Experimental Evidence of Lubricant Droplet Transfer from Slider to Disk

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Abstract

To enable the smaller slider-disk spacing that is required for the continual increase in data storage density, the interaction between the slider and the lubricant layer must be understood. In this paper, an interesting experimental phenomenon of sudden lubricant droplet transfer from the slider to the disk is reported and investigated. This phenomenon is different from the lubricant moguls and ripples previous researchers have identified. Is it expected that this sudden lubricant drop-off will degrade head-disk spacing and magnetic signal. Therefore it is imperative to understand the mechanism and the driving conditions so that it can be prevented.

I. INTRODUCTION

At a fundamental level, hard drive areal density is tied to magnetic spacing in that higher areal density necessitates smaller magnetic spacing. With current industry goals in mind, the magnetic spacing for 3.1 Tbit/in^2 is about 2.8 nm. This drives a physical spacing of 1.1 nm between the slider and the disk surface, including the lubricant layer. With a physical spacing this small, anything that disturbs this spacing has potentially catastrophic consequences for hard drive design. Traditionally, a lubricant layer has been used in hard drives to lower friction in the case of contact-start-stop designs as well as to protect the interface against intermittent slider-disk contacts and corrosion. The behavior of lubricants has been studied extensively by previous researchers who reported the appearance of lubricant moguls [1] and ripples [2] as a slider flies above a particular disk track. These phenomena are ascribed to slider-induced air shear by Marchon et al. [3]. These phenomena are important in designing the interface, as they can contribute to magnetic spacing loss.

During investigations into the behavior of lubricants as applied to thermally-activated slider (TFC) designs, a new phenomenon was discovered. Sudden lubricant drop-off was observed when an un-actuated TFC slider was flown over a relatively thick Zdol + X1P lubricant disk. After a few minutes a sudden spike in AE and/or LDV sensor signal was seen to correspond to the sudden appearance of a thick lubricant drop as measured by a Candela OSA. This thick lubricant drop was subsequently "smeared out" with continuing passes of the slider (on the order of a few seconds to minutes). The relatively large height of these lubricant drops (on the order of a few nm) suggests that understanding and controlling the drops is necessary to achieve a stable magnetic spacing. Such a degradation of magnetic signal was reported previously by Pit et al. [4] in response to a nominal fly-height change of 15 nm caused by a lubricant droplet intentionally introduced into the interface.

II. Experimental Setup

For these experiments, a current-generation femto form-factor ABS design was used with simulated nominal fly-height around 14 nm. The disk was coated with Zdol + X1P, 2000 g/mol, 20.1 angstroms thickness, 7% bonded ratio, and 0.6 angstroms additive. The pre-test lubricant roughness (three sigma) was around 0.45 nm. The disk was 0.050" thick with an outer diameter of 95 mm.

Experiments were performed using a Candela 5100 OSA system with a speed-controlled air-bearing spindle. The Q Phase channel was used to measure lubricant thickness before and during the tests. The slider-suspension assembly was manually loaded onto the disk using a micrometer with resolution of 0.0001". For all tests, the skew was zero degrees. An acoustic emission (AE) sensor mounted on the arm that holds the baseplate was used to monitor for contact events. In addition, a Polytec LDV was focused on the back of the flexure and used to monitor the fly-height modulation of the slider after a 2 kHz high-pass filter. Both AE and LDV sensor outputs were captured continuously at 10k samples/second by a TTi data acquisition system for the duration of the test.

At the beginning of each test, the slider was loaded manually at the load radius and then moved inward by 1mm to the test radius. The LDV was focused on the rear of the flexure after movement to the test radius. Once loaded this way, the slider remained on-track at the test radius for approximately 20 minutes. At one minute intervals OSA scans were taken over the entire disk circumference and a radial range of 2 mm (test radius +/- 1mm). The resolution of the OSA scan was 2 μm in the radial direction and approximately 0.044 degrees (20 to 30 μm) circumferentially. At the end of the test, the slider was unloaded manually and then inspected using a microscope for lubricant pick-up.

III. Data analysis method

The OSA data were converted to lubricant change data by subtracting the before-test "base" scan from the in-situ scans. The scan area was reduced from 2 mm wide to 1 mm wide to reduce the size of the data to analyze, but care was taken to ensure that the entire flying track was still covered. The reflectivity data was imported into a Matlab program where a custom data processing code converted the reflectivity measurements into lubricant thickness changes after high-pass filtering at 10 kHz. Some results were found by subtracting the previous in-situ OSA scan from a particular in-situ scan.

IV. Experimental results

The different measurement systems were correlated through the stopwatch measurements taken at each OSA scan and at the end of the AE/LDV data capture. Through these time measurements the events captured by the AE and LDV sensors can be correlated to the OSA lubricant thickness data.

(A) AE and LDV spikes

During a standard on-track flying test, the AE/LDV data capture looks like the example shown in Figure 1. The data capture length was usually two minutes longer than the flying time to allow for loading and unloading the slider. Since the AE and LDV sensor captures were started before the slider was loaded and continued after the slider was unloaded, the severe spikes seen at the beginning and end of the data set represent those loading events. In this example at 30 m/s linear speed, spikes are clearly seen in both the AE (top) and LDV (bottom) sensor data. Close inspection of the captured data shows that the timing of the spikes is virtually identical, meaning that neither sensor captures the event before the other one at this sampling rate. The delay between spikes varies widely between tens of seconds and minutes. The region after the first set of spike events is interesting in that it shows that once the events begin, they may end abruptly only to re-start later.

The shape of a single spike event as recorded by the AE sensor is shown in Figure 2. This figure reveals that each spike event is not a single spike, but a region of higher signal within a decay envelope. The region has duration of around 700 micro-seconds (on the order of 100 revolutions). The decay envelope appears to be roughly exponential as expected from a spring-mass-damper type response. This supports the interpretation that the slider is encountering an obstacle in its path and flying over it; with every pass reducing the size of the obstacle. The magnitude of the AE spike is as much as 15 times larger than the non-spike AE magnitude. A similar figure for the LDV spike shows a magnitude about three times larger than the non-spike LDV magnitude (figure not shown). This indicates that during the spike event the fly-height modulation (FHM) velocity is three times higher than usual, or either the slider is moving enough to de-focus the LDV spot. Either interpretation suggests a severe change in FHM.

(B) OSA MEASUREMENTS

Sample OSA measurements taken during the test depicted in Figure 1 are shown in Figures 3 and 4. Figure 3 shows typical OSA scans during time intervals where there are no AE/LDV spikes. The images shown in 3a and 3b are typical lubricant modulation patterns found by subtracting the before-test scan of the disk surface from the in-situ scans at 9 and 8 minutes, respectively. Of interest here is the result found by subtracting successive OSA scans to illuminate the changes in lubricant thickness during the 60 seconds between scans (Fig. 3c). The relative uniformity of Figure 3c as compared to 3a and 3b shows that while the lubricant modulation pattern is strong, it is not changing very rapidly in the minute between scans. This slow change in lubricant modulation is typical of most experiments. The OSA images in Figure 4 are taken from the same area of the disk as the images from Figure 3, but later in the test. At first glance, the images shown in Figures 4a and 4b, taken at 16 and 15 minutes, seem very similar to the images in Figures 3a and 3b. However, when the successive scans are subtracted, Figure 4c shows a major change in lubricant occurred between the 15 and 16 minute scans. The dark line in the middle of Figure 4c represents a region were the lubricant thickness at 16 minutes is much thicker than it was at 15 minutes. The relative uniformity of the rest of the image shows that this is an isolated region of higher thickness. It is clear from Figures 4a and 4b that the sudden thickness increase in lubricant may not be easily visible in the standard “measurement – base” screen capture. A “measurement – previous measurement” difference may be required to see the change. Thus, in-situ OSA scans are required to observe the phenomena described here.

Figures 5 and 6 present the lubricant height data for Figure 4c in oblique and angular views. Examination of the OSA data shows that these thicker lubricant regions can easily be on the order of 1 nm thicker than the surrounding area. Considering that the thickness measured by the OSA is the thickness after the end of the spike event, it is expected that the thickness during the spike event will be higher than the 1 nm measured here. As the lubricant thickness for this particular disk is only 2 nm, this region of thicker lubricant represents a significant change in the lubricant profile to which the slider must adapt to maintain constant slider-disk spacing.

During repeated testing, time intervals that include AE/LDV spike events, such as seen in Figure 1, also show some amount of sudden lubricant thickness increase as measured by the OSA. Only one example is given here, but the result has been observed in multiple experiments. AE/LDV spike events and OSA regions of suddenly thicker lubricant were observed during a later test using a disk coated with 20.8 angstroms of Zdol, spinning at approximately 30 m/s. This result suggests that lubricant droplets do not appear to require the additive X1P. After all tests, some lubricant pickup was observed at the trailing edge center (TEC) of the slider (near the sensors). However, the lubricant was easily removed through dipping the ABS surface in an HFE ultrasonic bath as seen in Figure 7.

(C) Lubricant dragging

During another test using the same disk of Zdol + X1P, at a linear speed of 30 m/s, intermittent LDV spikes were seen during the first seven minutes of the test (with corresponding sudden changes in lubricant thickness as measured by the OSA). After about seven minutes of flying time, the LDV signal broadened noticeably until about 11.5 minutes after which there were no more events. The LDV data captured is shown in Figure 8. While the magnitude of the broadened region is less than the adjacent spike event, the continuous nature implies a somewhat different origin. In investigating the corresponding OSA scans, some difference images were obtained and are shown in Figure 9. In Figure 9, the difference images are presented in sequential order, from bottom right moving upwards and then bottom left moving upwards. At 5 minutes (not shown), a long region of thicker lubricant appeared, similar to that seen in Figure 4. By the 6 minute scan, that region was gone (producing the light band in the middle) and replaced by a very short region of thicker lubricant, near the left of the 6 minute minus 5 minute image. From 6 minutes through 12 minutes, the short region moved in the down-track direction about 4 degrees (2 mm) every minute which corresponds to approximately 0.2 microns/revolution. Finally at 13 minutes, the feature was gone. Figure 10 shows the height of this lubricant droplet from each OSA scan in a combined image. Notice that the peak height of this lubricant droplet is around 45 nm while the thickness of the disk lubricant layer is approximately 2 nm. The height of the lubricant droplet drops smoothly with time. The broadened LDV sensor data from Figure 7 returned to the baseline level at approximately 11.5 minutes which corresponds to a peak droplet height of between 26 and 14 nm. The CMLAir simulation results of this slider and experimental conditions show a nominal fly-height of about 14 nm. The obvious interpretation of this data is that during the time period where the lubricant droplet height was larger than the nominal fly-height, the flight of the slider was disturbed by the lubricant droplet, resulting in the broadening of the LDV sensor data. A similar lubricant dragging result was found in a later experiment, indicating repeatability. It is not immediately clear why these lubricant droplets remained on the disk for several minutes while other droplets did not.

V. CONCLUSION

While the exact physical process responsible for these lubricant drops is currently being investigated, the experimental data presented here shows unequivocally that such lubricant drops can occur naturally in some slider-disk interfaces. The following physical process is hypothesized: First, the slider gathers lubricant over the entire flying track through evaporation, shear effects, corrugation instabilities, and/or intermolecular force-induced dewetting as suggested by Ambekar et al. [5]. As it continues to fly, the lubricant on the ABS surface migrates towards the trailing edge as reported by Kubotera and Bogy [6]. Next, due to some physical process, the lubricant gathered near the trailing edge forms a droplet and is deposited on the disk, possibly due to an intermittent contact event or intermolecular forces. During the next revolution, the slider encounters the lubricant droplet as an obstacle in its path and the vibration of the slider is what is picked up by the AE and LDV sensors. After tens to hundreds of revolutions, the physical slider-droplet encounter and slider-induced air-shear spreads out the lubricant droplet enough so that the flying path is not severely affected and the AE and LDV sensor data return to their baseline values. For the lubricant dragging result, it is hypothesized that the original lubricant droplet may be so large as to cause a significant increase in fly-height with associated decrease in air shear and thus may remain on the disk far longer than smaller droplets. Experiments are currently being conducted to investigate under what conditions formation of these lubricant drops is likely to occur.

ACKNOWLEDGMENT

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REFERENCES

[1] R. Pit, B. Marchon, S. Meeks, V. Velidandla, “Formation of lubricant “moguls” at the head/disk interface”, Tribology Letters vol. 10, no. 3, pp. 133-142, 2001

[2] X. Ma, H. Tang, M. Stirniman, J. Gui, “Lubricant Thickness Modulation Induced by Head-Disk Dynamic Interactions”, IEEE Trans. Magn., vol. 38, no. 1, pp. 112-117, 2002

[3] B. Marchon, Q. Dai, V. Nayak, R. Pit, “The Physics of Disk Lubricant in the Continuum Picture”, IEEE Trans. Magn., vol. 41, no. 2, pp. 616-620, 2005

[4] R. Pit, Q. H. Zeng, Q. Dai, B. Marchon, “Experimental Study of Lubricant-Slider Interactions”, IEEE Trans. Magn., vol. 39, no. 2, pp. 740-742, 2003

[5] R. Ambekar, D. B. Bogy, Q. Dai, B. Marchon, “Critical clearance and lubricant instability at the head-disk interface of a disk drive”, Applied Physics Letters, vol. 92, no. 3, pp. 033104-1-3, 2008

[6] H. Kubotera and D. B. Bogy, “Effect of various physical factors on thin lubricant film migration on the flying head slider at the head-disk interface of hard disk drives”, Journal of Applied Physics, vol. 102, pp. 054309-1-6, 2007

FIGURES

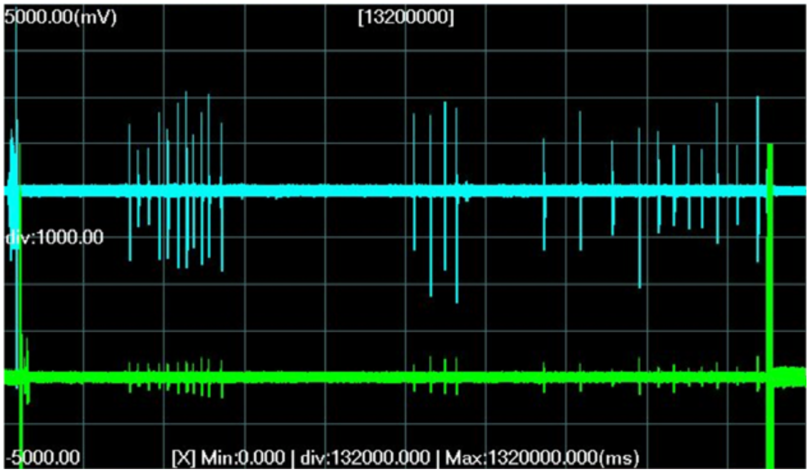

Fig. 1. AE (top) and LDV (bottom) data showing intermittent spikes during a 20-minute flying test at approximately 30m/s linear speed.

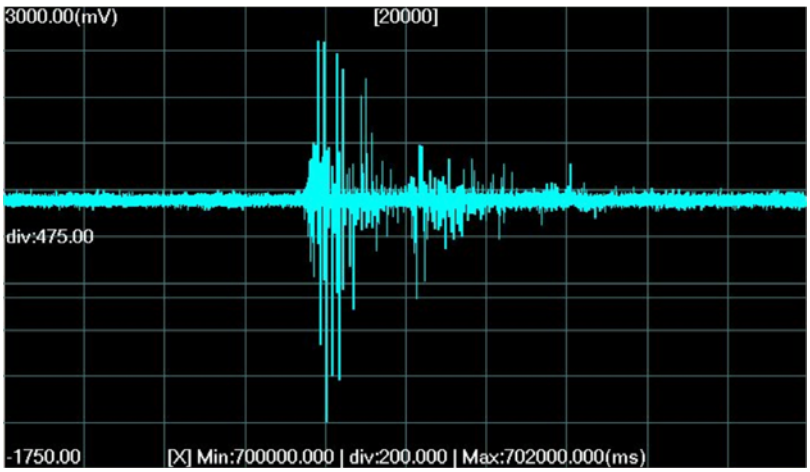

Fig. 2. Example AE sensor spike (x-axis length is 2 seconds).

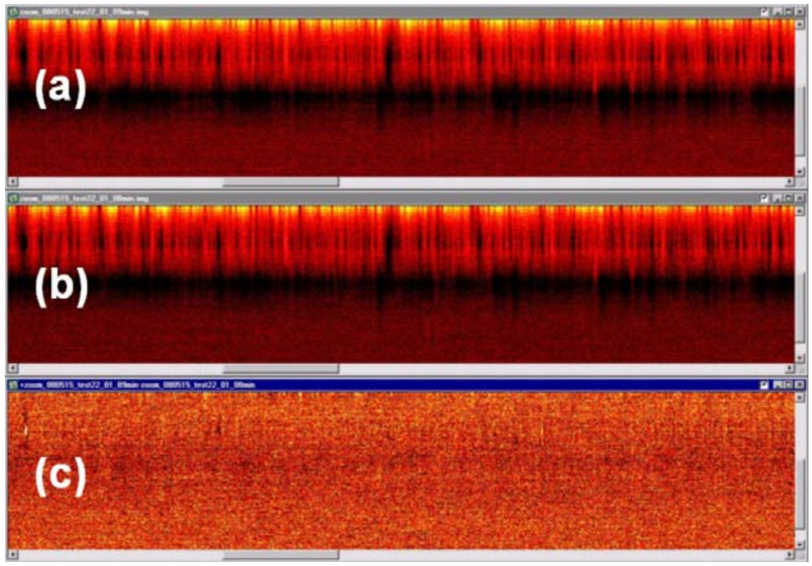

Fig. 3. OSA screenshot showing lubricant thickness over 500 µm x 54 degree area (darker = thicker) showing an interval with no lubricant droplets or AE/LDV spikes (a) 9 minute – base (b) 8 minute – base (c) 9 minute – 8 minute.

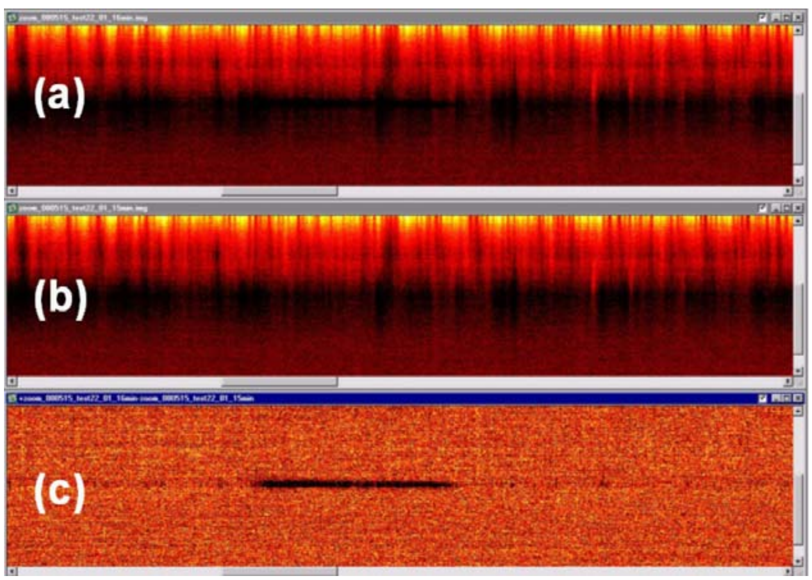

Fig. 4. OSA screenshot showing lubricant thickness over 500 µm x 54 degree area (darker = thicker) showing a lubricant droplet (a) 15 minute – base (b) 16 minute – base (c) 16 minute – 15 minute.

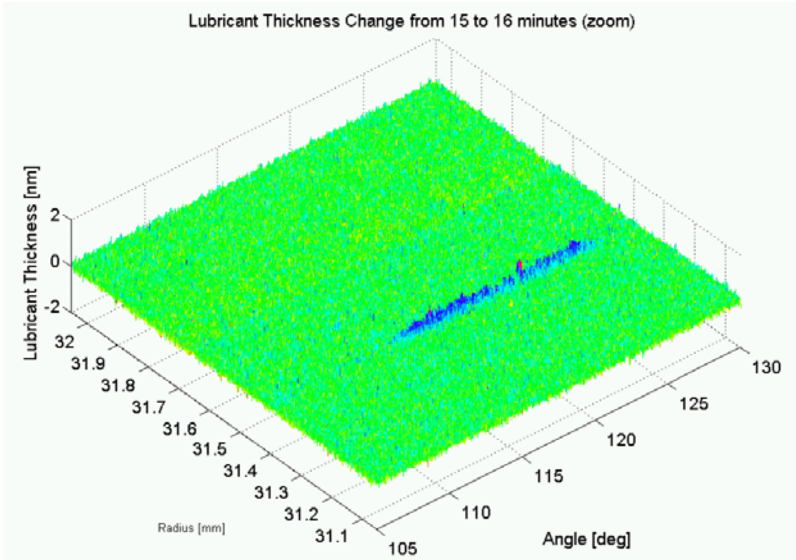

Fig. 5. Lubricant height from 16 minute – 15 minute data showing 1 mm x 25 degree area around lubricant drop (oblique view).

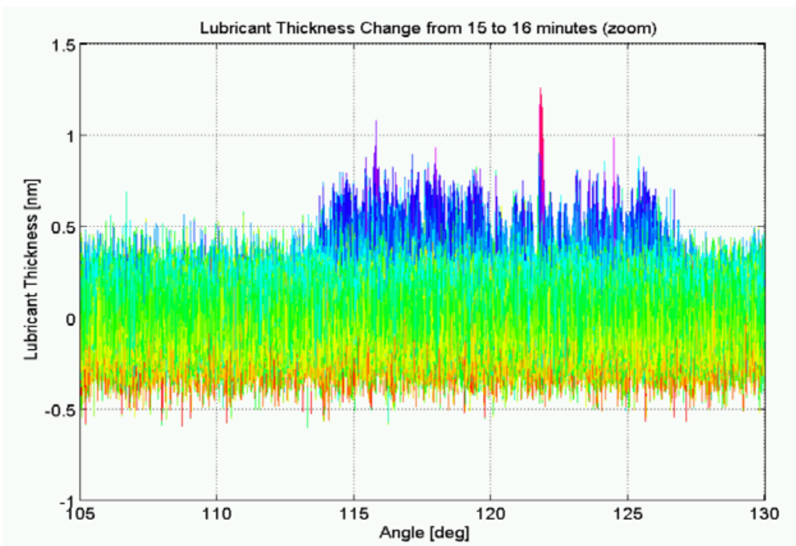

Fig. 6. Lubricant height from 16 minute – 15 minute data showing 1 mm x 25 degree area around lubricant drop (angular view).

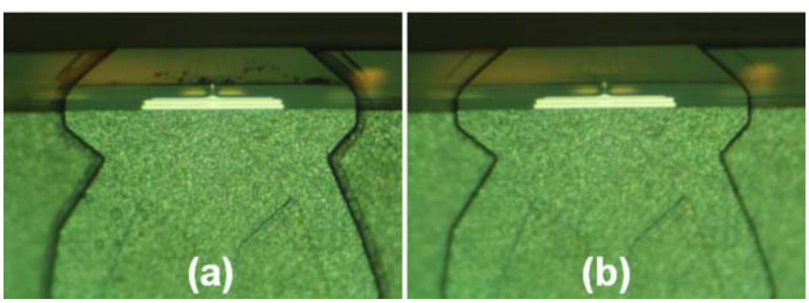

Fig. 7. Lubricant pickup at TEC (a) after a 20 minute on-track flying test (b) after cleaning with HFE ultrasonic bath.

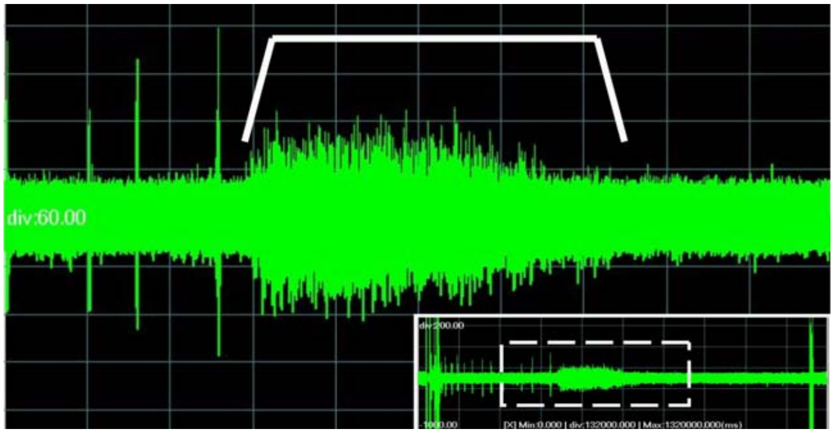

Fig. 8. LDV sensor data from lubricant dragging result, zoomed view of 4 to 14 minutes with broadened region bracketed. Inset shows the entire 20 minute test data with the 4 to 14 minute region outlined.

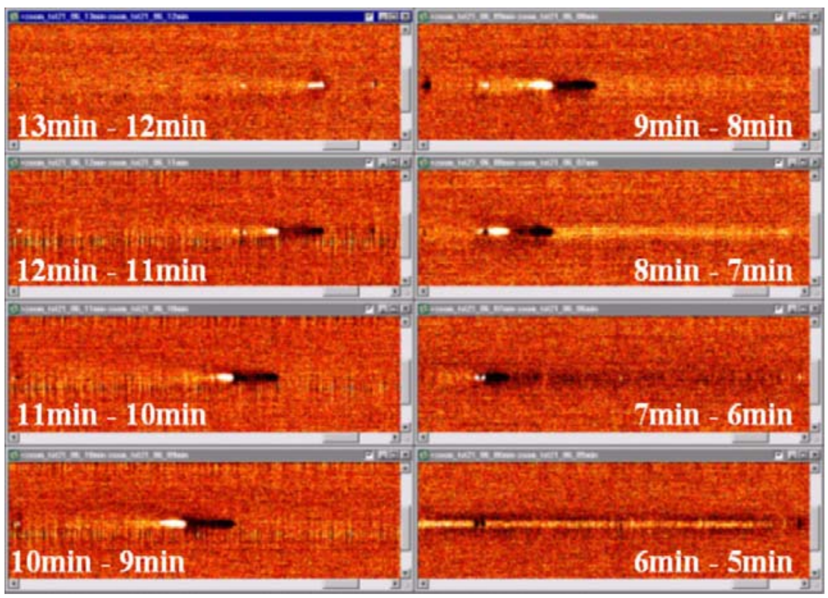

Fig. 9. OSA screenshot of changes in lubricant thickness between scans over 350 µm x 27 degree area (darker = thicker) showing down-track motion of a large lubricant droplet (down-track is to the right of each frame).

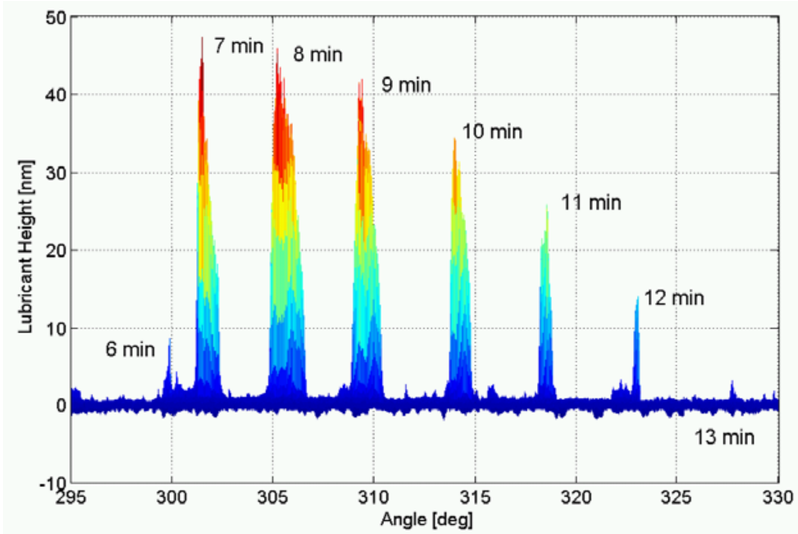

Fig. 10. Angular view of lubricant droplet height data as it moves down-track with successive OSA scans (6 min to 13 min).