On the Touchdown-Takeoff Hysteresis Observed At the Head-Disk Interface In Hard Disk Drives

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Abstract

As the flying height in hard disk drives is reduced below 5nm a variety of phenomena such as intermolecular forces and meniscus forces may affect the ability of the slider to fly stably over the disk. The presence of these proximity interactions leads to a dynamic instability. Identification of these forces is important for achieving the necessary interface for the areal density goal of 1 Tb/sq.in. To achieve this identification, we study the touchdown-takeoff hysteresis observed in hard disk drives. The touchdown and takeoff velocities are a measure of slider stability as they indicate how soon the slider loses its stability and how soon it regains it, respectively. Thus the hysteresis is a measure of recovery of the slider from contact to a stable flying regime.

We conducted touchdown-takeoff tests at different humidities and for different slider-disk combinations. It was found that the touchdown-takeoff hysteresis is a complex phenomenon that depends on many interactions. The slider dynamics itself during the touchdown-takeoff process introduces a hysteresis. In addition, intermolecular forces and meniscus forces contribute to the hysteresis. The long range IMF are mainly attractive in nature and increase the adhesion between the slider and disk. Meniscus forces act through lubricant mediated adhesion which occurs when a flying slider or a slider in partial contact picks up lubricant from the disk. Rough or contaminated disks can also cause early touchdown, though burnishing during contact can help regain the slider stability.

Introduction:

In order to achieve areal recording density of 1Tb/in^2, the head-disk spacing has to be reduced below 3 nm at which intermittent contact will be unavoidable. It has been experimentally observed that at such spacing there exists operational instability at the head-disk interface [2]. It has been shown through modeling that the stability of the head depends on phenomena such as the intermolecular forces (IMF) [2] and meniscus forces [3, 11]. In order to achieve operational stability, it is important to identify these phenomena experimentally and determine their contribution to the observed instability.

One of the methods by which we can achieve this is by studying the touchdown-takeoff hysteresis. The touchdown and takeoff velocities are a measure of slider stability as they indicate how soon the slider loses its stability and how soon it regains it, respectively. Thus the hysteresis is a measure of recovery of the slider from contact to a stable flying regime. Hence, to increase the stability at the head-disk interface, it is desirable to reduce the touchdown velocity, takeoff velocity and the resultant hysteresis.

To do an experimental study of the hysteresis we conducted touchdown-takeoff tests and concluded that intermolecular forces were present [1]. In this paper we present some findings on the dependence of hysteresis on other factors, including meniscus forces and the disk topography. It is hoped that this knowledge will provide a better understanding of the proximity phenomena at the head-disk interface and help in the control of the observed instability. The rationale for the experiment was as follows:

Since there are many phenomena such as the intermolecular forces, meniscus forces, external excitation due to lubricant modulation or disk waviness, slider-lubricant interactions and the dynamics of the slider itself that can affect hysteresis and stability, they can only be separated by knowing their “domain of operation” [1]. The touchdown velocity will only be affected by non-contact phenomena such as intermolecular force or external excitation due to lubricant modulation or disk topography. If the external excitation is kept constant by using disks of the same topography (roughness and micro-waviness) throughout the experiments while varying lubricant thickness, which changes the intermolecular force, the variation of the touchdown velocity can be attributed to a variation in the intermolecular forces. Thus, from these tests, the presence of intermolecular forces was concluded by observing the touchdown velocity [1]. Similarly, the variation in takeoff velocity was examined as a function of mainly contact interactions which include slider-lubricant interactions causing lubricant pickup by the slider and lubricant depletion and redistribution on the disk as well as the disk burnishing due to slider-disk contact.

Experiments

A. Touchdown-takeoff tests

A detailed description of the touchdown-takeoff tests has been provided in [1] and is briefly described by Figure 1. These tests were conducted on a CETR tester using an acoustic emission (AE) sensor to detect contact. The test conditions (humidity, disk lubricant thickness and slider design) were varied and the variation of touchdown speed, takeoff speed and the resultant hysteresis was observed. The slider and the disk were examined using an optical microscope and a Candela Optical Surface Analyzer, respectively, to determine the slider air-bearing surface (ABS) contamination and lubricant profile change on the disk.

B. Stability tests for effect of lube pickup

From the tests described above, only variations in takeoff velocity could be observed since a clean slider was used for every test. However, in operation, lubricant pickup and contamination occurs continuously. To study the effect of this accumulation, a different set of tests was conducted on a TTi spinstand using a Laser Doppler Vibrometer (LDV) to detect contact. These tests were similar to the tests described above with the exception that touchdown-takeoff tests were carried out continuously without cleaning of the slider before each test. For all the subsequent tests, a CML-7nm pico slider (Figure 2(a)) was used.

In these tests three disks from the same batch (INSIC-IV) but having different lubricant thicknesses (SG Lube) were used. Touchdown-takeoff tests were conducted on each of the disks in the order 1.2 nm, 0.8 nm and 2.0 nm (disks A, B and C respectively) of lubricant thicknesses of ZDOL and at a constant skew of zero degrees on different tracks in the order 1.5”, 1.1” and 1.4” on each disk. The rpm of the disks were adjusted for different tracks so as to have a constant linear velocity for all the tracks. The slider was carefully cleaned to remove the ABS contamination before beginning a test on each disk.

C. Stability tests for effect of disk topography

These tests were conducted later on a TTi spinstand using a LDV to study the slider dynamics and an AE sensor to detect contact. A fresh INSIC batch IV disk with 1.2 nm of SG lube was used (Disk D). This disk showed better properties than the disks used in the previous experiment as regards to ABS contamination due to lube pickup. Repeated touchdown-takeoff tests were conducted on a particular track to see the effect of disk burnishing on the touchdown and takeoff velocities. Since the slider ABS was always clean after every touchdown-takeoff cycle, when seen under the optical microscope, these tests discounted the effect of lubricant pickup. The slider dynamics were also observed, and this gave information about the evolution of slider bouncing velocities during contact.

D. Dependence on velocity profile (experimental bias)

In addition to the different phenomena that contribute to hysteresis, the touchdown and takeoff velocities may also depend on the deceleration or acceleration of the disk during the tests, i.e. the velocity profile (Figure 1**)**. Hence, while comparing the effect of different lubricant thicknesses or humidity conditions, the velocity profile was maintained constant across experiments. However, since it was possible to get a repeatable hysteresis for disk D (described in detail in the results section), the dependence of the touchdown and takeoff velocities on the velocity profile was also studied. The velocity profile used was similar to that shown in Figure 1, except that there was no dwell at the minimum rpm in this case.

Two different pico sliders, CML 7nm and 5nm (Figure 2) were flown over different tracks (1.1” and 1.0” respectively) on disk D and the disk rpm was varied as 8000→2400→8000 symmetrically and linearly in 10, 15, 20 and 25 secs (called “acc-time” henceforth). In all, 20 runs were conducted (5 runs corresponding to each acc-time) in random order of acc-times to eliminate any procedure-biased errors. The variation of the touchdown and takeoff velocities was studied for the above four different acceleration/deceleration rates.

Results:

A. Touchdown-takeoff tests

During the touchdown-takeoff tests it was seen that when the slider picked up lubricant the takeoff velocity was relatively high. This lubricant pickup could be observed on the slider using the optical microscope. Figure 3 shows results for tests in which the same slider and disk were used with the same ambient humidity. In this figure the AE signal is plotted against the disk rpm. The time axis folds back on itself so that the hysteresis is evident. The dashed and solid curves show the AE signal corresponding to the cases where there was presence and absence of lubricant on the slider ABS, respectively. The touchdown velocity does not show much variation while there is variation of takeoff rpm associated with lubricant pickup. Based on these and similar other tests, it is concluded that due to the lubricant pickup and the ABS contamination of the slider during its contact with the disk there is an increase in the takeoff velocity.

B. Stability tests for effect of lube pickup

Figure 4 shows the experimental results from the stability tests. The time of touchdown in seconds has been plotted for each track on each disk. It should be noted that the later the slider comes into contact with the disk, the more stable is its flying. The labels “cleaned” indicate that the slider was cleaned before conducting that test.

For each of the disks the first bar corresponds to the time of touchdown when the ABS is clean. When the slider comes into contact with the disk the ABS gets contaminated. It is seen that for the 1.2nm (lubricant thickness) disk, when the slider was flown over different tracks successively without cleaning, its stability kept decreasing. This observation can also be made for the 0.8 nm and 2.0 nm disks. However, after the slider was cleaned, it regained its flying stability.

During the tests it was found that the slider ABS was contaminated as a result of contact with the disk. Figure 5(a) shows ABS contamination after the slider was flown twice over the 2.0 nm disk without cleaning (corresponding to the lowest stability in Figure 4). Figure 5(b) shows a magnified image of the trailing pad corner marked by the rectangle in Figure 5(a), where a significant lubricant pickup is observed. A consistent lubricant pickup similar to that shown in Figure 5(b) was seen during all the tests.

C. Stability tests for effect of disk topography

From the tests it was found that the presence of contaminants or asperities on the track destabilizes the slider. For this reason rough or contaminated disks show high touchdown velocity. The presence of contaminants can also explain the loss of stability in the takeoff zone, as seen in Figure 8. However, once in contact, burnishing of the track may occur and the takeoff velocity can become lower than the touchdown velocity causing an "inverse hysteresis" (Figure 7(a)). Upon conducting repeated tests on such a burnished track it was seen that the touchdown velocity kept decreasing due to successive burnishing of the disk during subsequent contacts, thus decreasing or eliminating the inverse hysteresis (Figure 9) or even the slider-disk contact all together (Figure 7 (b)).

It was seen that the hysteresis, in general, was not very repeatable as it depends on a variety of factors which cannot be maintained constant as the slider-disk contact changes the disk topography, redistributes the lubricant and it also contaminates the slider ABS. However, when many tests were conducted on disk D it was possible to achieve a "steady-state" hysteresis (Figure 10 and Figure 11). When the tests started on a new track, the touchdown and takeoff velocities were relatively high, but kept dropping as the tests progressed, finally achieving a steady-state.

D. Dependence on velocity profile

In addition to the above mentioned factors, it is also generally considered that the touchdown and takeoff velocities may also depend on the deceleration or acceleration of disk during the tests**.** Hence, while comparing the effect of different lubricant thicknesses or humidity conditions, the velocity profile was maintained constant across experiments. Further, the above premise can be tested experimentally only if the hysteresis is a repeatable phenomenon and its variation due to change in the disk acceleration/deceleration can be compared. Since this repeatability of hysteresis was achieved for disk D experiments were conducted to study the dependence of hysteresis on the disk acceleration/deceleration. The results are shown in Figure 12 and Figure 13.

In these figures the mean values of touchdown (shorter bar) and the takeoff (taller bar) velocities are plotted for each of the four times, along with the error bars corresponding to their standard deviation (5 readings). It is seen from the small standard deviation that the touchdown and takeoff velocities show good repeatability. For both sliders it is also seen that the steady-state touchdown and takeoff velocities (and the hysteresis) does not depend on acceleration time within the range of accelerations considered.

Discussion:

A. Intermolecular Forces

A detailed account of the nature of intermolecular forces (IMF) and their effect on the head-disk interface has been given in [1]. To summarize, the IMF are modeled using a Lenard-Jones potential, which contains a long range attractive force term and a short range repulsive force term. The repulsive force term comes into play when the distance between the bodies is less than 0.3 nm, which in the case of the slider-disk, is contact. The long range attractive force is responsible for slightly decreasing the fly height of the slider and increasing adhesion between the slider and the disk, which causes the slider to come into contact earlier. A force balance between the airbearing force (providing lift), the IMF and the electrostatic forces

[17], reveals multiple equilibriums for the slider flying height [2]. The slider exhibits a chaotic motion due to the presence of these multiple equilibriums and contributes to instability and hysteresis [2].

The presence of IMF at the head-disk interface was experimentally seen from the effect of lubricant thickness on the touchdown velocity [1], a trend which was opposite to that predicted by the meniscus forces. Multilayer modeling of the IMF was carried out to determine the IMF between the slider and the disk. Using the fact that the IMF depends on the refractive indices of the interacting mediums, it was shown that the presence of lubricant reduces these IMF, thus explaining the experimentally observed trend.

Thus, from this study, the contribution of intermolecular forces to instability and hysteresis was determined. We now proceed with a detailed discussion of the other factors influencing hysteresis.

B. Lubricant Pickup

From the results of the touchdown-takeoff tests we see that the takeoff velocity, which is the measure of the recovery of the slider from contact to stability, is higher in the presence of lubricant pickup. Thus, lubricant pickup decreases the slider's stability. Further, it also causes ABS contamination, which in turn may collect miniscule debris particles as seen in Figure 5(b). This would cause accelerated wear at the head-disk interface.

However, due to the high shear rates at the HDI, the contaminants are washed away from the ABS in most cases. From the pictures taken after the tests it is evident that these contaminants accumulate behind the trailing pad of the slider. This accumulation is especially more near the corner of the trailing pad which flies lower and therefore is the lowest flying point on the slider (in the absence of pole tip protrusion, as in case of the sliders used). Since this part first makes contact with the disk, and there is a consistent lubricant pickup around this area, it is estimated that the lubricant-lubricant adhesion (Figure 6) between the slider and the disk affects the interface from this point. These adhesive forces can be termed as meniscus forces as this lubricant-lubricant adhesion is similar to forming a meniscus bridge between the slider and the disk. However, we note that this definition of meniscus forces is a broader definition since it is not known if an actual meniscus bridge can form during a slider-disk contact which typically last for less than 1μs [2].

From the stability tests we see that once lubricant pickup occurs, even the touchdown velocity in the subsequent tests increases (i.e. the time taken for touchdown decreases). Thus, lubricant pickup not only hampers the slider's ability to recover from contact but also increases the instability by making the slider go into contact earlier.

Head-disk contact may not be the only way by which lubricant pickup occurs. Many researchers [5-7] are studying the problem of disk to slider lubricant transfer even in the absence of contact. In any regime, contact or flying, if there is lubricant pickup on the ABS, it is estimated that some of it will be sheared off towards the trailing edge and will accumulate behind it [5]. Thus, there would be lubricant on the low-flying slider area as well as on the disk, causing lubricant-mediated adhesion.

To model the effect of lubricant pickup on adhesion between the slider and disk we used a simplified adhesion model based on surface energy of interacting materials at the interface [8,9,10]. The work of adhesion between two surfaces *a* and *b* in the absence of lubrication is given by

$$\begin{aligned} W_{ab} &= (\gamma_a + \gamma_b - \gamma_{ab}) \\ &= C\,(\gamma_a + \gamma_b), \qquad 0 \le C \le 1, \end{aligned} \tag{1}$$

where *C* is the "compatibility index", the values of which are prescribed for different combinations of surfaces including metals and non-metals of different compatibilities [8]. In the presence of lubrication a parameter c_l is included in (1) to incorporate the dependence on lubrication. The combined parameter $c_l C$ is called the "combined compatibility index". The values of $c_l C$ are provided as a function of the degree of lubrication or contamination for various interfaces like metal-metal, metal-nonmetal and nonmetal-nonmetal and degree of compatibility between these surfaces [8]. Figure 14 shows such a plot which was used to obtain the value of the combined compatibility index.

For the head-disk interface DLC overcoat on the slider and the lube on the disk are nonmetallic. They are assumed to be dissimilar nonmetals (other categories being identical and similar) and the air-bearing lubrication is a lubrication equivalent to that in clean air. For such an interface we obtain $c_l C = 0.36$. In case of lube-lube interaction, since the lubes on the disk and slider are identical, $c_l C = 1.0$. In addition, assuming surface energies γ_{lube}~23 erg/cm^2 and γ_{DLC}~40 erg/cm^2, we obtain:

$$W_{lube\text{-}lube} = 1(23+23) \qquad = 46\ \text{erg/cm}^2 \qquad (2)$$

(with lubricant pickup)

$$W_{lube\text{-}slider} = 0.36(23+40) \qquad = 22.68\ \text{erg/cm}^2 \qquad (3)$$

(without lubricant pickup)

Thus, lubricant pickup is expected to increase adhesion and enhance wear of the disk as observed experimentally by Li et.al. [4]. Using this same model it is also seen that in the absence of lubricant the work of adhesion will be

$$W_{DLC\text{-}DLC} = 1(40+40) \qquad = 80\ \text{erg/cm}^2 \qquad (4)$$

This implies that the adhesion, and hence instability and wear are maximum in the absence of lubricant. The presence of lubricant helps in reducing the instability. However, lubricant pickup by the slider causes lubricant-mediated adhesion, which increases the instability.

C. Disk Topography

Disk topography provides external excitation to the flying slider. The rougher the disk, the more excitation the slider gets. There is also more probability of having high asperities on the disk track for a rougher disk. This increases the chance of losing flying stability by hitting an asperity. However, during the steady state operation of the drive, burnishing may take place due to intermittent contact forced by a rough topography or due to contact with an asperity. This in turn will smoothen the topography as well as reduce the glide height. Thus, the slider's stability may increase in the long run. The action of burnishing during contact is being used to explore new slider designs. In order to achieve lower flying heights and insensitivity to manufacturing tolerances, burnishing heads are being used [14].

It should also be noted however, that during the burnishing action debris particles are generated which contaminate the interface. Though these particles can aid in further burnishing, they also might contribute to excessive wear and friction heating if they are stuck in the interface [16]. During contact, there also can be a substantial lubricant pickup, which, if not sheared away behind the trailing edge or in recesses can causes ABS contamination thereby reducing the slider stability. Thus, the net effect of burnishing may also depend upon the slider ABS design [15] and lubricant at the interface [12].

D. Inherent Hysteresis

In addition to factors such as intermolecular forces, meniscus forces and disk topography influencing hysteresis, an inherent hysteresis also exists in the touchdown-takeoff process. Observing the slider velocities obtained by the LDV, it was seen that the slider "snapped" into contact showing high velocities and therefore high instability in its dynamics. When the disk velocity started increasing in the takeoff leg, the slider dynamics gradually stabilized showing less velocities before the slider finally lost contact with the disk at the takeoff velocity (Figure 15).

During the touchdown-takeoff sequence, the slider loses its fly height during the touchdown leg, as the disk velocity decreases. Due to this, the slider is affected by proximity phenomena as well as the uneven disk topography, thus reducing its stability. When it comes into contact with the disk the slider-suspension system starts vibrating with much higher amplitudes due to the impact forces, which in turn adds more energy into the vibrating system. As a result, there are sustained high amplitude vibrations during contact. When the velocity starts increasing again, the mean fly height of the slider starts increasing and the high vibrations due to impact are resisted by a stiffer air-bearing. This tends to stabilize the system and decrease the vibration as experimentally seen using the LDV. But the stiffer air-bearing now required to curb these vibrations also requires a higher disk velocity; thus, more energy has to be expended now to stabilize an unstable system as compared with that required to maintain the system stability in the absence of contact or high vibrations which was the case during the touchdown leg. Hence, the slider dynamics during contact may be seen as an inherent reason for the hysteresis observed.

Conclusions

Touchdown-takeoff and stability tests were conducted to investigate the factors causing the touchdown-takeoff hysteresis, a measure of dynamic instability at the head-disk interface. It is concluded that the slider dynamics itself during the touchdown-takeoff process introduces a hysteresis. In addition, intermolecular forces, meniscus forces and disk topography influence the hysteresis. The long range intermolecular forces are mainly attractive in nature. Their presence causes the slider to have a slightly reduced fly height and to have multiple equilibriums which affect the stability of the slider. Meniscus forces act through lubricant pickup, which causes lubricant mediated adhesion. This causes the slider to come into contact with the disk earlier and delays its recovery from contact as well. Rough and contaminated disks increase the probability of slider-disk contact compromising the slider's stability. However, during slider-disk contact, burnishing takes place which increases the stability of the slider.

Acknowledgements:

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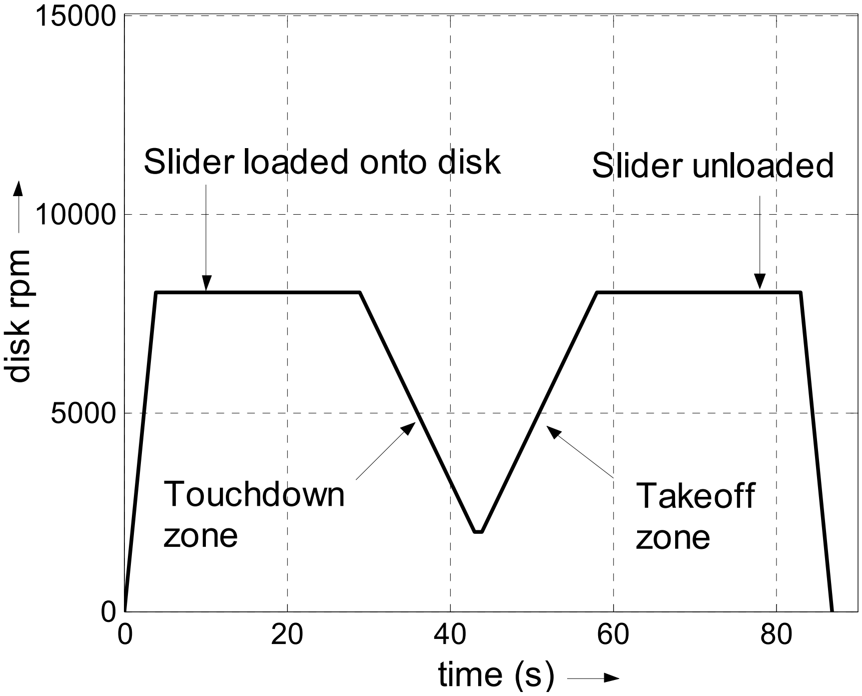
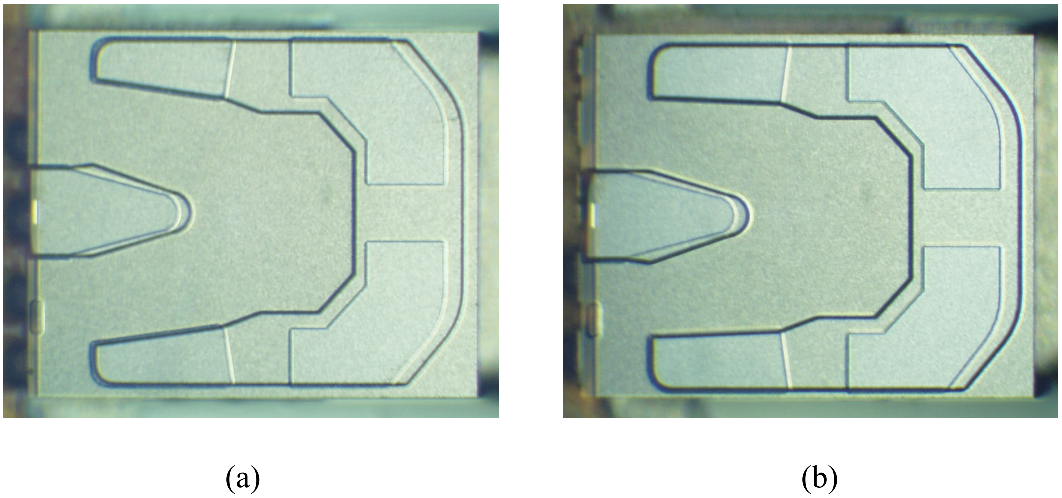


Figure 1: Disk velocity profile during touchdown-takeoff tests



(a)

(b)

Figure 2: Sliders used (a) CML 7nm : For tests A, B, C and D ; (b) CML 5 nm: For test D

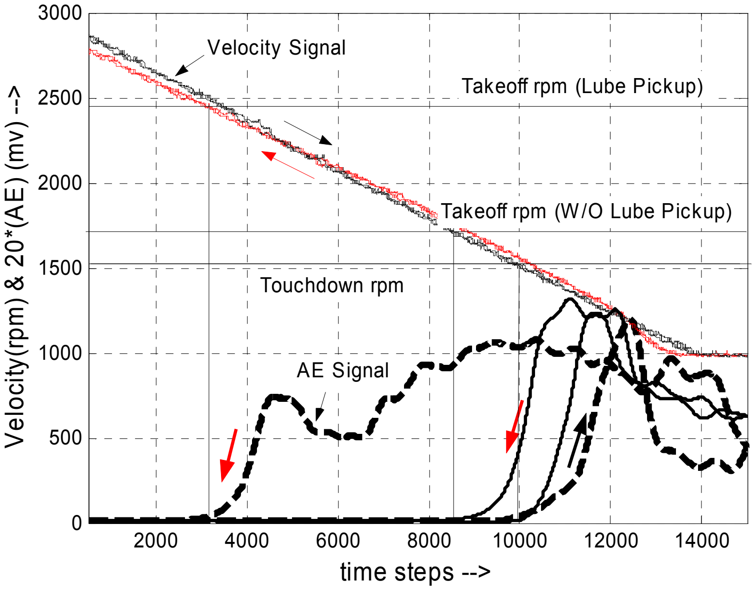


Figure 3: Increased takeoff velocity due to lubricant pickup (dashed curve).

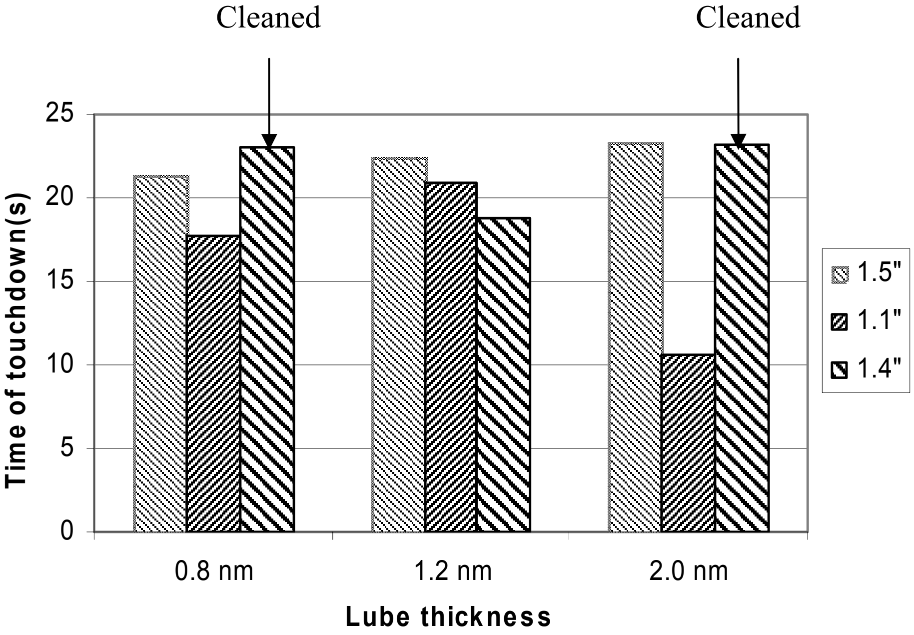
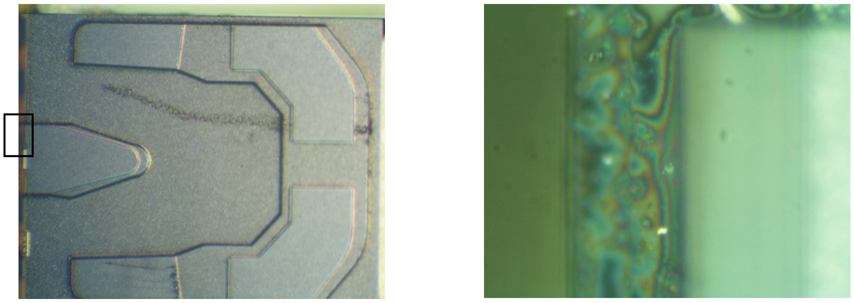


Figure 4: Effect of lubricant pickup on stability



(a) (b)

Figure 5: (a) ABS contamination during stability tests; (b) Lubricant pickup behind the trailing pad

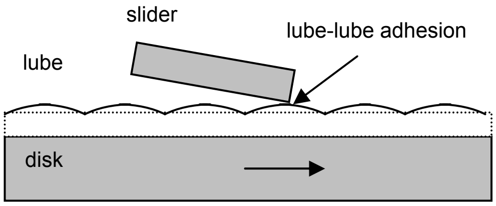
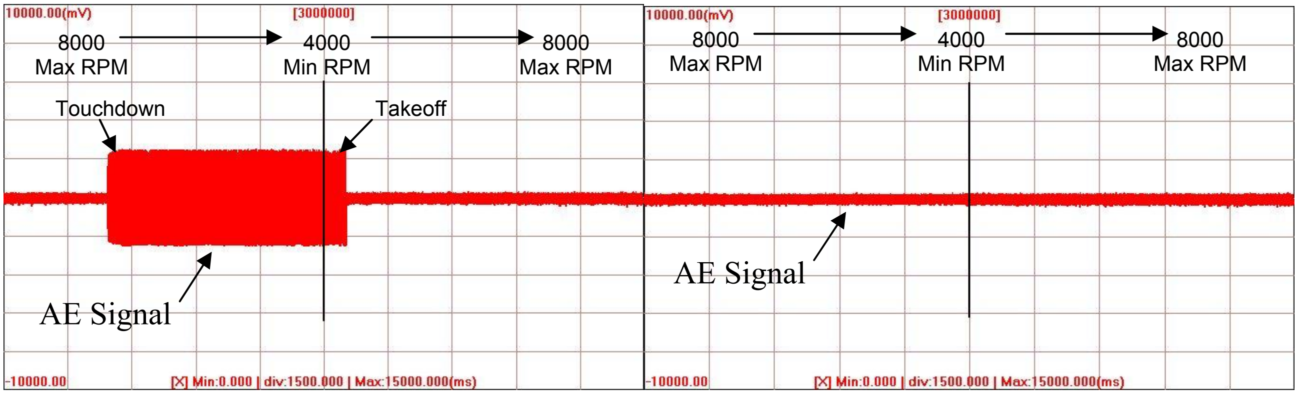


Figure 6: Schematic of the lube-lube interaction in the event of lubricant pickup by the slider.



(a) (b)

Figure 7: (a) Inverse hysteresis; (b) Effect of burnishing

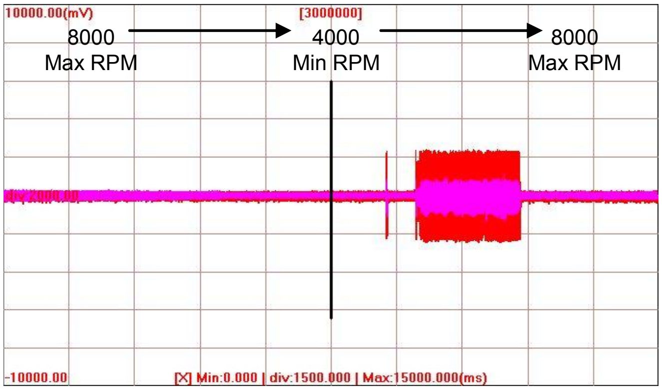
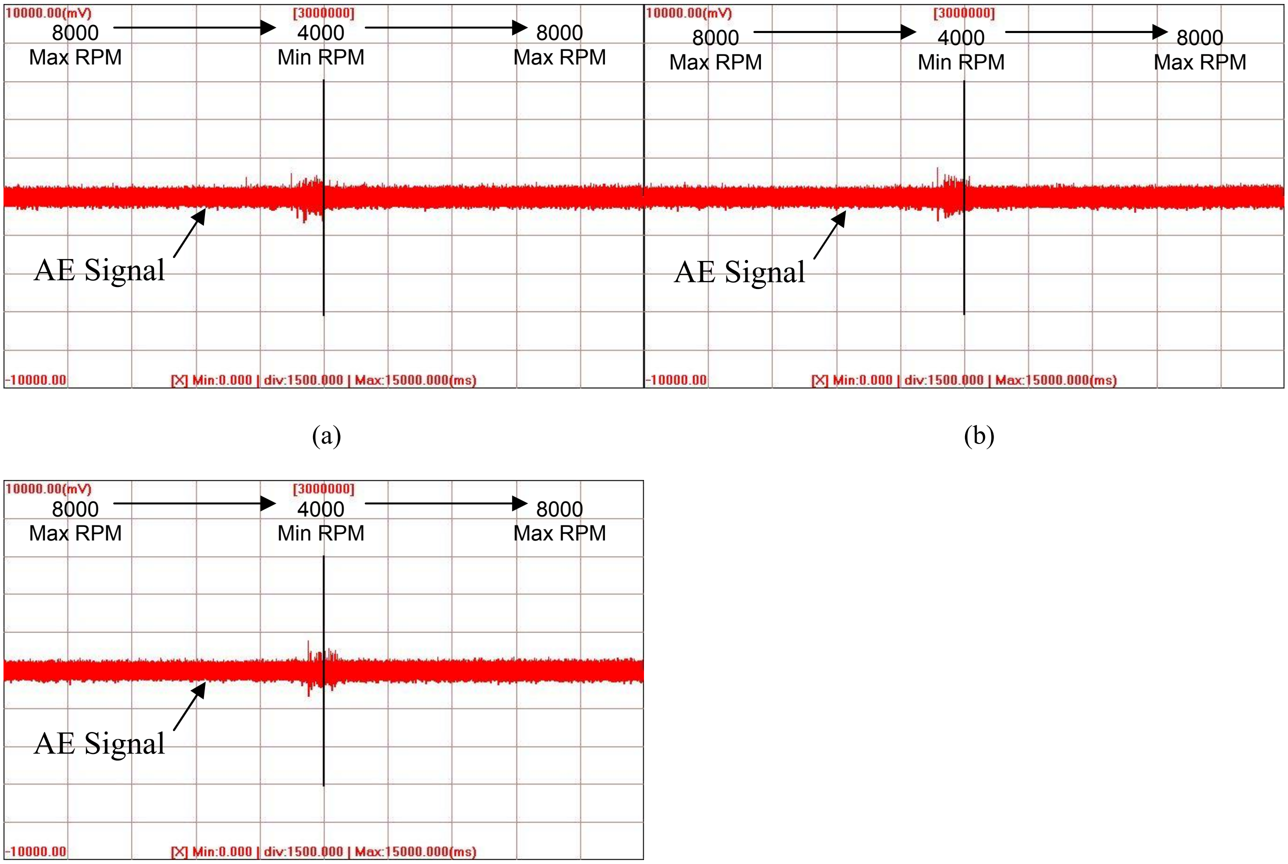


Figure 8: Contact in the Takeoff Leg (Effect of contamination)

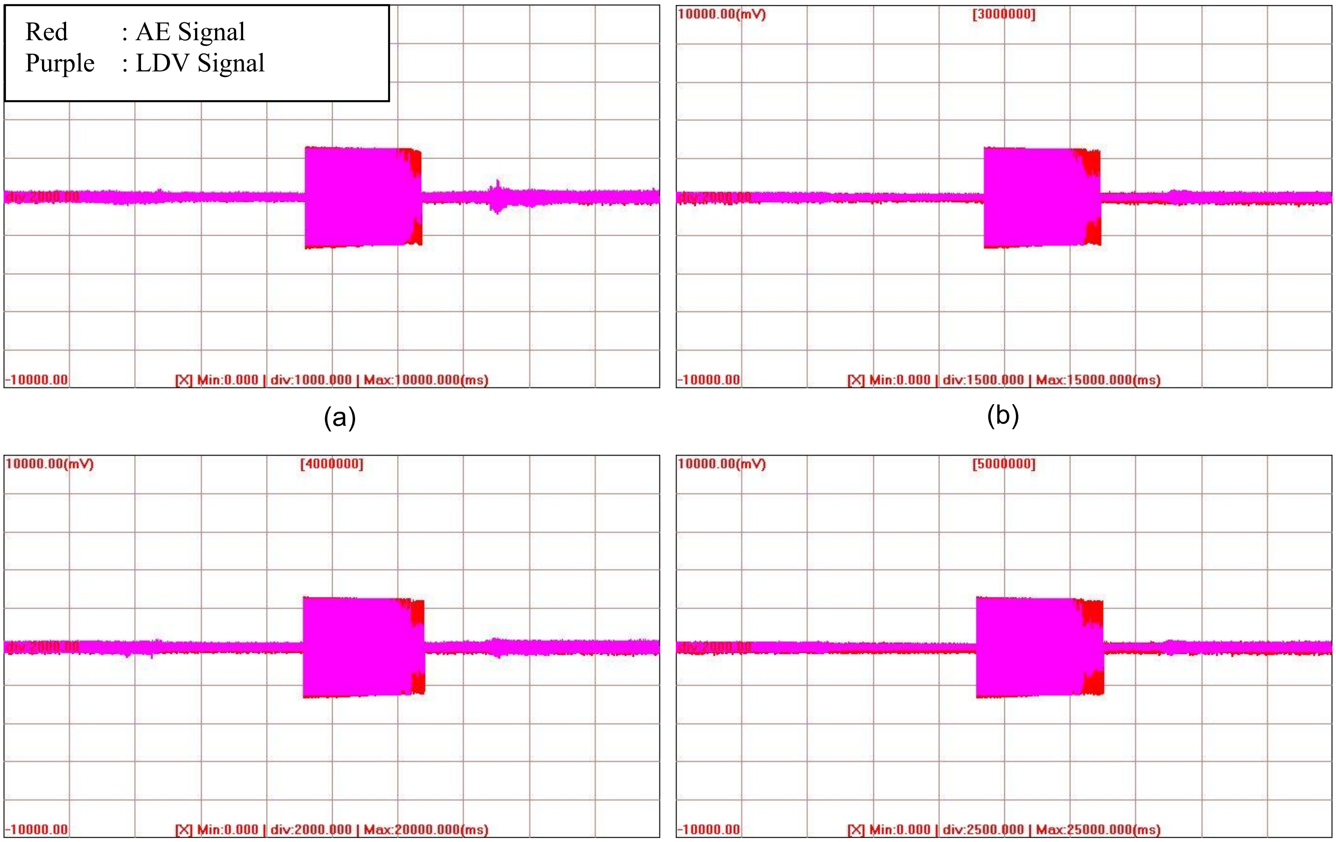


(a)

(b)

(c)

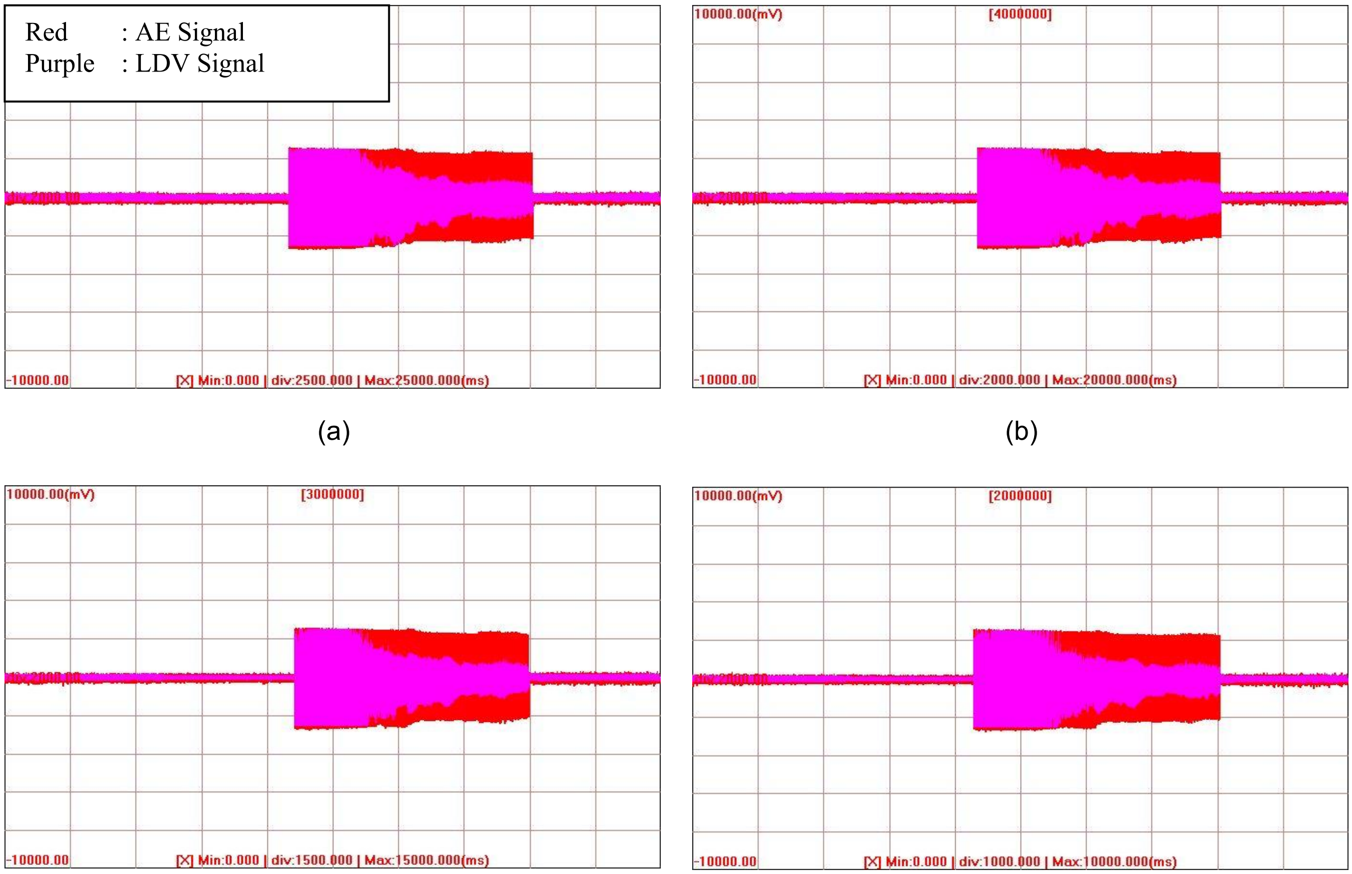
Figure 9: Shifting of the hysteresis to the right



(a) (b)

(c) (d)

Figure 10: Steady State Hysteresis for CML-7nm slider



(a) (b)

(c) (d)

Figure 11: Steady State Hysteresis for CML-5nm slider

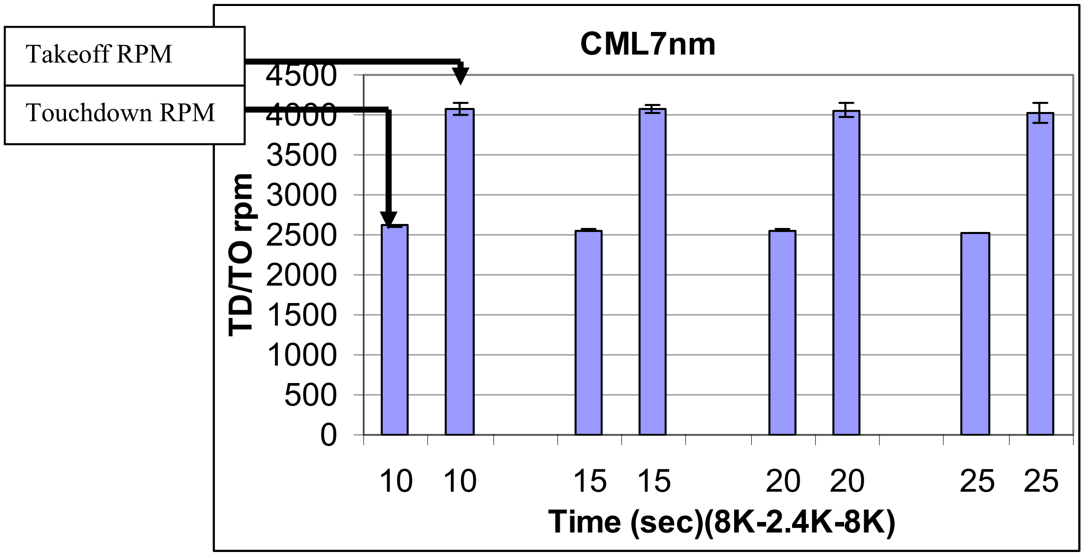


Figure 12: Dependence of Acceleration/Deceleration

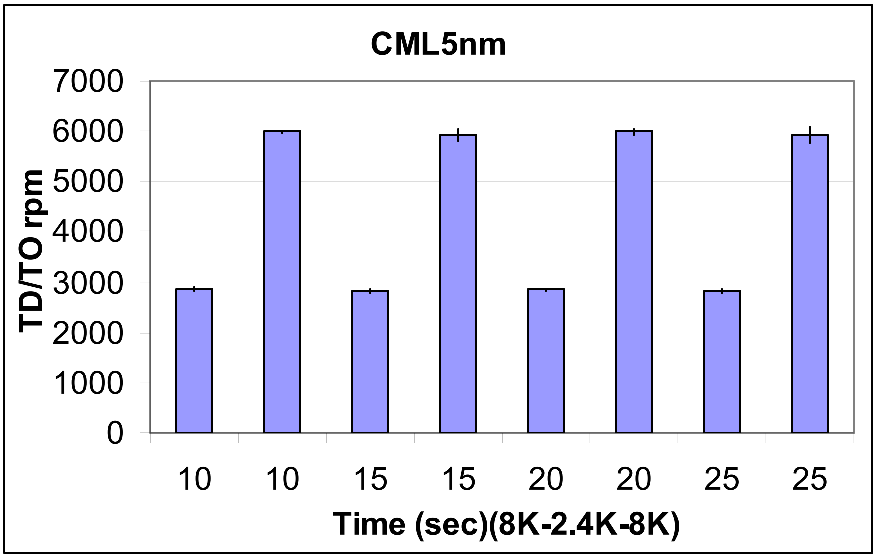


Figure 13: Dependence of Acceleration/Deceleration

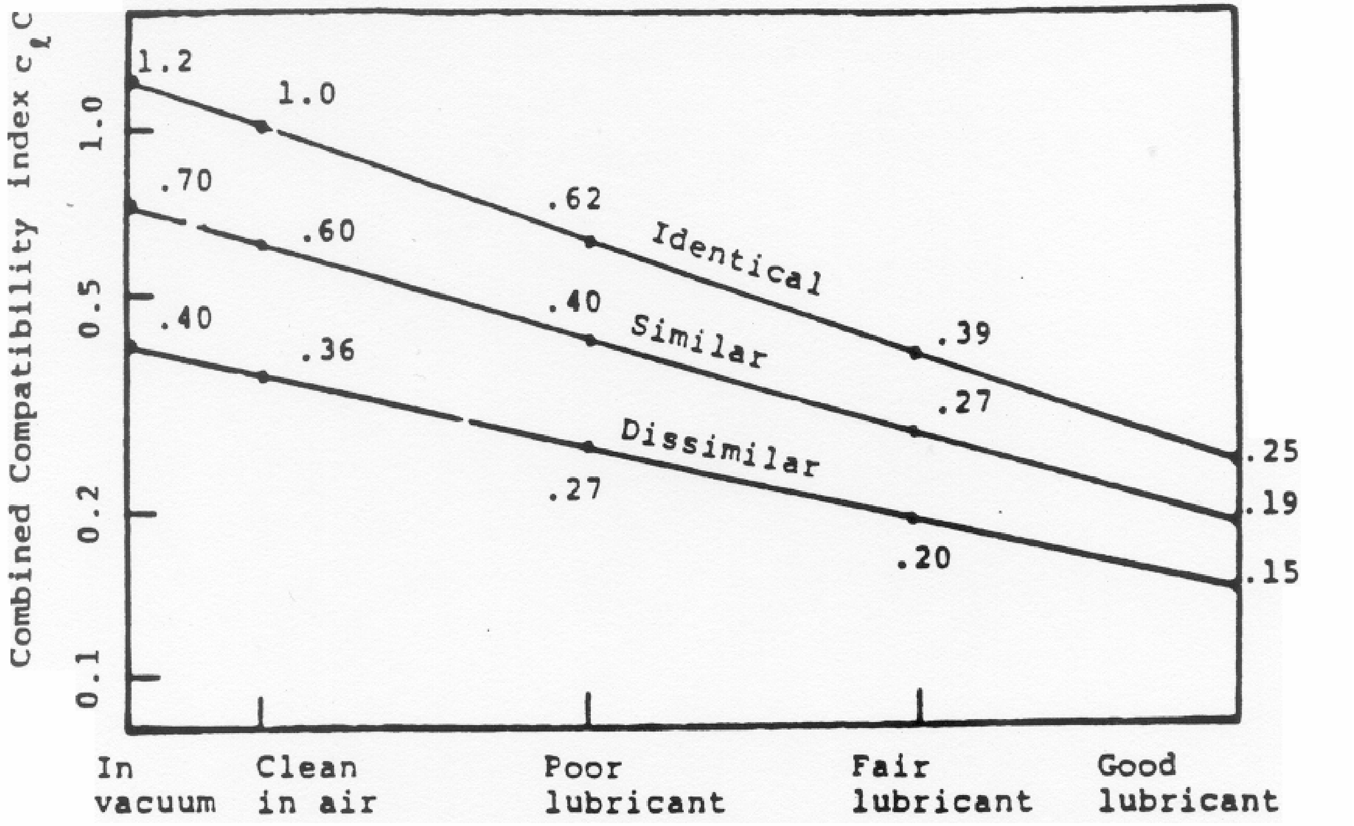
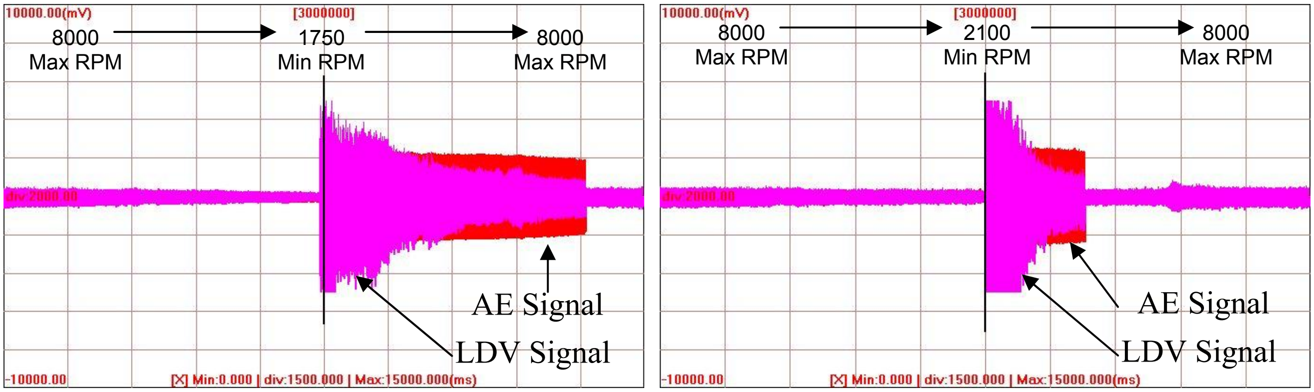


Figure 14: Plot of combined compatibility index as a function of the degree of lubrication or contamination, for use when at least one of the two contacting materials is non-metallic.



(a) (b)

Figure 15: Inherent hysteresis