introduction

The disk lubricant plays an important role in a magnetic disk drive head-disk interface (HDI). Indeed, for optimal tribological performance of the HDI, it is essential that the lube layer be retained with near uniformity on the disk surface. Even if no contact occurs between the disk and slider, lube flow is affected by several factors correlated with head-disk interaction. In particular, the air bearing pressure has significant effects on thin lube films, and it may possibly cause uneven lube distribution. Moreover, magnetic recording density has been rapidly increasing at a rate of more than 100 percent per year requiring reduced slider to disk spacing. Also the disk rotational speed has substantially increased. Therefore slider-disk interaction effects on the lube flow have become more pronounced. Consequently it is now more important to study and understand lube flow caused by slider-disk interaction to ensure effective disk lubrication.

Some of the issues discussed above have already been observed in a few published papers. Kawakubo *et al.* calculated the change in lube thickness due to centrifugal force and air bearing shear flow effects on the lubrication surface of the disk [1]. Pit *et al.* studied a lubricant "pattern" under a flying head using an OSA [2]. They called these lube patterns "moguls". Ma *et al.* studied the correlation between moguls and the slider dynamics [3]. We also studied lube modulation under a flying nano (2.0×1.6mm) slider in our previous research [4]. However, the relationship between a flying head slider and lube flow still requires more study to provide a further understanding of the phenomena.

In this paper, we study lubricant displacement under a flying head slider caused by slider–disk interaction, especially effects of air bearing pressure and disk surface topography, which we detected by executing long-term flyability tests using an Optical Surface Analyzer (OSA).

2.Experimental Procedure and Set-Up

An Optical Surface Analyzer (Candela TS5100), including a slider mount fixture, was used to conduct long-term flyability tests. Pico-size negative pressure sliders were used in this test with the ABS design as shown in Fig.2.1. The flying height of the slider is 20 nm at 10,000 rpm. The disks were commercially available aluminum disks with carbon overcoat lubricated by a dipping process. Details of lubes we used in each test are described in Appendix I.

[Long-term flyability test]

The long-term flyability tests were conducted as follows. First we mounted the disk on the air bearing spindle of the OSA as shown in Fig.2.2 and brought the rotational speed up to 10,000 RPM. Next, the slider was moved to a chosen radius position. The slider continued to fly on the same track while changes of lube thickness under the flying slider were observed throughout the experiment, a typical result of which is shown in Fig.2.3. Possible contacts between disk and slider were monitored by an AE sensor.

The OSA is an optical measurement instrument designed to detect carbon wear, lubricant wear, lubricant depletion, lubricant accumulation, surface roughness, and lubricant decomposition on carbon coated thin film disks [5]. The thickness resolution of the OSA is less than 1 Å.

3.Results and discussion

3.1 Lubricant depletion under the flying head slider at each radial position

Long-term flyability tests were performed at three radial positions (21mm, 25mm, and 30mm). Figure 31.1 shows lube thickness modulation after a 5-minute flying test. The slider flying direction is from left to right on these pictures and bright areas correspond to thinner lubricant compared with surrounding areas. There were some differences in the three cases. Two lube modulation lines were clearly observed at the radius of 21mm, while only one line was observed at the radius of 30mm.

The slider's flying heights and attitudes at the three radial positions (21mm, 25mm, and 30mm) were calculated using the CML ABS Simulation code, and the results are shown in TABLE 3.1.1. These results indicated a roll angle difference in the three cases. From a comparison with the OSA results, we see that a high roll angle (30mm case) produced only one lube modulation line, while a low roll angle slider (21mm case) made two lines. Therefore, we concluded that the slider's attitude affected the lube lines, and the high roll angle slider had a reduced air bearing pressure under the higher rail, causing less lube displacements.

3.2 Lubricant thickness modulation under a flying head

Figure 3.2.1 shows a lube thickness modulation line under a flying slider after a

1-minute flying test. Figure 32.2 shows the lube thickness modulation along this line, and Fig. 3.2.3 shows the spectrum analysis result of this lube modulation. It was found that the lube modulation amplitude was only a few angstroms and the frequencies of lube modulation showed two important peaks, around 100 kHz and 140 kHz.

Figure 3.2.4 shows the displacement of the trailing edge corner of the flying slider as detected by an LDV. The left graph in Fig. 3.2.4 shows the slider and disk displacement during slider flying. The right graph shows the spectrum analysis of the slider displacement. In these measurements, the frequencies of the slider's displacement had two notable peaks, 105 kHz and 138 kHz. In comparison with the OSA results (Fig.3.2.3), we see that the lube modulation frequencies were consistent with the slider vibration modes detected by the LDV.

3.3 Lube thickness modulation growth and recovery under a flying head slider

Figures 3.3.1 and 3.3.2 show the lube modulation growth and recovery during a 60-minute test. In this test the slider was moved to another radial position after 30 minutes, but the disk continued to rotate for an additional 30 minutes. Figure 3.3.1 shows the change of the lube thickness during the 60 minutes. Figure 3.3.2 shows the standard deviation of the lube modulation vs. Time. Observable lube modulation occurred after only 1 minute. Then its standard deviation slowly increased during the flying test. After stopping the flying test, the modulation gradually decreased.

From these results it is clear that the lube modulation was formed in a short time just after starting the flying test, and the lube modulation continued to grow during the flying test, but then it relaxed after stopping the flying test.

3.4 Lube modulation recovery after a re-flying test

Figures 3.4.1 and 3.4.2 show the lube thickness recovery after a flying and re-flying test. In this test the slider flew for 30 minutes, then it was stopped for 15 hours. Afterwards, we resumed the flying test at the same track. Figure 3.4.1 shows changes in the lube modulation. The lube thickness was almost recovered after the 15 dwell hours, but lube modulation occurred again after the flying test resumed. Figure 3.4.2 shows the comparison of the lube modulations along the track of Fig. 3.4.1, and it indicates that a similar lube modulation occurred the second time at the same place.

Therefore, it is obvious that the lube modulation is repeatable on the disk surface. This implies that lube modulation was affected by the disk surface geometry.

3.5 Lube thickness modulation along texture lines

Figure 3.5.1 shows the lube modulation along a texture line on the disk surface. Before the test we observed texture lines in the direction indicated by the arrows in Fig. 3.5.1, one of which was a clear "valley" on the disk surface. After a 1-minute flying test, we observed two "lube lines". One was in the slider's flying direction, the other was consistent with the texture direction. After a 30-minute flying test, the modulation increased in both directions.

In this case there were two "lube lines" in different directions. Therefore, it was obvious that the lube modulation was not only affected by air bearing pressure but also by disk topography, such as the texture lines in this case.

3.6 Lube modulation associated with disk surface topography

Based on the previous results, we sought to establish a direct correlation between the lube modulation and the disk surface topography.

Figure 3.6.1 shows a lube profile image of a rail track after flying the slider, as detected by the OSA. The lube layer was modulated as was shown in the previous section.

Figure 3.6.2 shows a cross section of the lube modulation, along the path indicated as a dotted line in Fig.3.6.1. In Fig.3.6.2, the lube modulation is shown as the top line, on the other hand, disk surface topography is shown by the bottom line.

In this region, there are a few peaks in the lube profile, as indicated by the arrows in Fig.3.6.2, which means the lube layer was thicker there. Likewise, the bottom line has some positive and negative peaks. In the comparison of the two lines, we realized there is a correlation between the two, i.e. thick lube areas seem to be in the "valleys", while thin lube areas are on the peaks of the disk surface.

Fig.3.6.3 shows the frequency spectrum of the disk topography along the lube modulation track. There were no remarkable peaks in this region. This implies that the lube modulation along the disk topography had no periodic profile such as the resonances associated with the air bearing resonance frequencies.

3.7 Comparison between the flying slider vibration effect and the disk topography effect on lube modulation

In the previous section, we observed that not only the slider vibration but also the disk topography affect lube modulation. In order to understand the correlation between the two mechanisms, we used the cross correlation method. If significant peaks emerge in this analysis, it means there are common notable frequency peaks in both of them.

[Cross correlation analysis]

The equation for a cross correlation function (Rxy(t)) is:

$$R_{yx}(?)\ ?\ ?_{??}^{?}\ y(t)\,?x(t\ ?\ ?)\,dt \qquad (1)$$

where x(t). y(t) are arbitrary functions of time for which we want to study a correlation. It can identify the existence of common frequencies between the two functions.

In this analysis, we selected the disk topography data as y(t), and the lube modulation data as x(t).

[Analysis result]

Figures 3.7.1-3.7.10 show lube surface profiles detected by the OSA and spectrum analysis results derived from the cross correlation functions. These figures show surface profiles for different times at 0 minute (Fig. 3.7.1-3.7.2), 1 minute (Fig. 3.7.3-3.7.4), 2 minutes (Fig. 3.7.5-3.7.6), 5 minutes (Fig. 3.7.7-3.7.8) and 10 minutes (Fig. 3.7.9-3.7.10), respectively.

There is no peak shown in Figs. 3.7.1 and 3.7.2 (t=0min). But, after a flying test was conducted for only one minute, some outstanding peaks were found (Fig. 3.7.3-3.7.4). Some observable peaks are seen in the low frequency region (below 100 kHz) and the high frequency region (140 kHz). Both of these frequency peaks continued to grow as shown in Fig.3.7.3-3.7.10 (t=0-10min).

From these results, we concluded there are correlations, at both low frequencies (below 100 kHz) and high frequencies (140 kHz), between the lube modulation and disk topography.

Judging from the frequency numbers, we concluded that the former was due to disk waviness effects (Wave lengths > 0.314mm), and the latter was caused by slider vibration modes, i.e., air bearing shear flow pushed away the lube along the disk waviness peaks in the former case, and pressure variations from the slider vibration depressed the lube layer periodically in latter case.

[Comparison between disk waviness effects and slider vibration effects]

To gain further understanding of initial lube flow, we performed another flying test ("track seeking test"). We first flew a slider at radius 28mm and then moved it to 33mm at a speed of 0.42 mm/sec as shown in Fig.3.7.11. The OSA measurement was then taken at the radius 30mm as shown in Fig.3.7.12. After that, the slider was returned to radius 30mm and a flyability test was as completed as shown in Fig. 3.7.13.

These figures show results at times: at 0 minute (Fig. 3.7.14-3.7.15), after a track seeking transient (Fig. 3.7.16-3.7.17), and after a 1-minute flying test (Fig. 3.7.18-3.7.19), respectively.

In comparing the lube modulation between Fig.3.7.15 and 3.7.17, we observed low frequency modes (<50kHz) but not high modes (>100kHz) caused during the seeking transient (around 30mm). But after again flying at the radius of 30mm, we observed both of the previously observed frequency peaks.

Therefore, we concluded that disk waviness affects the lube layer more readily than slider vibration. But when the slider flew again on the same track, the slider vibration influenced the lube layer immediately.

3.8 Consideration of molecular force effect

In the previous sections, it was concluded that the air bearing pressure and air bearing shear force cause lube flow and modulation. But, according to other research papers [2][7], it has been suggested that the lube displacement may be affected by molecular force between lube layer and slider surface. However, Wu *et al.* revealed that the molecular force between a slider and disk is not significant for spacing greater than 5 nm [8]. Therefore, we performed another flyability test to confirm the molecular force effects.

[Experiment]

We selected the disk rotational speed as the control parameter. The experimental conditions were:

Test1) Flying time 10 min / Flying track at 28mm / Disk rotational speed 10,000rpm
Test2) Flying time 10 min / Flying track at 28mm / Disk rotational speed 2,000rpm

The only difference between the two was the disk rotational speed. In Table 3.8.1 we show the slider flying heights as calculated by the CML software. Both the flying height and the air bearing pressure in test1 (10,000 rpm) are larger than those in test2 (2,000 rpm). The experimental results are shown in Figs. 3.8.1-3.8.2. The lube depletion depth was almost 2 angstrom in test1 (10,000 rpm). The change was very small in test2 (2,000 rpm).

If the effect of the attractive molecular force is stronger than that of air bearing pressure repulsive force, the lube surface in the test 2 (2,000 rpm) case should be affected more than that in test1 (10,000 rpm) case. But, the tests indicated the opposite result, i.e. lube depletion depth in the test1 case was deeper than that in the test 2 case.

Therefore, we concluded that lube modulation was not affected by molecular force but by air bearing pressure in this research. This is consistent with the results of Wu *et al*, showing no effect of van der Waals forces for spacing above 5 nm.

4. The mechanism of lube displacement under a flying slider

Once a slider flies on a track, the lube layer is pushed by air bearing pressure and air bearing shear flow. In a short time, such as a few seconds, the lubricant starts to be moved by air bearing shear force but not by air bearing pressure. But soon, the lubricant is also modulated by air bearing pressure in less than 1 minute. As long as the slider continues flying on a same track after that, both of these effects are active and lube modulation grows.

As for the molecular force effect between a slider and disk surface, we concluded that the is little or no effect on lube modulation for sliders flying at 20 nm. This is evidently too high for molecular forces to work on the lube layer.

5. Summary

We observed lube thickness modulation under flying sliders using an OSA having high sensitivity to the thickness change of the lube layer. The lube layer under the flying sliders was depleted through long-term flyability test. In summary:

- Lube depletion correlated with slider attitude, i.e., a high roll angle decreased effects of air bearing pressure at the higher rail.
- Lube thickness modulation occurred in the circumferential direction and modulation frequencies were consistent with the slider's air bearing vibration modes, i.e., it was caused by air bearing pressure.
- Lube modulation formed after only 1 minute and it gradually grew during the time of slider flying, but it recovered after stopping the flying test.
- Lube modulation showed thicker lube in the "valleys", and thinner lube on the peak of the disk surface, i.e., it was not only affected by air bearing pressure but also by disk surface topography.

- According to the spectrum analysis, low frequency modes (<100kHz) of the lube modulation profile were stimulated but high frequency modes (>100kHz) were not yet stimulated just after the beginning of the flying test, i.e., disk waviness influences the lube layer more readily than slider vibration. If the slider remains at the same track, the slider vibration influences the lube layer immediately.
- We concluded that the former was due to a disk waviness effect, and the latter was caused by a slider vibration mode, i.e., the air bearing shear flow pushed away lubricant along disk waviness, and slider vibration thrusts the lube layer periodically.
- Lube modulation was not affected by molecular force but by air bearing pressure in this research, when the flying height was about 20 nm.

- There was no AE signal during the slider flying tests, i.e., no contact between the slider and disk occurred. Therefore it is clear that the lubricant was modulated by slider-disk air bearing interaction.
- The lube thickness modulation is expected to increase markedly as flying height decreases. Therefore, more research should be carried out to determine the optimal mix of bonded and mobile lubricant.

Appendix.I

Table. Details of lubes we used in each test

Section	Type of lubricant	Lubricant thickness [nm]
3.1	Z-dol	1.5
3.2	AM3001 + X1-P	1.6
3.3	AM3001 + X1-P	1.6
3.4	AM3001 + X1-P	1.6
3.5	AM3001 + X1-P	1.6
3.6	AM3001	1.25
3.7	AM3001	1.25
3.8	Z-dol	1.5

6. Acknowledgment

The authors would like to thank Brian Thornton for the LDV measurements and modal analysis of the slider vibration. This work was supported by the Computer Mechanics Laboratory and Fuji Electric Co.,Ltd.

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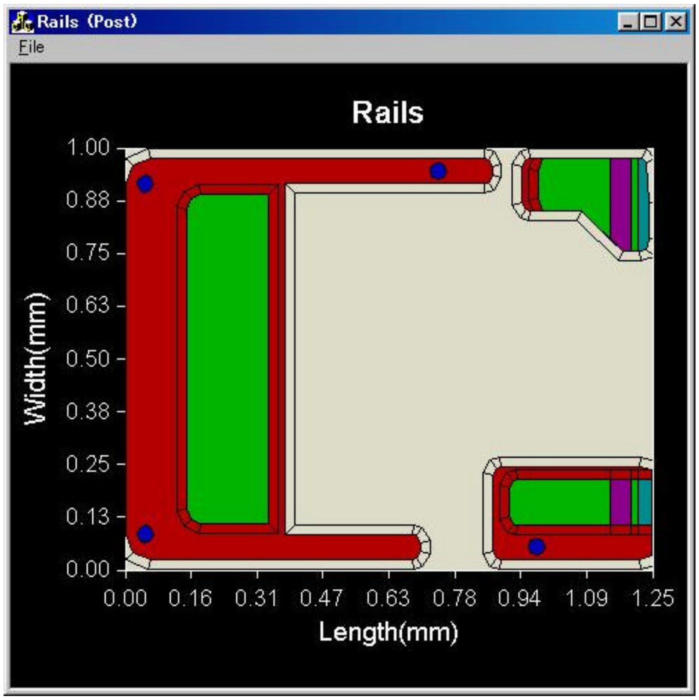

Fig. 2.1 Pico-size negative pressure slider

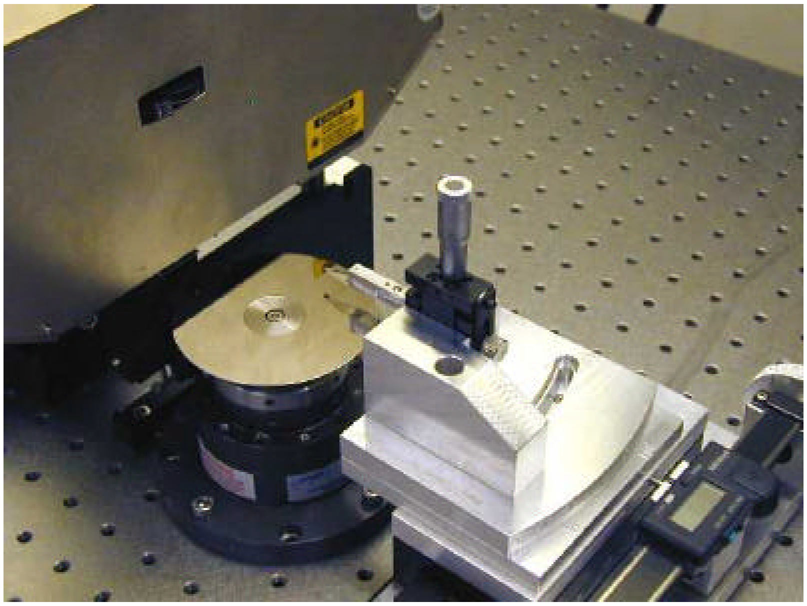

Fig. 2.2 Mounted disk on air bearing spindle of OSA

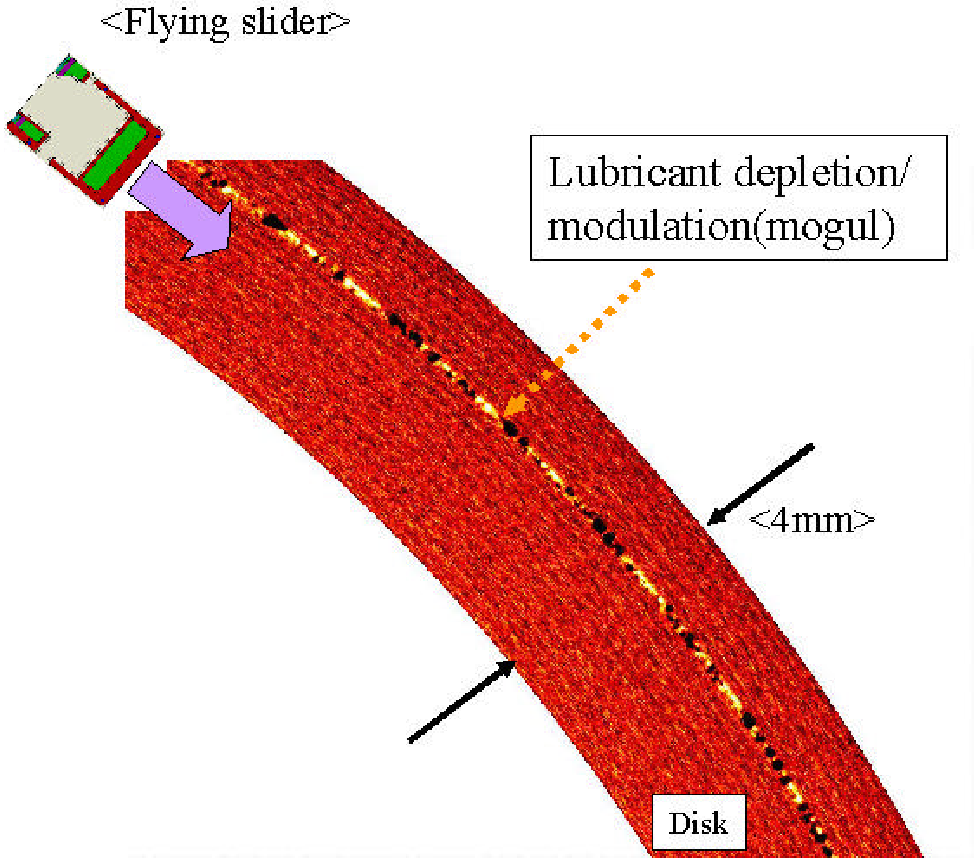

Fig. 2.3 Outline of long-term flyability test

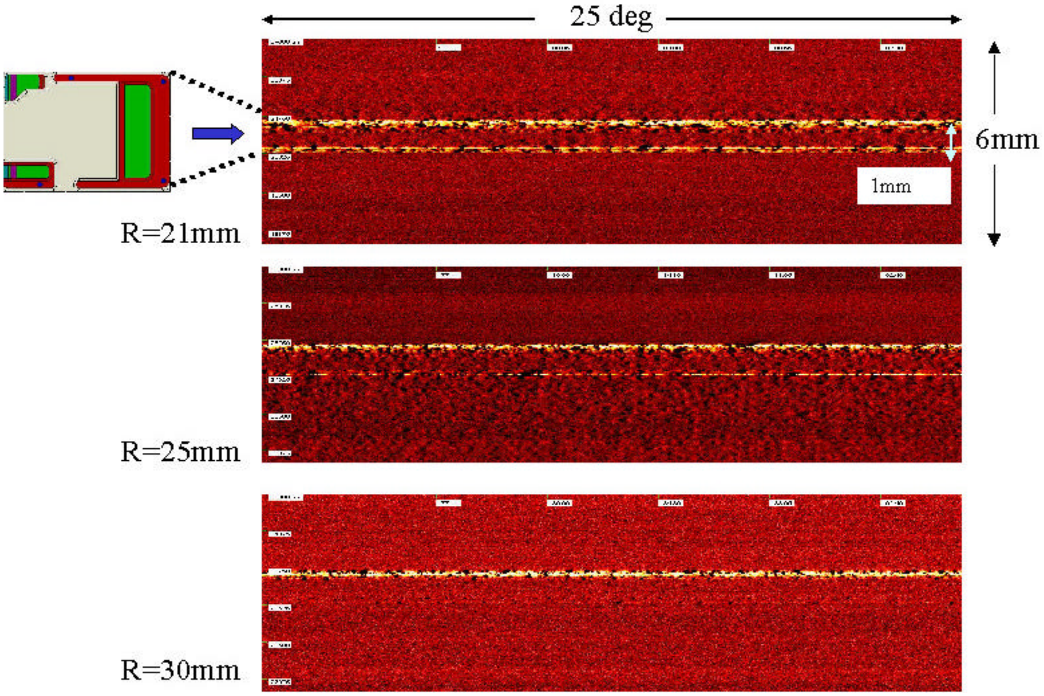

Fig. 3.1.1 Lube thickness modulation after a 5-minute flying test at three radial positions (21mm, 25mm, and 30mm)

Table 3.1.1 Slider flying heights at three radial positions (21mm, 25mm, and 30mm)

R=21mm	R=25mm	R=30mm
Min FH=20.43[nm] Pitch Angle=124.49[urad] Roll=19.31[urad]	Min FH=21.31[nm] Pitch Angle=119.52[urad] Roll=22.40[urad]	Min FH=22.0[nm] Pitch Angle=115.44[urad] Roll=26.40[urad]

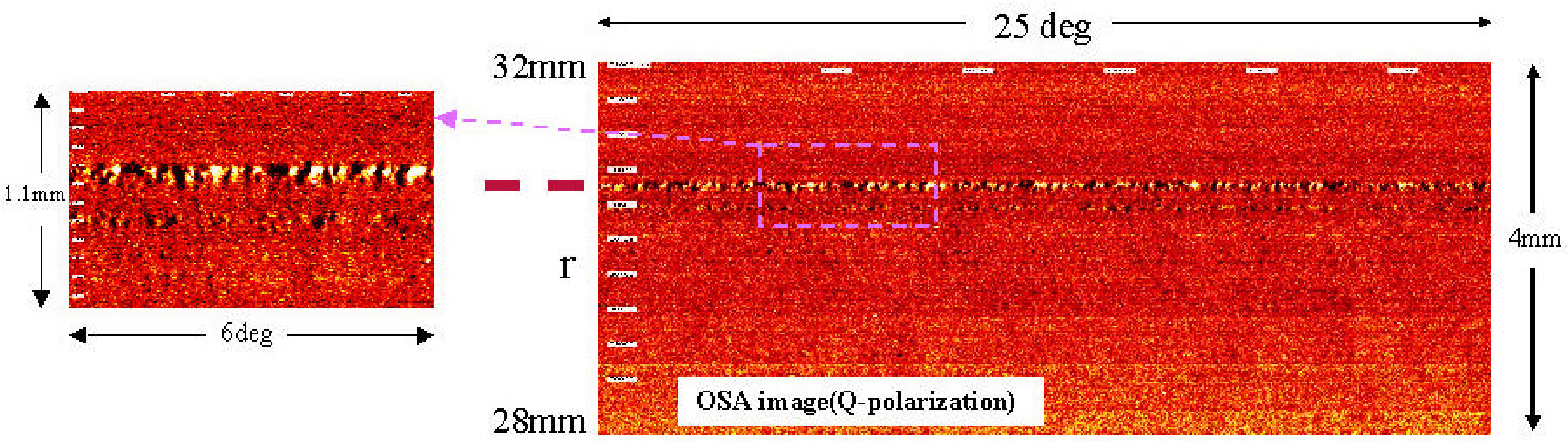

Fig. 3.2.1 Lube thickness modulation under flying slider after a 1-minute flying test obtained by the OSA (Left picture is a magnified image of the right picture.)

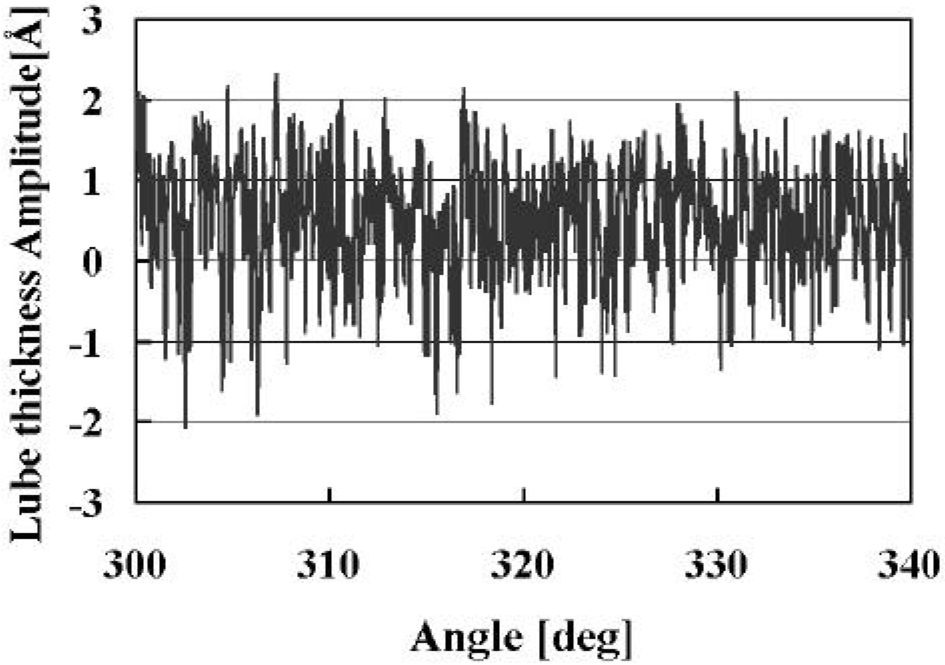

Fig. 3.2.2 Lube thickness profile along the lube modulation after 1-min flying test

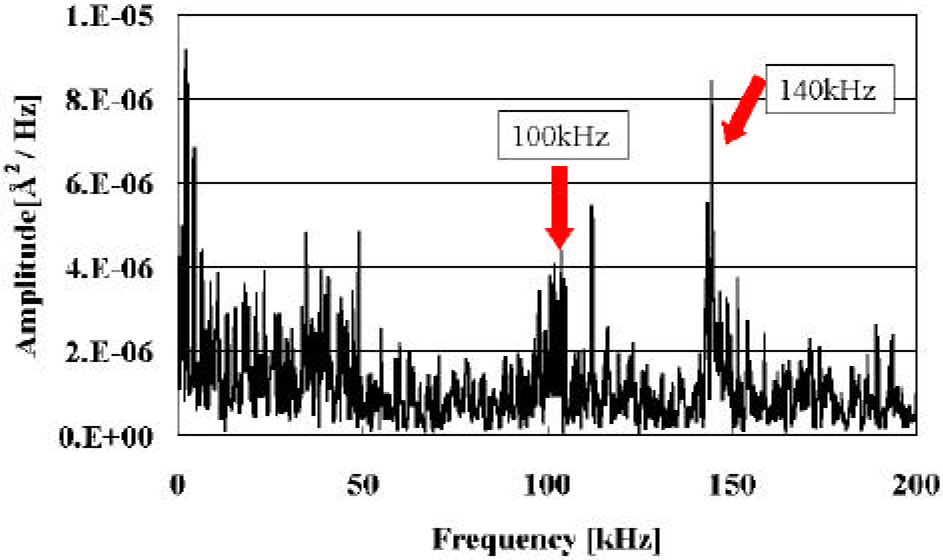

Fig. 3.2.3 Spectrum analysis result of the lube thickness modulation

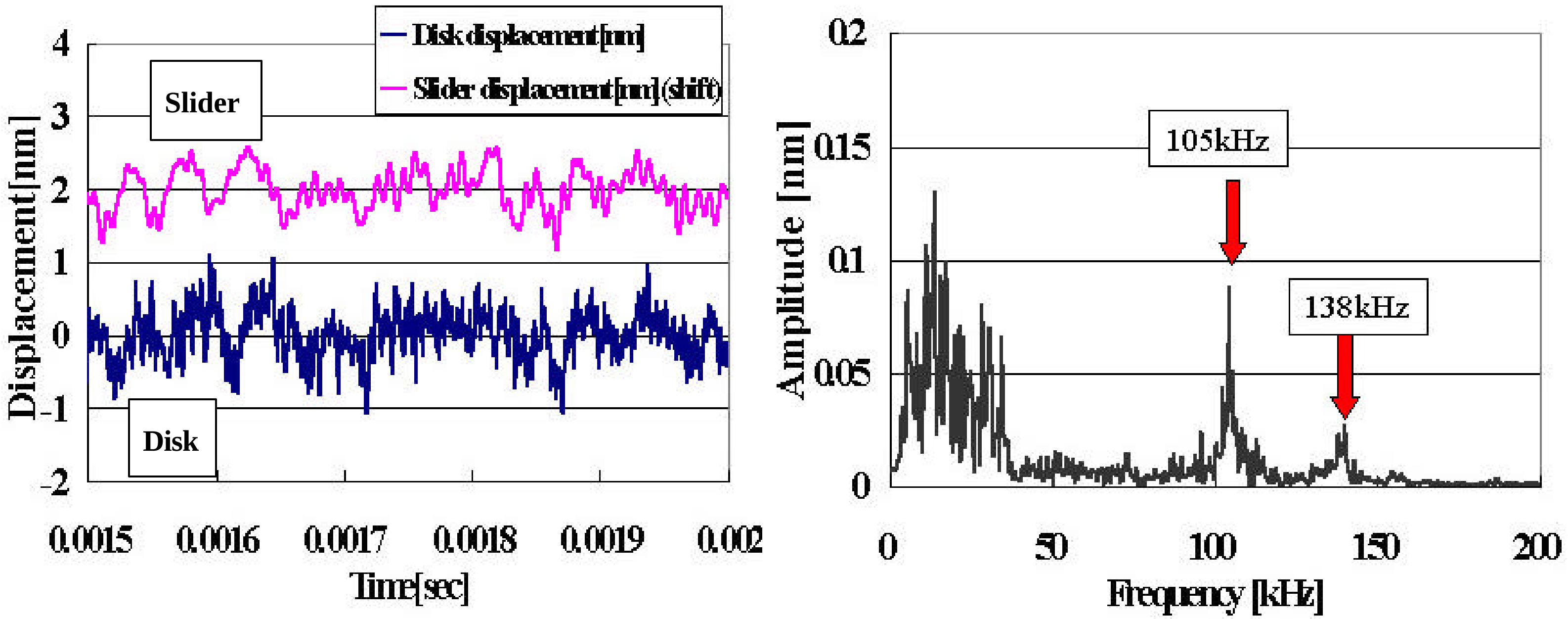

Fig. 3.2.4 Slider and disk displacement during slider flying
(Left) Displacement of flying slider detected by LDV
(Right) Spectrum analysis result of slider displacement

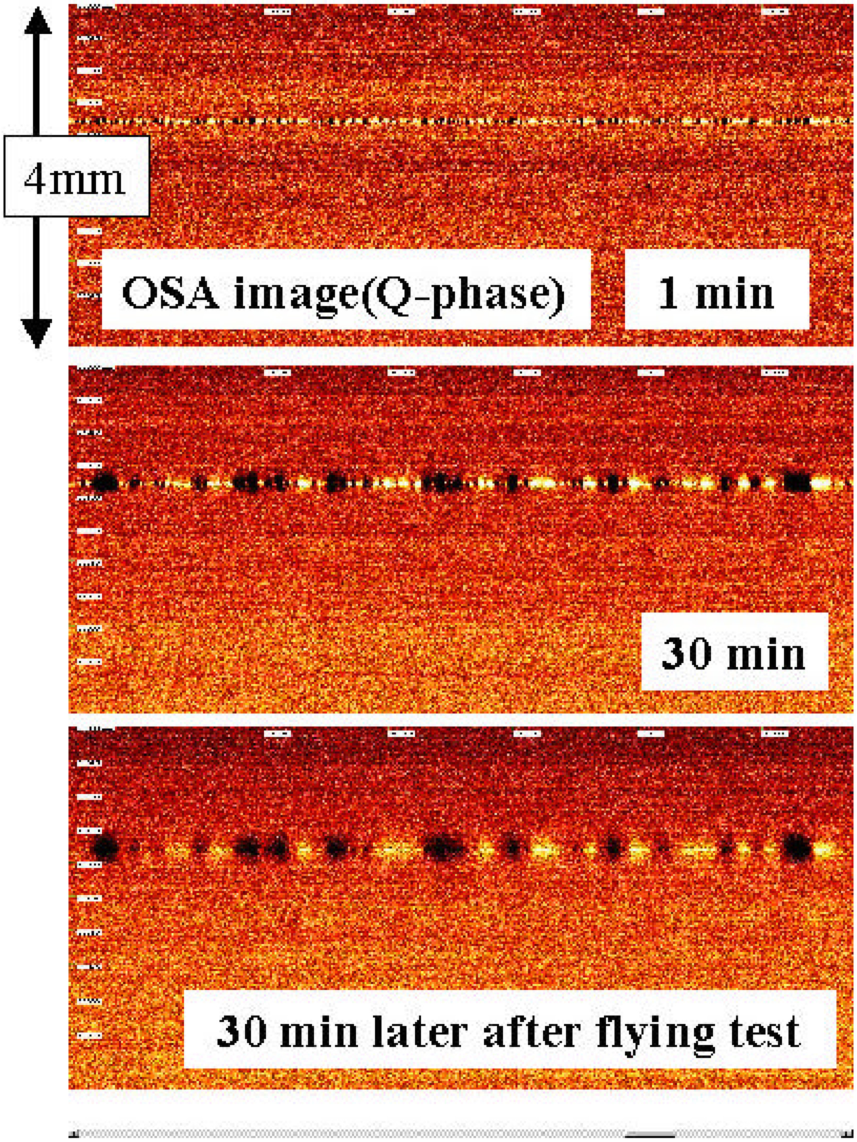

Fig. 3.3.1 Lube modulation growth-recovery test during 60 min flying (Flying 0-30min, recovery -60min)

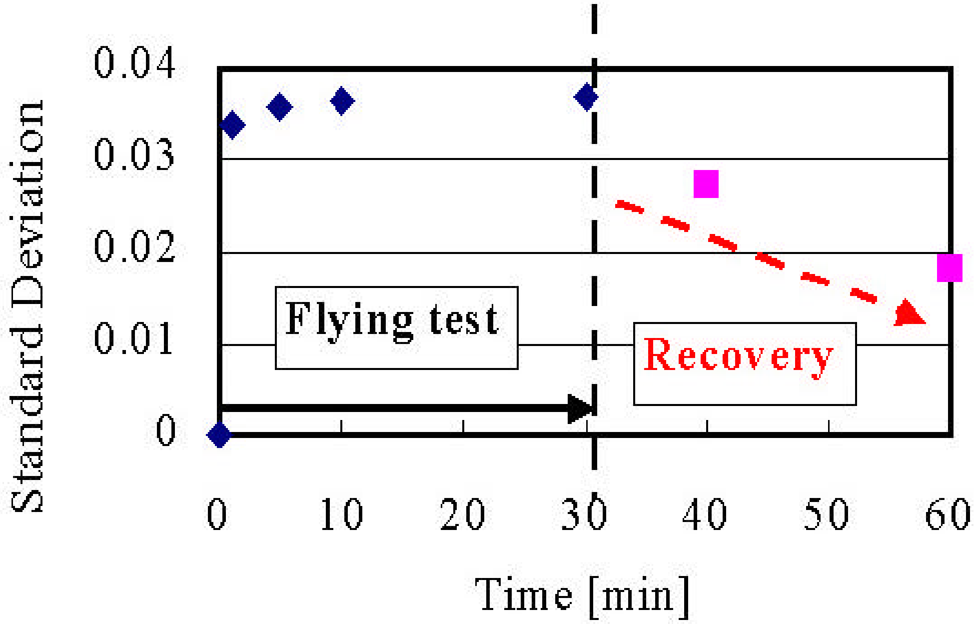

Fig. 3.3.2 Standard deviation of the lube modulation vs. Time during 60-minute flying test

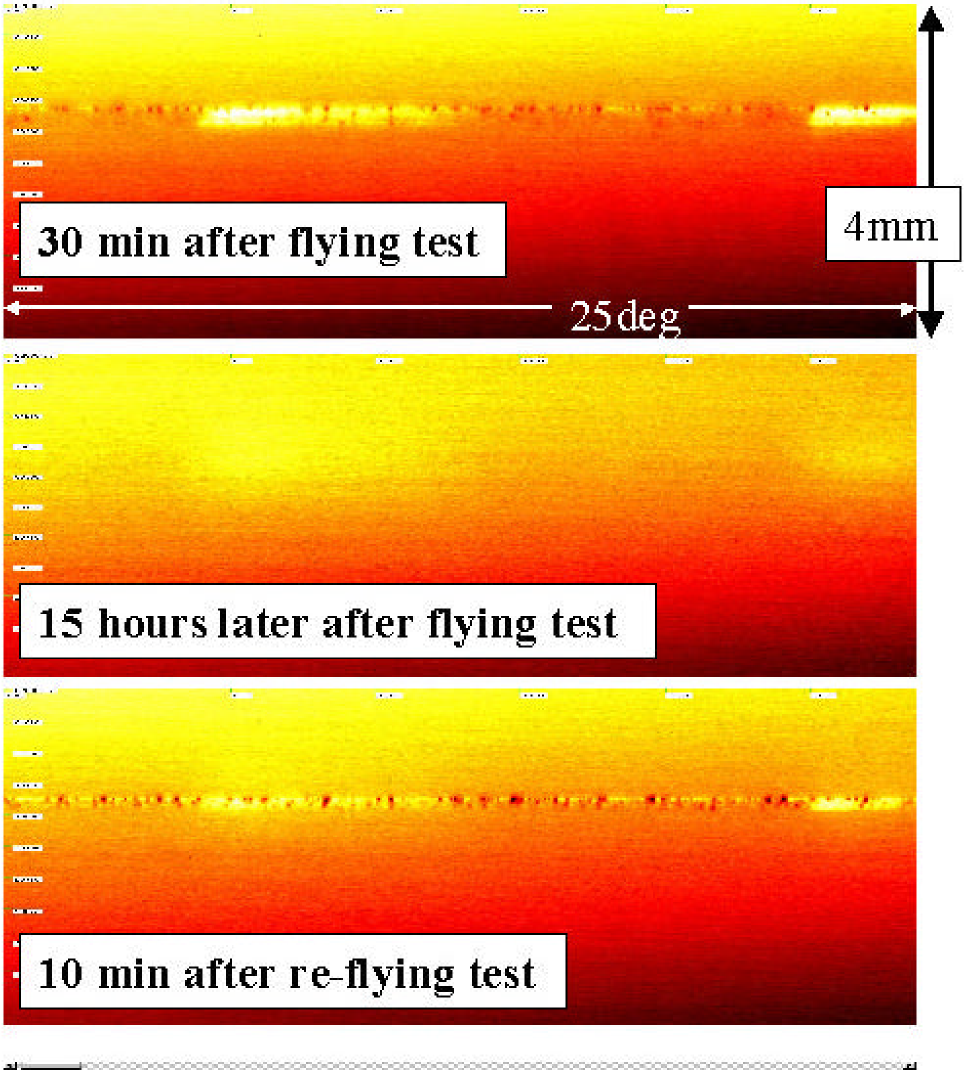

Fig. 3.4.1 Lubricant recovery and re -flying test results after 15 hours later after flying test

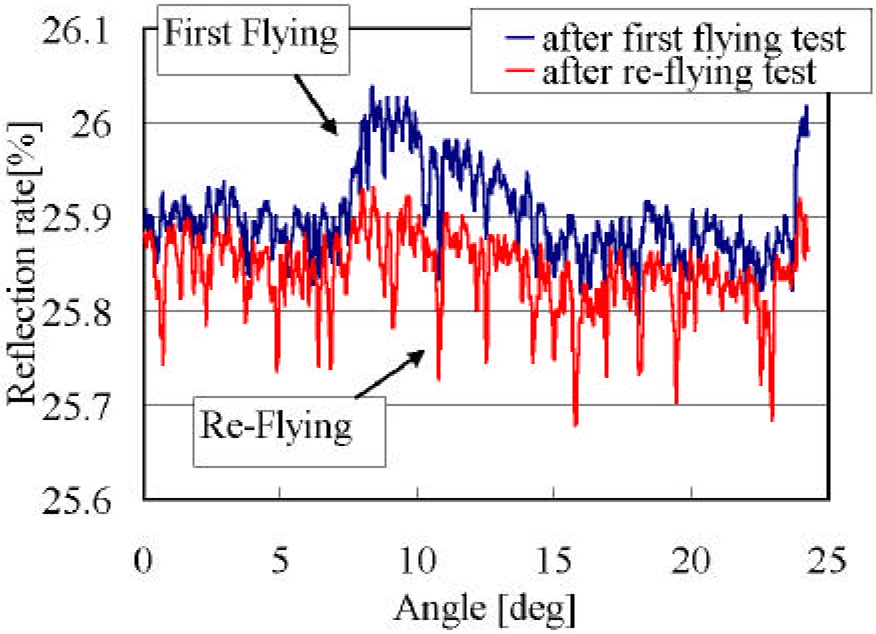

Fig. 3.4.2 Lube thickness modulation along the lube modulation in Fig. 3.4.1

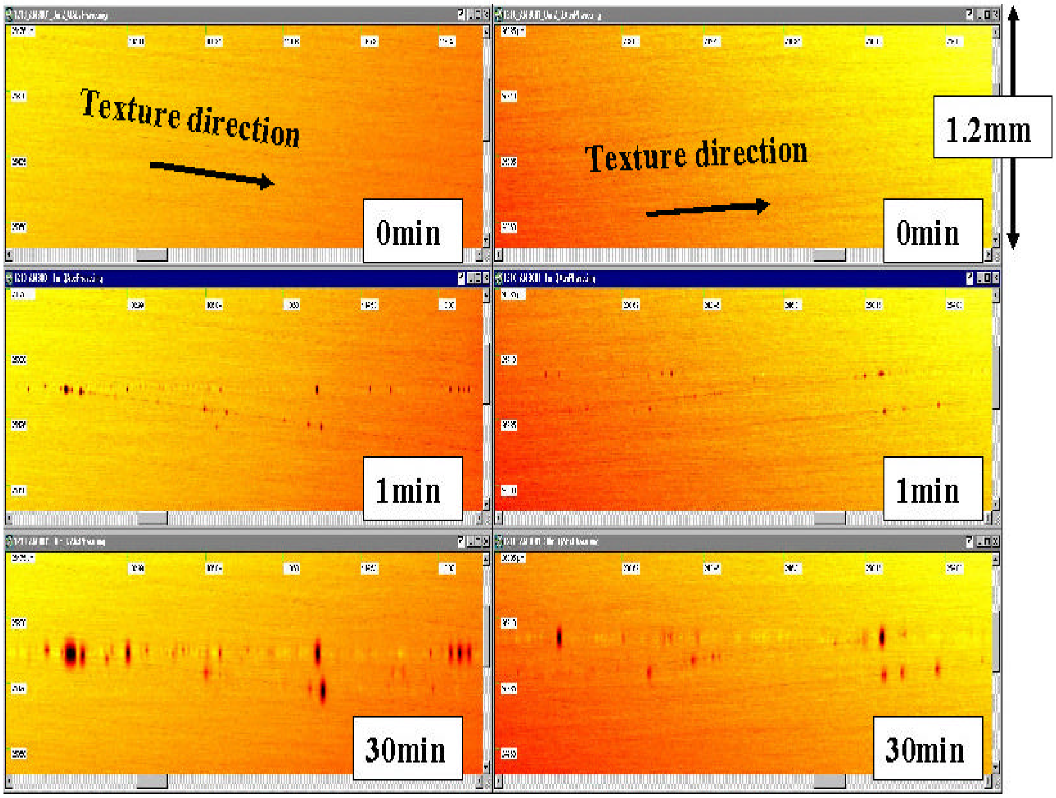

Fig. 3.5.1 Lube modulation along textured lines on disk surface

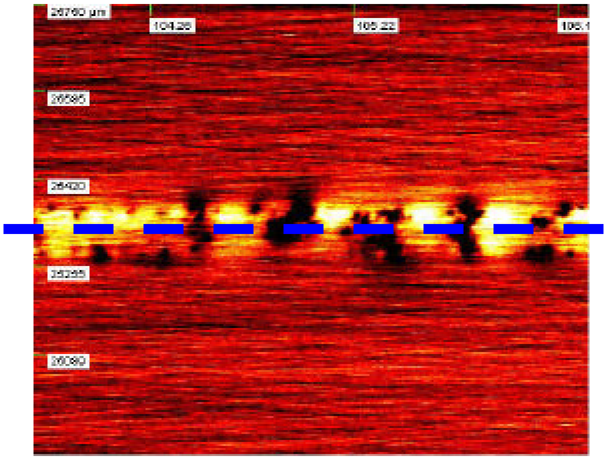

Fig. 3.6.1 A lube profile image after a slider flying detected by OSA

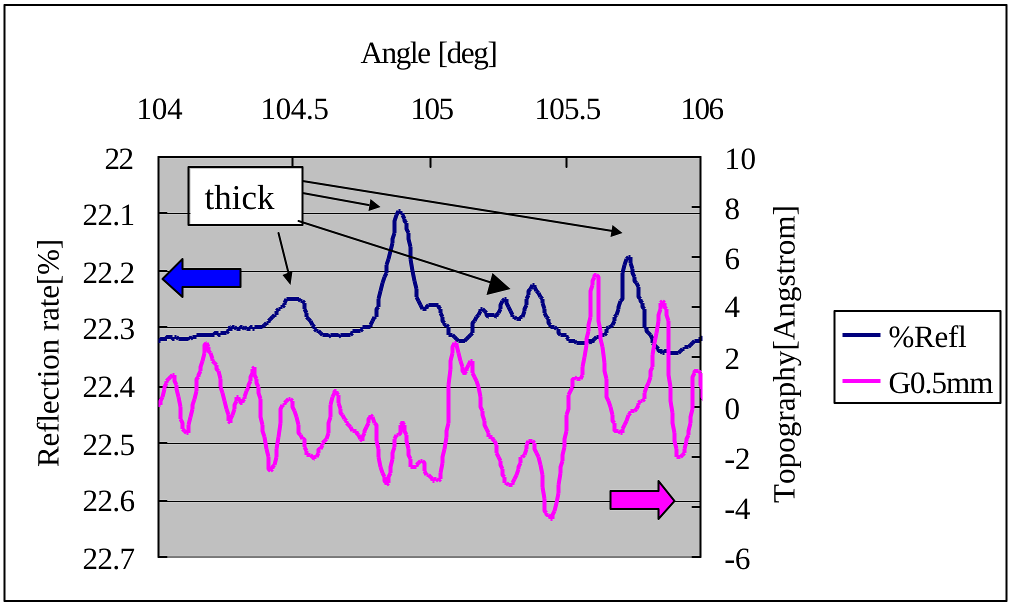

Fig. 3.6.2 A cross section of the lube modulation indicated as a dot line in Fig.3.6.1

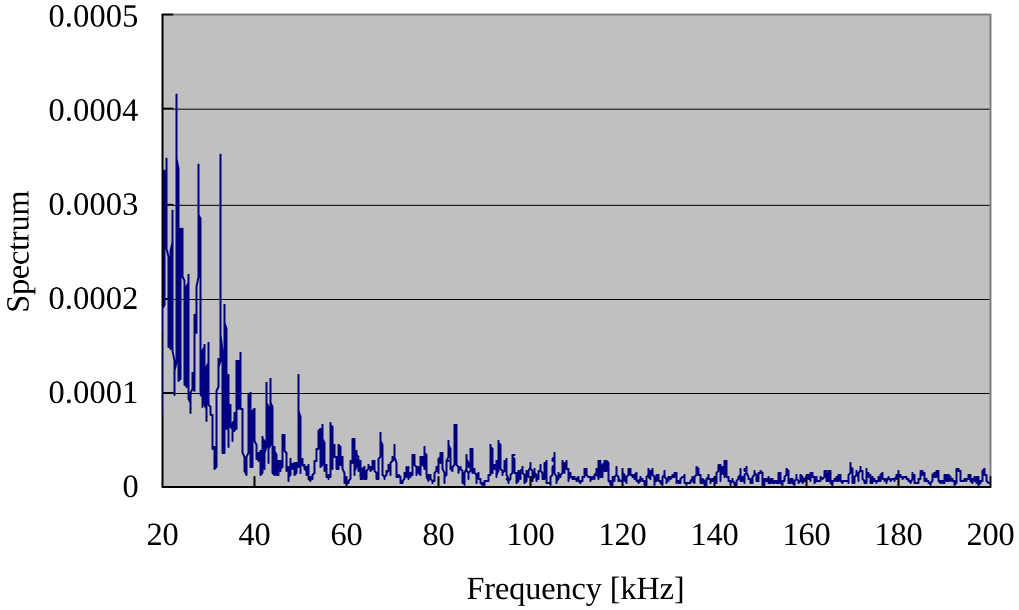

Fig. 3.6.3 Spectrum analysis result of the disk topography along lube modulation

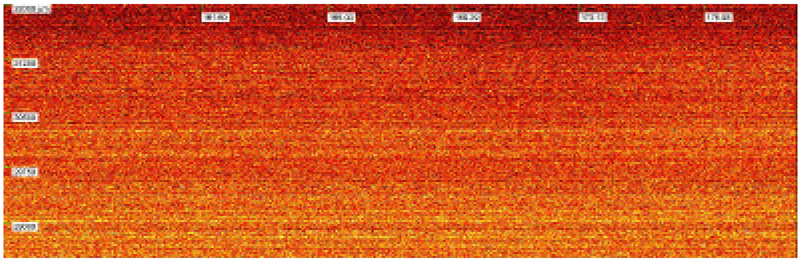

Fig. 3.7.1 Lube surface profiles detected by OSA at 0 minute

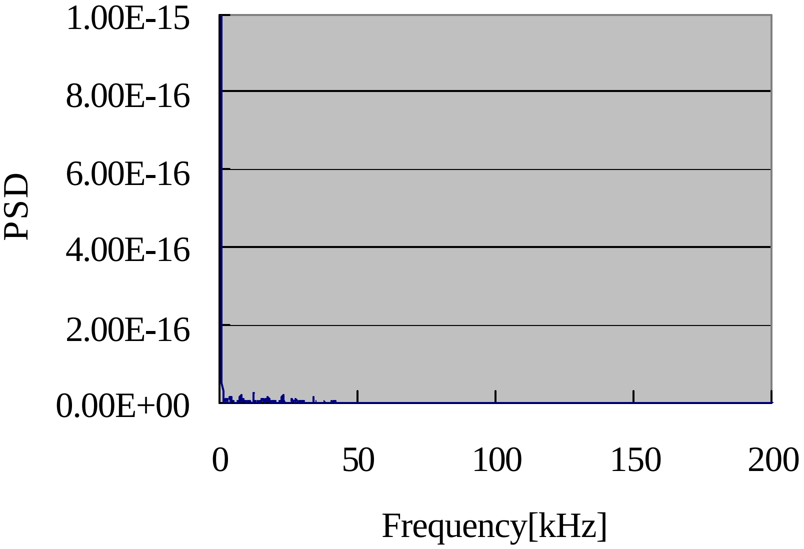

Fig. 3.7.2 Spectrum analysis result derived from cross correlation function at 0 minute

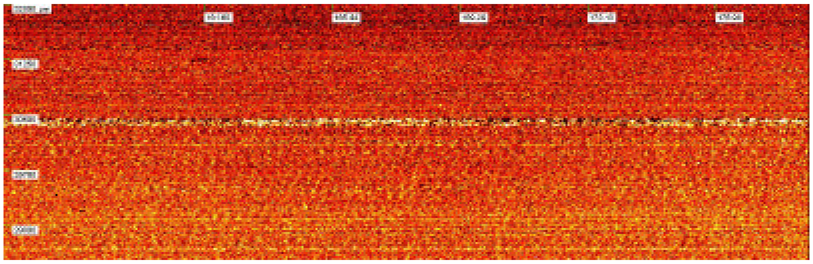

Fig. 3.7.3 Lube surface profiles detected by OSA at 1 minute

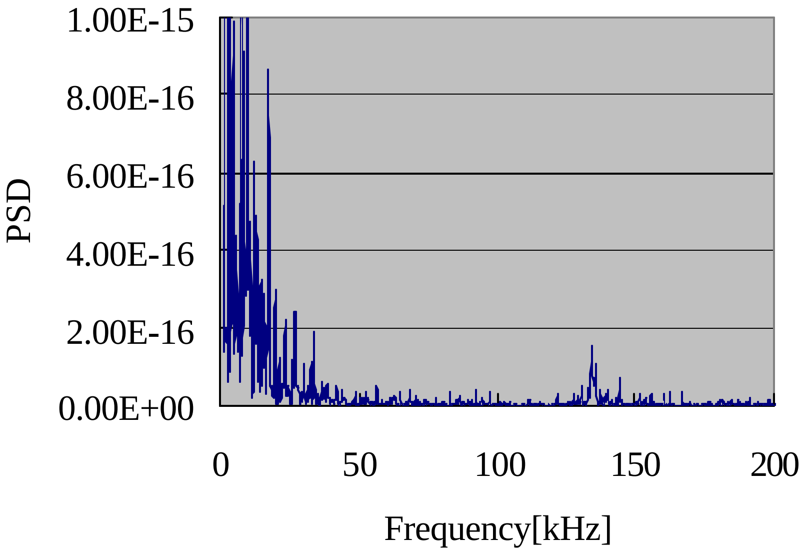

Fig. 3.7.4 Spectrum analysis result derived from cross correlation function at 1 minute

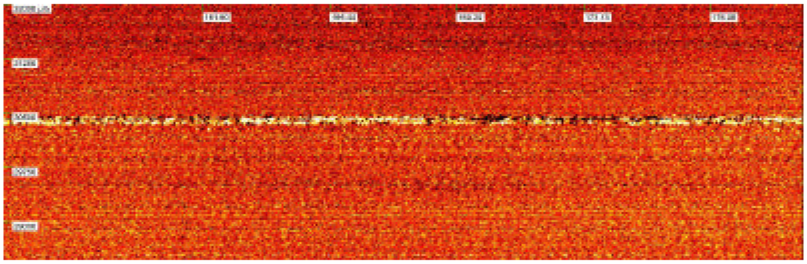

Fig. 3.7.5 Lube surface profiles detected by OSA at 2 minutes

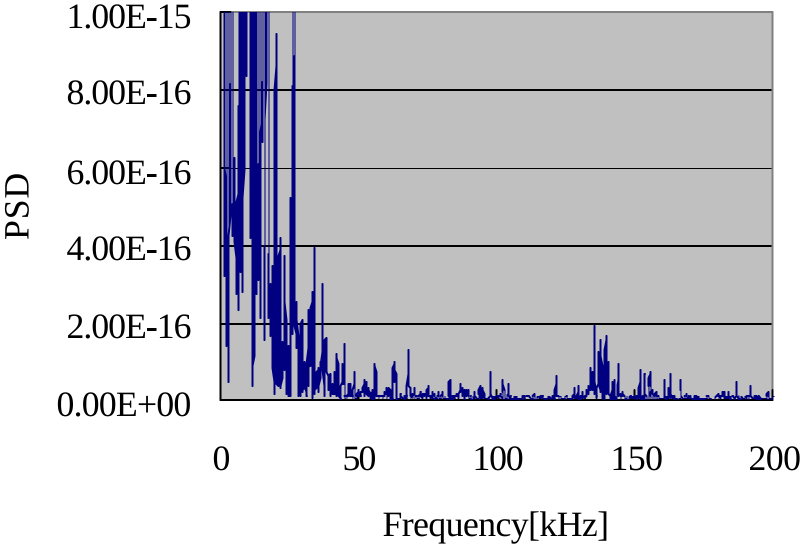

Fig. 3.7.6 Spectrum analysis result derived from cross correlation function at 2 minutes

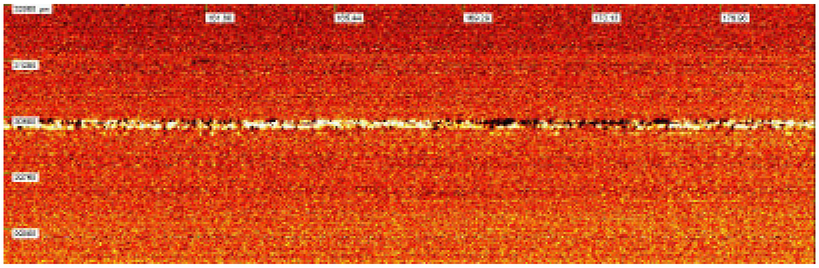

Fig. 3.7.7 Lube surface profiles detected by OSA at 5 minutes

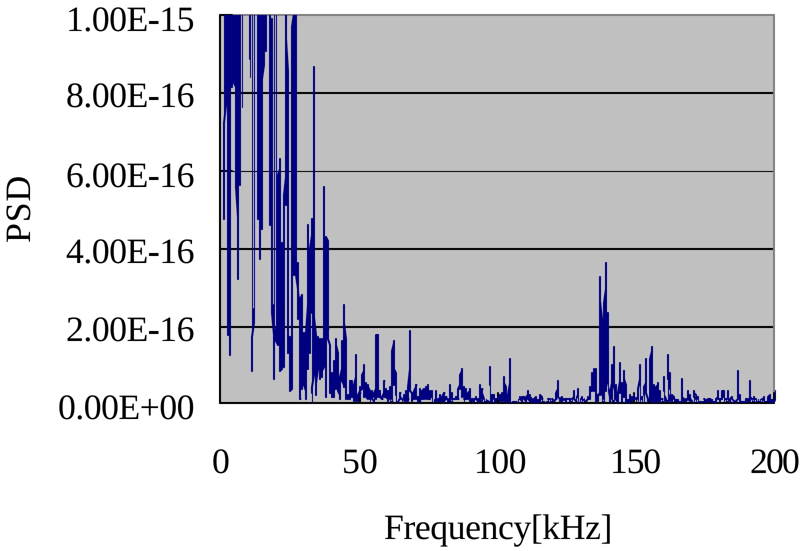

Fig. 3.7.8 Spectrum analysis result derived from cross correlation function at 5 minutes

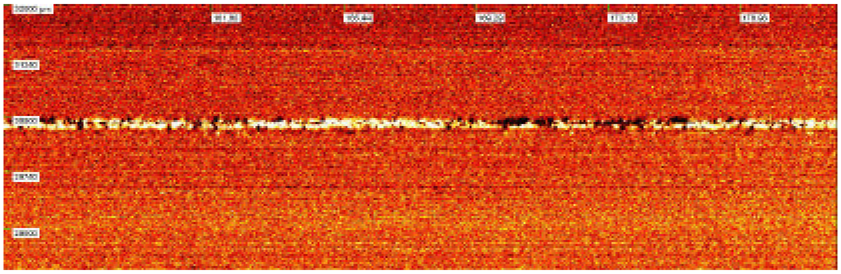

Fig. 3.7.9 Lube surface profiles detected by OSA at 10 minutes

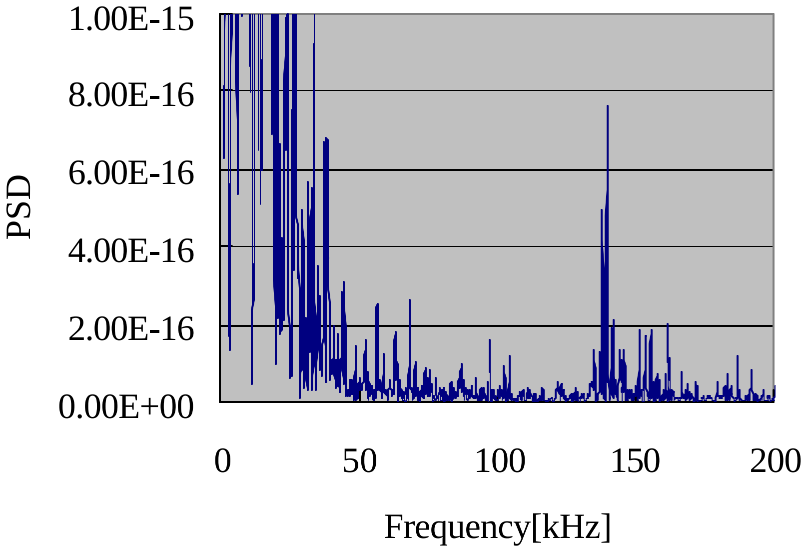

Fig. 3.7.10 Spectrum analysis result derived from cross correlation function at 10 minutes

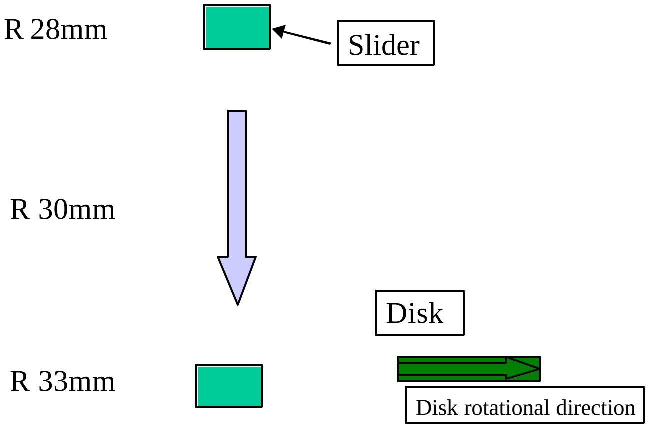

Fig. 3.7.11 A method of "slider passage test"
1. We first flew a slider at radius 28mm and then moved it to 33mm.

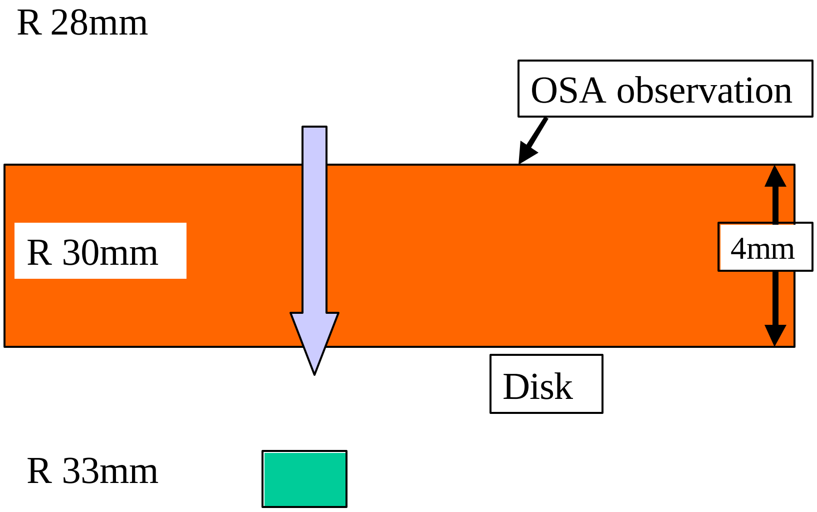

Fig. 3.7.12 A method of "slider passage test"
2. We detected nearby radius 30mm area after the flying slider going through there.

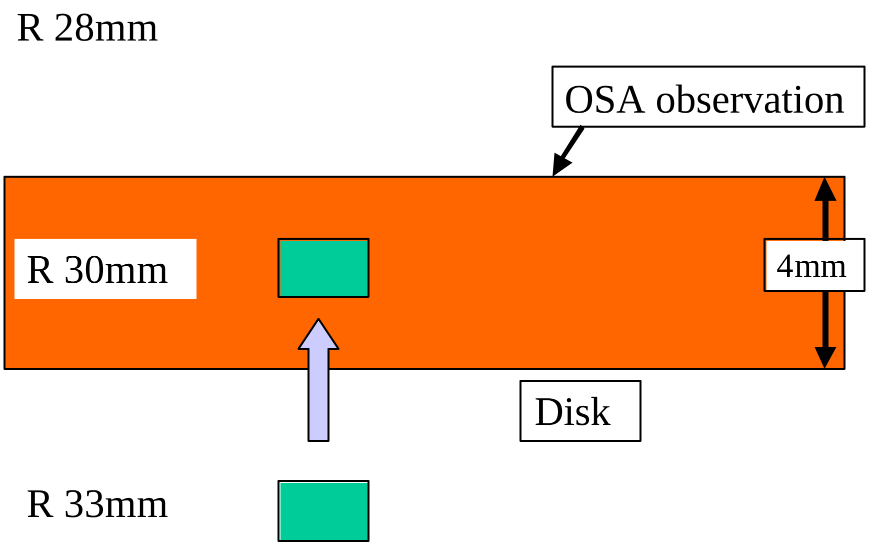

Fig. 3.7.13 A method of “slider passage test”

3. We returned it to radius 30mm and fulfilled a flyability test again.

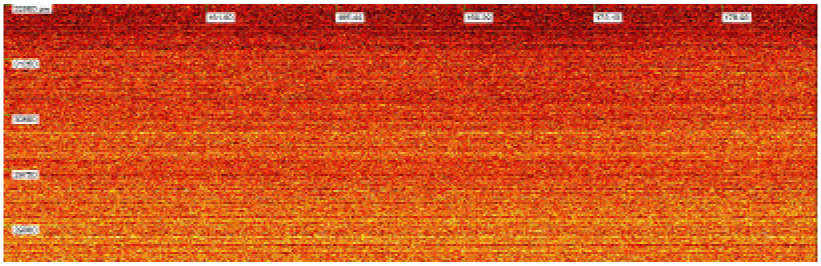

Fig. 3.7.14 Lube surface profiles detected by OSA at 0 minutes

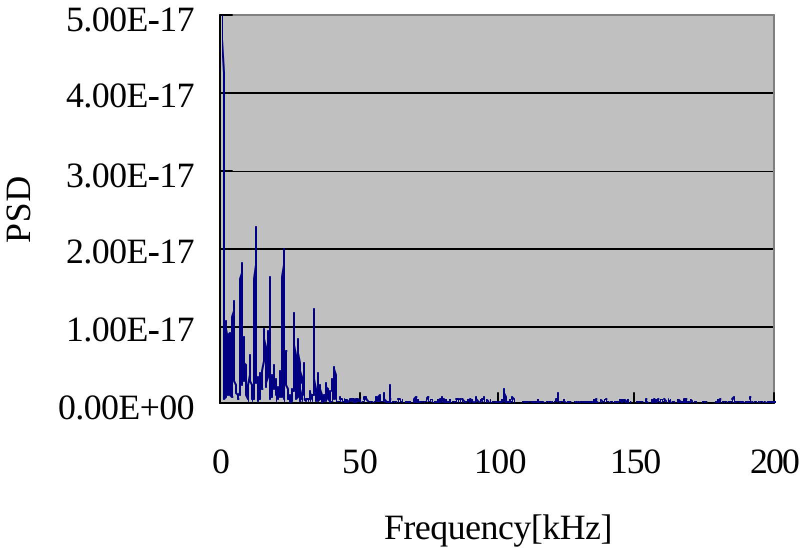

Fig. 3.7.15 Spectrum analysis result derived from cross correlation function at 0 minute

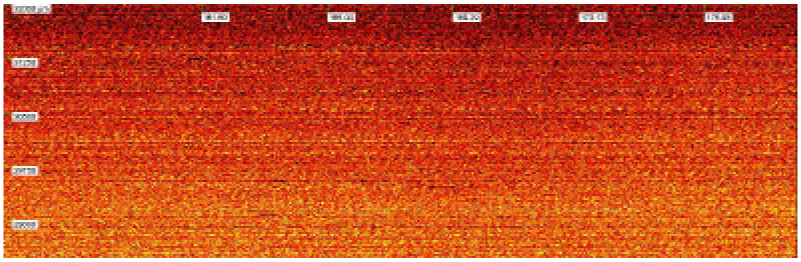

Fig. 3.7.16 Lube surface profiles detected by OSA after the flying slider going through

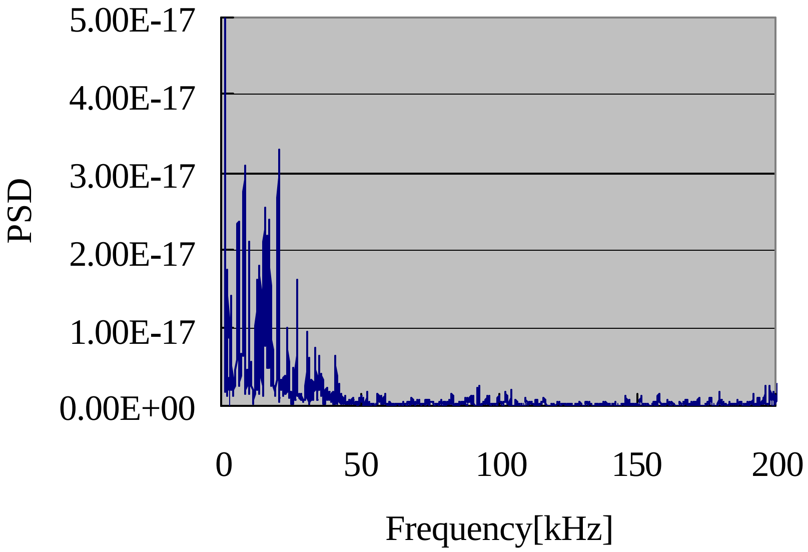

Fig. 3.7.17 Spectrum analysis result derived from cross correlation function after the flying slider going through

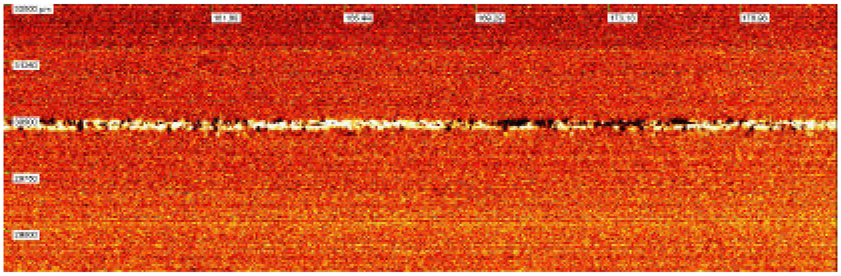

Fig. 3.7.18 Lube surface profiles detected by OSA at 1 minute

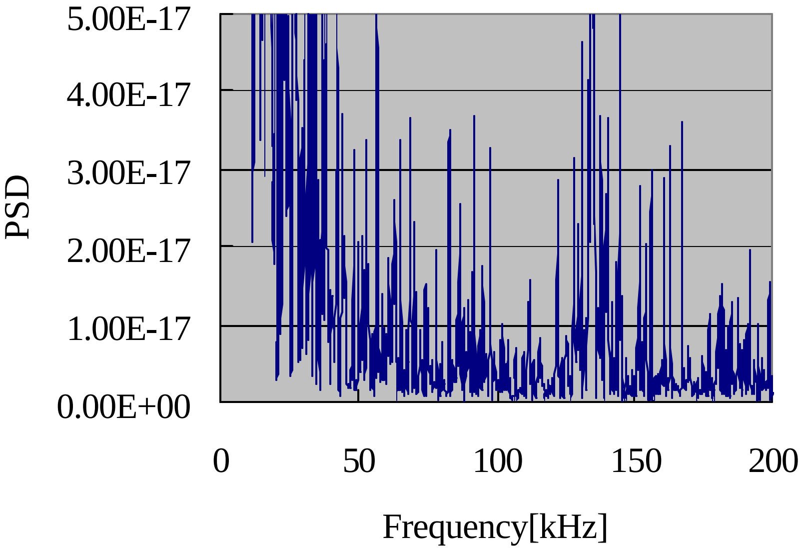

Fig. 3.7.19 Spectrum analysis result derived from cross correlation function at 1 minute

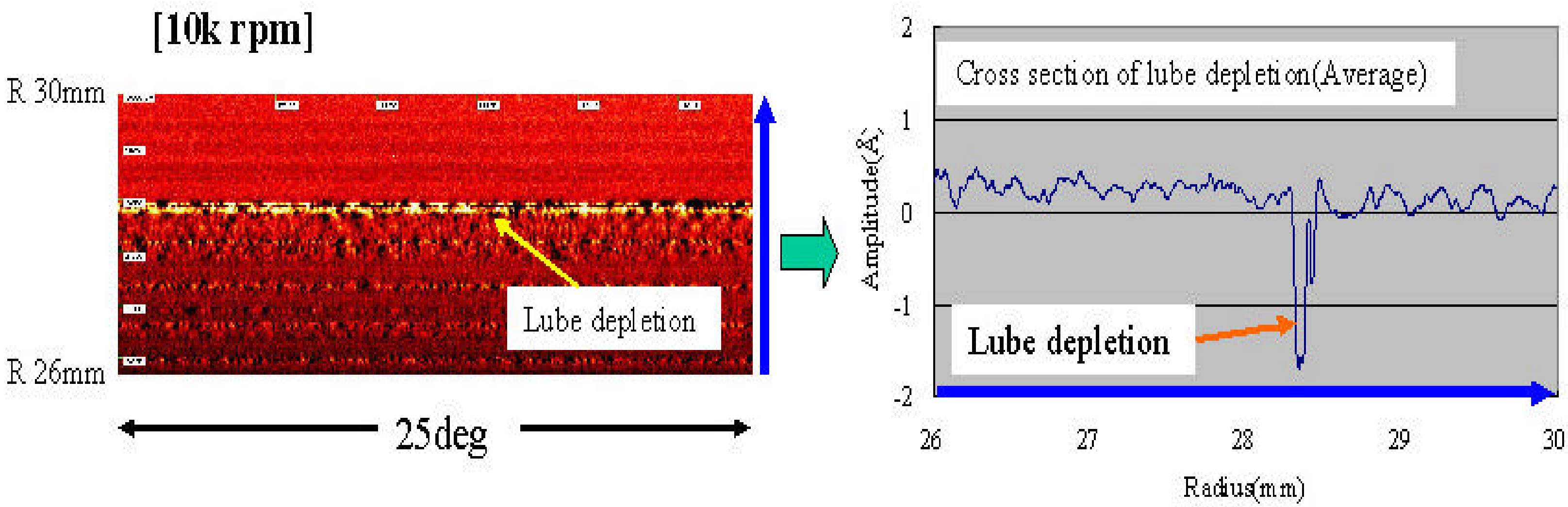

Fig. 3.8.1 Lube depletion depth after 10 minutes flying test at 10,000 rpm case

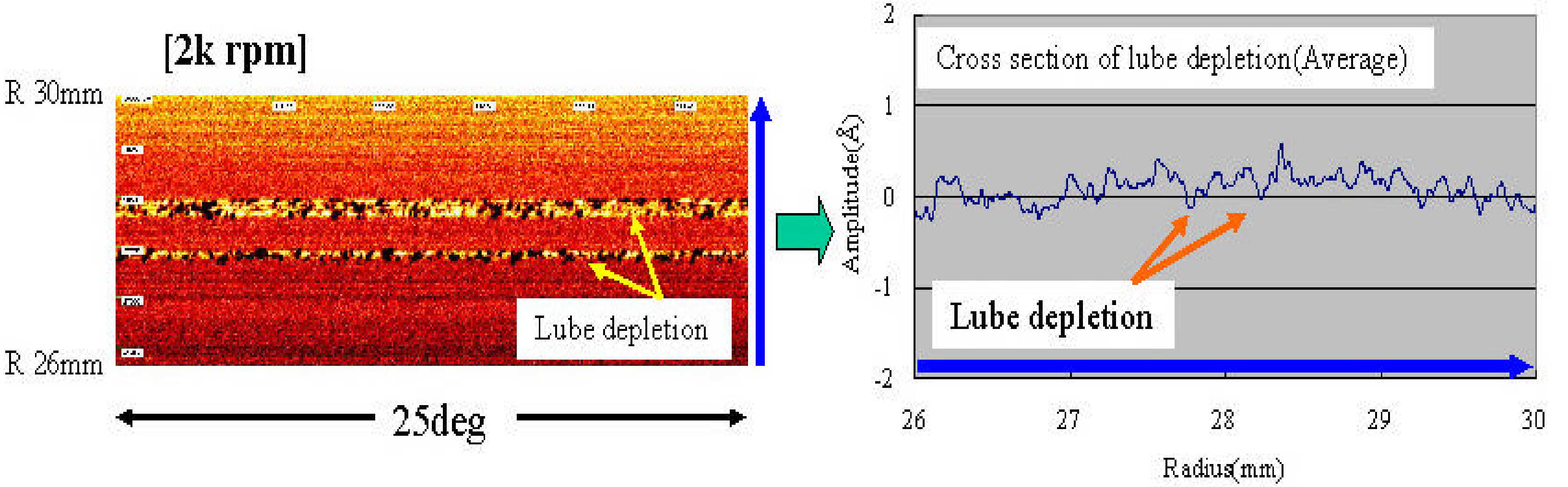

Fig. 3.8.2 Lube depletion depth after 10 minutes flying test at 2,000 rpm case

R=28mm at 10k rpm	R=28mm at 2k rpm
Min FH=21.35[nm] Pitch Angle=117.28[urad] Roll=25.09[urad] Max.Pressure=9.43[atm]	Min FH=16.96[nm] Pitch Angle=185.08[urad] Roll=3.80[urad] Max.Pressure=5.11[atm]

Table. 3.8.1 Slider flying heights calculated by using CML software