The Effects of Intermolecular Forces on the Stability of the Head-Disk Interface

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ABSTRACT – This paper presents a nonlinear dynamic analysis of the head-disk interface for sub- 5 nm flying air bearing sliders. It is found that by including intermolecular forces between the slider and disk, the dynamic stability of the slider is dramatically compromised. It is shown by a bifurcation diagram that a slider can easily be forced into unstable motions. It is also shown that the experimentally observed flying-height hysteresis, intermittent instability, and "snapping" from stable to unstable proximity can be explained by intermolecular forces.

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INTRODUCTION

In order to achieve a magnetic areal density of 1 Tbit/in^2, it is projected that the physical spacing between the media and transducer or flying-height (FH) will have to be 3.5 nm [1]. For a head-disk interface (HDI) to perform reliably, both tribologically and magnetically, the fluctuations in the FH must be held to a minimum. One of the roadblocks thus far for realizing a 3.5 nm FH is the dynamic instability of the HDI. It has been seen experimentally that a slider can transition from stable to unstable proximity flying by decreasing the FH only slightly. This “snapping” effect between stability and instability is evidence of a complicated dynamical system when operating in the sub- 5 nm FH regime. As the slider and disk approach one another, surface interactions are evidently no longer negligible. Two physical models have been proposed to account for the interactions between the slider and the disk: one based on lubricant interacting with the slider causing a meniscus force and the other on intermolecular forces between the two intimate surfaces. Thus far, publications investigating the effect of intermolecular force on the HDI have been based on static analysis [2], [3]. It has been shown that for air bearing sliders flying in the sub-5 nm regime, intermolecular forces can become significant and cause a large decrease in static FH [2]. However, the implications of intermolecular forces on the dynamic stability of the HDI has not been published.

In this paper, we will present some experimental evidence of the abrupt stable to unstable flying transition. By accounting for the intermolecular forces through the Lennard-Jones potential and modeling the HDI as a lumped parameter single degree-of-freedom (SDOF) model, we will show that the system becomes highly nonlinear in the proximity region. The dynamics of this nonlinear system are extremely important and are discussed.

EXPERIMENTAL RESULTS

It has been widely observed that as a slider is forced into and back out of contact, a FH hysteresis is present. This hysteresis can been seen in Fig. 1a showing slider motion as the disk spindle RPM is lowered until the slider comes in contact with the disk (touchdown) and then the spindle RPM is increased and the slider ceases to contact the disk (takeoff). The touchdown RPM is lower than the takeoff RPM or the touchdown height (TDH) is less than the takeoff height (TOH). This difference in RPM or FH is what constitutes this hysteresis (TOH - TDH).

The sliders motion transitions abruptly from stable to unstable flying as shown in Fig. 1b. By lowering the disk linear speed 0.2 m/s, the slider "snaps" from stable to intermittent instability. The FH hysteresis and the "snapping" from stable proximity to unstable proximity flying are evidence of a highly complicated dynamic system.

HEAD-DISK INTERFACE MODEL

A. Modeling Intermolecular Forces

For modeling of the intermolecular forces, we adopted the method of Lin and Bogy who implemented an additional force into the CML Static Air Bearing Simulation Code via the Lennard-Jones potential [2]. This method takes the slider air bearing geometry and flying attitude into account, however, it assumes mathematically smooth surfaces. The fixed attitude solution is found by fixing the attitude of the slider (FH, pitch, and roll) and solving for the forces acting on the slider. When the forces and moments acting on the slider equal those of the suspension, the static solution is obtained. Figure 2a shows the resultant van der Waals force acting on a typical pico slider as a function of minimum FH for a roll angle of zero and pitch angle of 30 μrad. As the FH decreases, an attractive force becomes present and by further decreasing the FH, a strong repulsive force becomes present, as expected.

B. Static Force Analysis

Figure 2b shows the forces acting on the slider as a function of minimum FH for the fixed attitude solution. When intermolecular forces are accounted for, there can exist up to three equilibria – two stable and one unstable. It is seen that for small perturbations about the nominal FH solution of 7 nm, the solution is stable. However, at 2.8 nm, there exists an unstable equilibrium and another stable equilibrium at 0.2 nm. These additional equilibria suggest a very complicated nonlinear system, which is the focus of the following dynamic analysis.

C. Dynamic SDOF Model

In order to simplify the HDI for the following analysis, we use a simple lumped parameter model. In this model, the air bearing slider system is modeled with a nonlinear spring, *k(s)*, with mass, $m = 1.6\times10^{-6}$ kg, and proportional damping, $c = 0.08$ kg/s. The nonlinear air bearing spring takes the form:

$$k(s) = b \cdot s^{a} \qquad (1)$$

where α and β are found from simulation and are taken here to be –0.48 and 244.1 N/m, respectively, and it is a function of the slider – disk spacing, *s* [4]. The disk topography, *d(t)*, can be modeled in various ways, as a numerically generated random wavy surface, a harmonic excitation, or using an experimentally measured surface. The intermolecular force acting on the slider takes the form:

$$F_{VdW}(s) = -\frac{A'}{s^3} + \frac{B'}{s^9} \quad (2)$$

where A' and B' are constants found from curve fitting the plot in Fig. 2a, taken to be 2.2×10^{-30} N·m^3 and 1.5×10^{-88} N·m^9, respectively. The equation of motion for this system can be written as a function of the sliders absolute motion with a zero mean, x, by subtracting the static FH, FH_s, where $x = s + d - FH_s$:

$$m\ddot{x} + c\dot{x} + (k - F_{VdW})x + (F_{VdW} - k)d - c\dot{d} = 0 \quad (3)$$

Due to the intermolecular force in Eq. (2) and the highly nonlinear spring stiffness in Eq. (1), Eq. (3) becomes highly nonlinear and the solution is no longer simple.

HEAD-DISK INTERFACE NONLINEAR ANALYSIS

A. Stability

Stability of the HDI model can be analyzed by considering the energy of the system. If we assume no forcing, $d(t) = 0$, and no damping, $c = 0$, the system is conservative and a potential energy method can be used to show equilibria and local stability. The potential energy of the system, U_{sys}, is comprised of the potential energy of the air bearing spring, U_{ab}, and the potential energy of the intermolecular force, U_{vdW}, derived from the Lennard-Jones potential. The criteria for equilibria, x_i^*, is an inflection point of the potential, and it is stable if the potential is a local minima and is unstable if the potential is a local maxima. For the nominal coefficients used, equilibria and stability as a function of static FH can be obtained numerically. Figure 3 is a bifurcation plot for this system showing the equilibria and stability as a function of static FH where static FH is defined as the equilibrium FH of the system without intermolecular forces acting at the interface. It is seen that when the static FH is greater than 7.25 nm only one equilibrium exists, x_1^*, the nominal FH solution. Between a static FH of 3.5 nm and 7.25 nm, three equilibria exist – two stable, x_1^* and x_3^* and one unstable, x_2^*. Below a static FH of 3.5 nm, only one stable equilibrium exists, x_3^*. The regime where the three equilibria exist is of utmost interest – both theoretically and for practical application.

Between a static FH of 3.5 nm and 7.25 nm three equilibria exist and within this regime the potential energy takes on a special form generally called a "double-well" or "two-well" potential. Double-well potential systems have been studied for the past two decades in the field of nonlinear dynamics [5]-[7]. Many systems have exhibited double-well potentials with very interesting dynamics, from mechanical systems to super conductivity. Within this regime, the dynamics of the system are extremely complex and can even be chaotic [5]-[7].

B. Unforced System

This system is considered to be unforced when the disk forcing is zero (e.g. for a perfectly smooth disk surface). From the bifurcation plot in Fig. 3, we observe one very important characteristic of the unforced system. This observation can be explained by a touchdown – takeoff simulation of decreasing and then increasing the static FH. From Fig. 3, the equilibrium solution can be found as a function of static FH as the static FH is lowered from 10 nm to 2 nm and then increased back to 10 nm. As the static FH is decreased from 10 nm to 3.5 nm, the equilibrium follows the nominal solution, x_1^* (a-b). However, below a static FH of 3.5 nm, the air bearing is overcome by the intermolecular forces and the nominal solution is annihilated by x_2^* and "snaps" down to the other stable equilibrium, x_3^* (b-c). Upon increasing the static FH back to 10 nm, the equilibrium solution will remain along x_3^* until it is annihilated by x_2^*, at a static FH of 7.25 nm (d-e). At 7.25 nm the equilibrium solution "snaps" from x_1^* to x_3^*, back to the nominal solution (e-f). This is shown in Fig. 4a, which depicts an unforced touchdown – takeoff simulation showing the slider remaining "stuck" on the disk until the static FH reaches 7.25 nm. The difference between the static FH where the slider becomes "stuck" while decreasing the static FH and when the slider become "unstuck" while increasing the static FH is called the "FH hysteresis". It is seen for an unforced system that the FH hysteresis is bound by the regime were multiple equilibria exist – namely the three equilibria, x_1^*, x_2^*, and x_3^*.

C. Forced System

Forced double-well potential systems have been found to exhibit *strange attractors* causing chaos and sensitivity to initial conditions; however, the important result for the HDI can be summarized as follows [5]-[7]. As long as the model of the HDI exhibits a double-well potential, the forced solution can be periodic, non-periodic, and chaotic for simple harmonic forcing. That is, for the nominal parameters used, this system can exhibit highly non-predictable dynamics between static FHs of 3.5 nm and 7.25 nm.

1. Touchdown – Takeoff Simulations

The topography of a disk is composed of harmonic and non-harmonic content at all wavelengths or frequencies as the disk spins. Figure 4b shows a touchdown – takeoff numerical simulation of Eq. (3) that is similar to that shown in Fig. 4a, however the system is now forced with a measured disk topography from a "super-smooth" disk. It is found that while decreasing the static FH the slider "snaps" from stable motions about x_3^* into chaotic motion. Once the slider has "snapped" into chaotic high amplitude motion it has the ability to oscillate about x_1^*, x_3^* or about both x_1^* and x_3^*. Upon increasing the static FH, stable slider motion is resumed about x_3^* exhibiting a FH hysteresis. Because this system exhibits *strange attractors* in the sub- 7 nm FH regime, the characteristics of the chaotic slider motion is highly dependent on the disk forcing. However, for all disk topographies investigated, an unstable motion exhibiting a FH hysteresis was always present due to the intermolecular force.

2. Transition between stable and unstable flying

Experimentally it was shown that by changing the FH only slightly, the transition between stable and intermittent unstable flying was abrupt (see Fig. 1b). By holding the static FH constant, simulations can be carried out that also show this phenomenon. Within the regime were the system exhibits a double-well potential, it has been shown that the slider can be easily forced into unstable motions. Figure 5 shows the slider motion exhibiting intermittent instability. By slightly increasing the static FH, the instability ceases to exist and by slightly decreasing the static FH, the instability will persist indefinitely.

CONCLUSION

Experimentally, it is observed that as a slider flies within proximity of the disk, HDI dynamic stability is dramatically compromised. A nonlinear dynamic analysis of a modeled HDI incorporating intermolecular forces revealed very interesting dynamics. By analyzing the systems equilibria and stability, it was found that multiple equilibria exist in the sub – 7 nm FH regime exhibiting a double-well potential system. Within this regime, the sliders motion can be stable or chaotically unstable when externally forced by a disk topography. Using this analysis, the experimentally measured FH hysteresis, intermittent slider instability and the abrupt transition between stable and unstable proximity can be explained.

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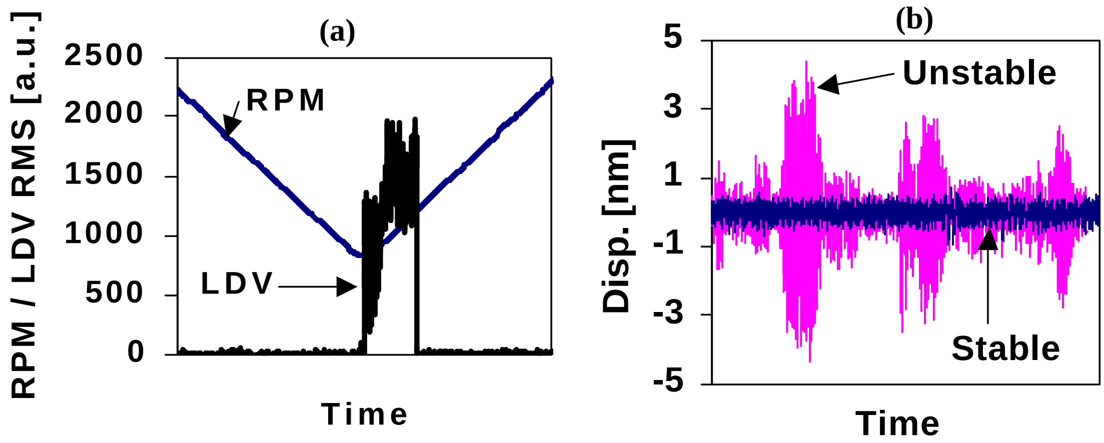

Fig. 1. (a) Slider transition from stable to unstable motion as a function of disk RPM detected by LDV and (b) stable slider motion (*v* = 3.6 m/s) and intermittent unstable slider motion (*v* = 3.4 m/s).

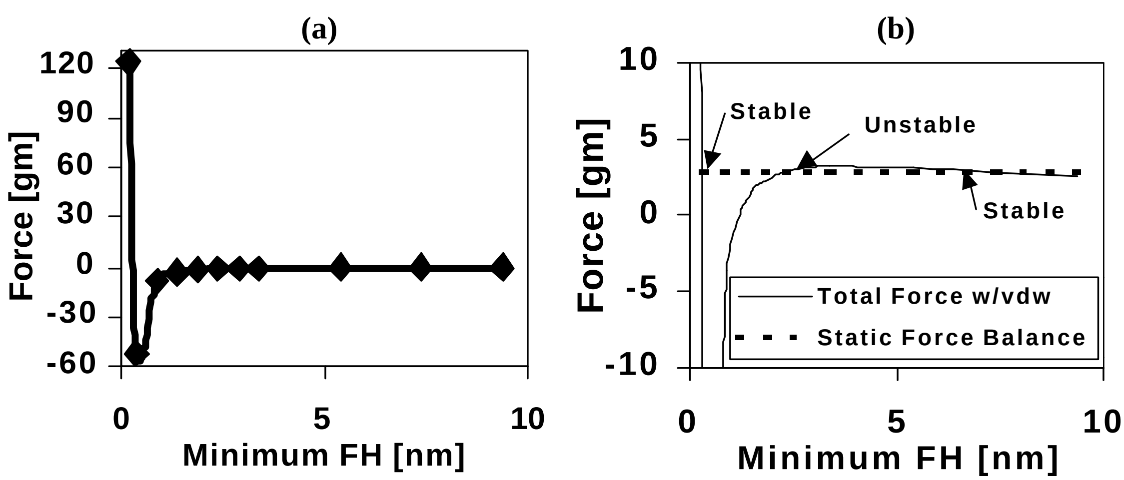

Fig. 2. (a) Intermolecular force as a function of minimum spacing and (b) total force acting on the slider as a function of minimum spacing showing three equilibria – two stable and one unstable.

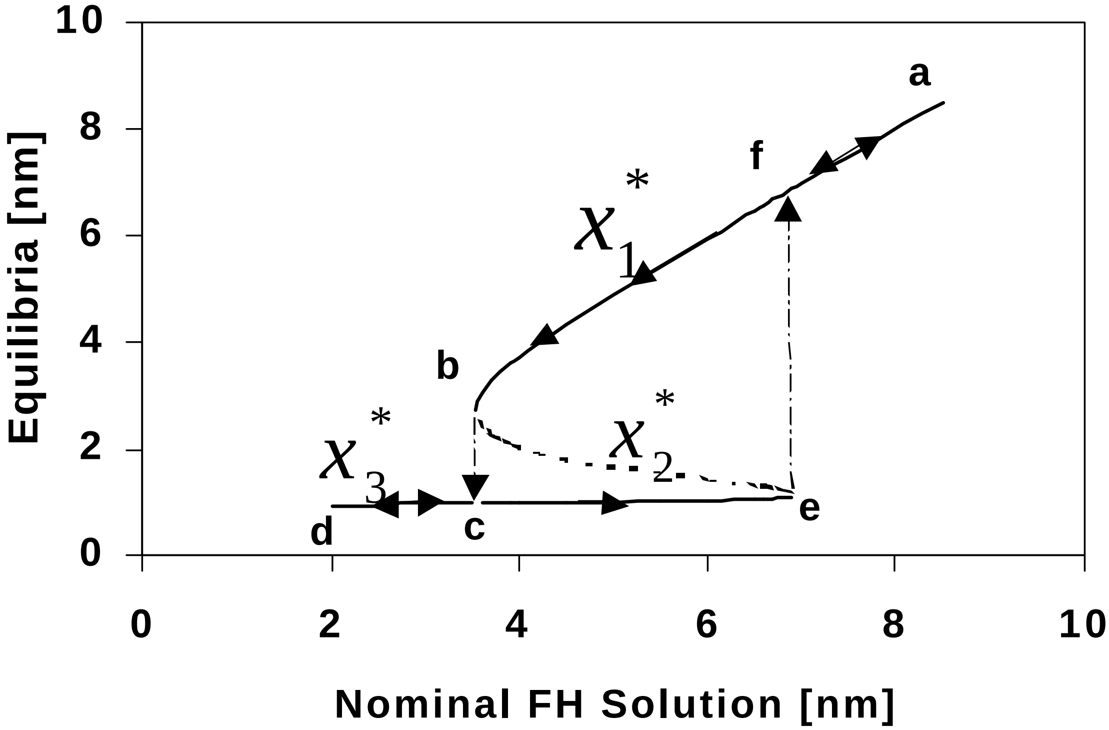

Fig. 3. Bifurcation diagram showing equilibria and stability. (—) stable and (- -) unstable.

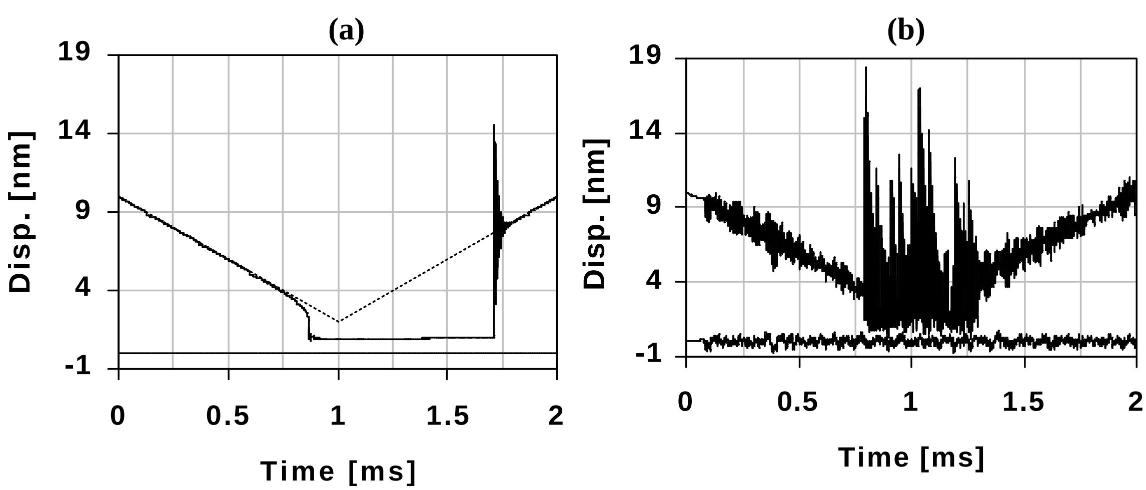

Fig. 4. (a) Unforced and (b) forced TD and TO curves. (- -) static FH.

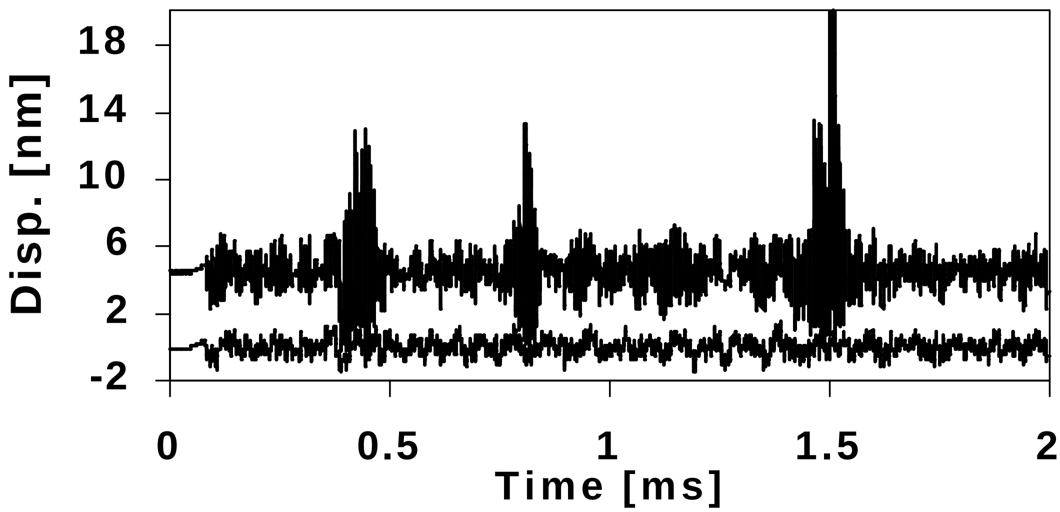

Fig. 5. Slider intermittent instability.