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Dynamic contact with friction of an ultra-low flying head-disk interface with thermal protrusion

A. I. Vakis, S.-C. Lee and A. A. Polycarpou

Abstract—A dynamic two-degree-of-freedom contact with friction model of the head-disk interface (HDI) is presented accounting for slider thermal protrusion and its influence on the HDI dynamics. Using this model, which includes roughness, the applied power to the thermal protrusion is calculated that leads to minimum flying-height modulations. The model predictions are verified by drive-level experimental results.

Index Terms—dynamic model; magnetic storage; head-disk interface; thermal protrusion.

I. INTRODUCTION

Current advances in the technology of hard-disk drives (HDDs) have established the use of thermally actuated pole tip protrusion, herein referred to simply as thermal protrusion (TP), as an effective method to practically reduce the head-media spacing (HMS) to nanometer order in order to achieve ultra-high density recording. This work presents a detailed dynamic contact model that allows for the calculation of the optimum TP height just before jump-to-contact occurs. The model is validated by drive-level experimental results.

The principle behind the operation of such a system is to fly the slider at a nominal flying height (FH), where the air-bearing dynamics are steady and predictable, and use a protrusion situated at the trailing edge (TE) of the slider to bring the read/write elements closer to the disk [1]. This protrusion can translate the read/write elements several nanometers towards the disk surface and, through the use of a feedback system, its height can be regulated accordingly to allow for “non-contacting” tracing of the disk motion while minimizing the HMS and flying-height modulation (FHM).

The model accounts for air-bearing dynamics, media roughness and dynamic microwaviness (DMW) and can predict the time-varying dynamic interfacial forces during both flying and contact. A schematic of the dynamic contact model is depicted in Figure 1. Experiments in terms of TP FH at the drive-level were performed and used to validate the dynamic contact model in terms of FHM and contact.

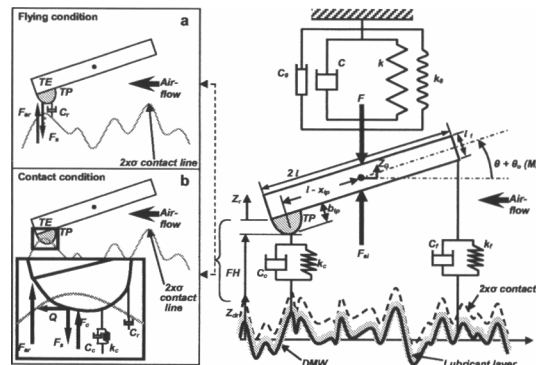


Fig. 1. Schematic of 2-DOF dynamic HDI contact model with thermal protrusion: inset (a) shows the flying condition where only air-bearing and adhesion forces are acting; and, (b) shows the contact condition where contact and friction forces also come into play.

II. DYNAMIC MODEL AND EXPERIMENTAL VALIDATION

The thermal protrusion geometry is modeled as an ellipsoid located at a constant distance away from the trailing edge. While the base of the ellipsoid, i.e. the elliptical outline of the protrusion on the slider surface, remains constant, its height in the direction perpendicular to the bottom surface of the slider changes according to the power applied to it. The correlation between applied power and TP height can be described based on FEA models, hence, it is possible to extract the value of the applied power given the TP height and vice versa.

For known thermal protrusion dimensions, we can precisely describe every point in the TP geometry in terms of a fixed reference point. Then, the nominal area of contact can be calculated by cutting the ellipsoid with a plane that is parallel to the plane of mean asperity heights at a distance of $2 \times \sigma$ (where σ is the composite rms roughness) from the lowest point of the TP and calculating the area of the resulting section projection (which is also an ellipse). Contact initiation is similarly defined using the $2 \times \sigma$ contact criterion, i.e. since $2 \times \sigma$ measured from the mean of asperity heights includes 95% of asperity summits, there is a 5% probability that contact has occurred.

Despite the curved nature of the TP geometry, the nominal contact area is assumed to be nominally flat. This is justified since the effective radius of curvature of the TP is large compared to its spatial dimensions. Hence, the model for the contact of two flat rough surfaces that was presented by Lee and Polycarpou [2] is valid and can be used in this work. This model, termed the Improved Sub-boundary Lubrication (ISBL) model, includes analytical expressions for the dynamic

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calculation of all relevant interfacial forces, namely adhesion, contact and friction forces, as well as the real area of contact [2] and was based on the work of Kogut and Etsion [3] (elastic/plastic contact deformation).

It has been previously shown that complex air-bearing dynamic characteristics can be approximated by a lumped parameter 2-DOF dynamic model. The lower mode corresponds to a primarily pitch mode and the higher mode to a predominantly normal (to the FH) mode. Moreover, the front (leading edge) air-bearing stiffness is assumed to be linear (constant stiffness value), and the rear (trailing edge) air-bearing is highly nonlinear. The air-bearing stiffness values were curve fitted to air-bearing simulation data [2]. In the case of a slider with a thermal protrusion, the nominal flying height remains relatively constant and the air-bearing forces can be both assumed to be constant. This assumption was utilized in the formulation of the current model.

TP flying height was measured using the following experimental procedure: A special pattern was written to a data track on the HDD, and the amplitude of the signal produced by the reader assessing that track was monitored while changing the amount of thermal protrusion until HDI contact was detected. By processing the obtained signal amplitude data and measuring the DMW using a Laser Doppler Vibrometer (LDV), HMS change could readily be obtained and compared with the modeled results.

III. RESULTS & DISCUSSION

Using the developed dynamic contact model, it is possible to precisely identify the jump-to-contact event. Figure 2 shows a plot of the thermal protrusion flying height time history for the cases when the TP height (size) increases from 6.7 to 6.8 nm. It can be clearly observed that contact is initiated for a TP height value somewhere in between these two values. In this specific simulation, a $3\times\sigma$ contact criterion was used corresponding to less than 1% probability for contact. In comparing the model with the experimental results we will investigate both the $2\times\sigma$ and $3\times\sigma$ contact criteria as a means to practically identify/define contact in a rough moving interface.

The TP flying height versus TP height plot (using the $3\times\sigma$ criterion), as shown in Figure 3, clearly shows the initiation of contact for a TP height of 6.8 nm. Note that the sub-3 nm HMS, equal to the TP FH, is within the projected specifications for ultra-high density recording [1].

Once the dynamic contact model is validated it will also be used to predict (a) contact stability (via FHM near contact) and (b) contact severity via normal and shear stresses at the interface.

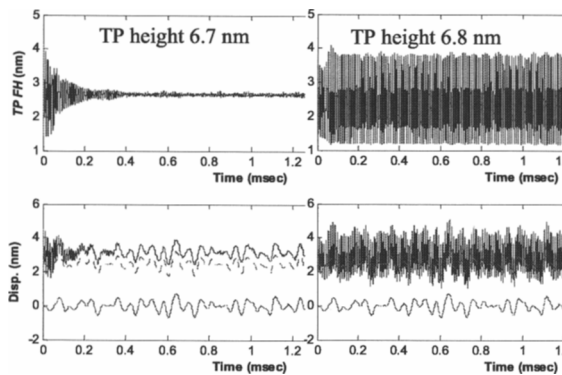


Fig. 2. Dynamic simulation results showcasing jump-to-contact: plot of the TP flying height time history compared to the disk dynamic profile DMW using the $3\times\sigma$ contact criterion for TP height of 6.7 nm (left) and 6.8 nm (right).

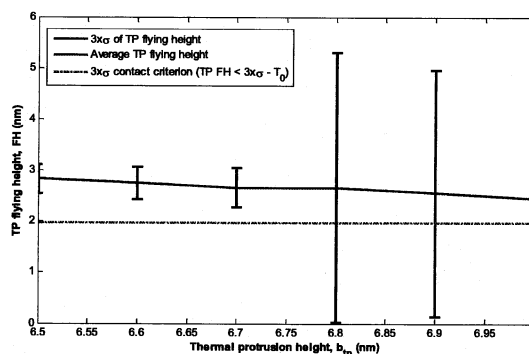


Fig. 3. Dynamic simulation results: plot of TP flying height against TP height showing initiation of contact using the $3\times\sigma$ contact criterion.

IV. SUMMARY

The current dynamic contact model improves on earlier work for ultra low flying HDIs by accurately accounting for the TP. The air-bearing dynamic model is coupled with advanced physics-based contact/friction model including roughness effects and can accurately predict FHM as well as interfacial dynamic varying forces, which can directly be related to HDI reliability. Drive-level experimental results validate the dynamic contact model and in turn can be used for robust estimation of the optimal flying and thermal protrusion parameters for ultra-high density recording.

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