Dynamic Adhesive Contact with Molecularly Thin Lubricant at the Head-Disk Interface of Hard Disk Drives

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INTRODUCTION
Thermal fly-height control (TFC) nanotechnology is used to reduce the spacing between the recording slider and magnetic disk in hard-disk drives—currently a few nanometers wide—by thermally actuating a small volume surrounding the read/write elements towards the rotating disk surface. In addition to normal displacement and pitch angle rotations accounted for in two degree-of-freedom (2-DOF) models,1,2 the third DOF, roll, has been included in this work to better simulate realistic slider behavior. Furthermore, contact with a molecularly thin lubricant layer, having a thickness of 1-2 nanometers, has been accounted for based on a recently developed molecularly thin lubricant (MTL) layer contact model,3 where the adhesive formulation of the improved sub-boundary lubrication (ISBL) model has also been modified to account for the variation of surface energy with penetration into the lubricant layer.

DYNAMIC CONTACT MODEL FORMULATION
The air bearing (AB) forces and moments, induced by the flow of air between the textured slider surface and the rotating disk, are modeled using lumped nonlinear springs as shown in Figure 1. The preload and suspension are designed to balance the AB forces...
and allow for the slider to fly at a nominal height (around 10 nanometers) from the disk. Slider geometry has been modeled for multiple possible points of contact on the slider air bearing surface. Each feature is described geometrically, e.g., as an ellipsoid, cuboid, etc., to calculate the nominal area using previously established methodology.\textsuperscript{1} The dynamic microwaviness (DMW) is the experimentally measured disk motion and provides the excitation to the system. At each point in time, the relative disk and slider locations determine whether the slider is flying, or operates within the lubricant or solid contact regimes.

The MTL dynamic contact model combines the solid contact formulations of the ISBL model, accounts for variable surface energy with penetration into the lubricant layer, and includes lubricant contact forces.\textsuperscript{3} Even though this is a continuum-based formulation, it includes sliding contact at the nanometer scale.

Dynamic shearing experiments yielding dynamic viscosity data, reported in the literature, were used in the formulation of a sphere-on-flat model; the limits of continuum theory were investigated, as was viscosity stiffening and interfacial slip.\textsuperscript{4} As shown in Figure 2, hydrodynamic formulations are used up to the expulsion of mobile molecules from the interface. The transition from hydrodynamic to solid contact is modeled by assuming a linear drop from the maximum hydrodynamic stiffness to the stiffness at the inception of solid contact. The sphere-on-flat model was extended for MTL layers on rough surfaces by extracting the effective stiffnesses in the normal and shear directions at very high shear rates.

In the absence of displacement control, the lubricant layer is assumed to be compressed to the minimum liquid thickness that scales with the molecular diameter.\textsuperscript{4} The experimentally observed limiting behavior was extrapolated to shear rates encountered in magnetic storage – of the order of $10^{10}$ s\textsuperscript{-1} – and the predicted peak normal bearing force compared favorably to experimental measurements.\textsuperscript{5} The lubricant’s contribution to friction was found to be negligible, as shown in Figure 3.

**RESULTS AND DISCUSSION**

The pole-tip flying height (FH @ PT), which is an experimentally measurable quantity, describing the clearance between the read/write elements and the disk, was calculated geometrically at the reader location for constant TFC actuation, as shown in Figure 4. The top time history (blue) corresponds to the slider motion at the TFC bulge (z\textsubscript{TFC}), while the bottom (black) is the input disk motion (DMW). If the slider comes within the gray line translated by 3σ from the DMW, representing

![Image](https://example.com/image1.png)

**Figure 2** | Physical description of confined lubricant molecules: (a) hydrodynamic regime, (b) shearing between bonded layers corresponding to critical viscosity and shear rate and (c) destruction of bonded lubricant layer and transition from lubricant to solid contact. Minimum solid-solid gap is $h_{\text{B, min}} = h_{b} + h_{B,\text{min}}$. Shear rate defined relative to liquid gap $d_{c}$.\textsuperscript{4}

![Image](https://example.com/image2.png)

**Figure 3** | Normal (a) and lateral (b) lubricant layer stiffnesses as a function of dimensionless separation ($h^{*} = h/\sigma$; $\sigma$ = combined RMS roughness).\textsuperscript{2}

![Image](https://example.com/image3.png)

**Figure 4** | Time histories of displacement at the TFC bulge (a) and clearance at the PT (b) for constant actuation.
the roughness at the interface, then we have solid contact; similarly, if the slider comes within the gray and red lines ($3\sigma < z_{TFC} - DMW < 3\sigma + t$), then we have lubricant contact. The 3-DOF model prediction of slider-disk clearance is within 1 nm of the expected value based on AB solver results.

An impulse force of 100 mN was applied over a period of 5 μsec resulting in brief solid contact at the TFC bulge. Protective contact pads also contact the disk, something that does not happen for moderate impulses (~1,000g). Hence, including roll appears to be important in the modeling of operational shock under severe conditions. The impulse shock excites all three AB modes, as shown in the wavelet transform of Figure 5, but vibrations die out fairly quickly and the slider resumes accurately tracking the DMW (not shown).

Next, a power profile is applied so that TFC actuation ramps up to a constant actuation and is then retracted to simulate realistic operation. As shown in Figure 6, the proposed MTL model predicts reduced transient vibrations relative to the ISBL model, since the MTL lubricant layer acts to dampen out slider motion as would be expected.

Contact occurs only on the TFC bulge and is contained within the lubricant layer during steady actuation, suggesting that near-contact or “surfing” recording is achievable. This would allow the maximization of the achievable recording density with currently available technologies.

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REFERENCES


