Effects of Altitude on Thermal Flying Height Control Actuation

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ABSTRACT

Thermal flying-height control (TFC) is now a key technology used in hard disk drives (HDD) as an effective way to push the magnetic spacing to sub-5nm. Precise control of the magnetic spacing, or in other words the actuation of the slider flying height (FH), is a major consideration in improving the read/write capability as well as reducing the reliability problem. In this paper, we investigate the response of actuated sliders to altitude change with a focus on the variation of actuation efficiency with altitude. Numerical and experimental results both indicated an increase in the actuation efficiency at higher altitudes. Simulations show that the increased TFC protrusion and less FH lift or pushback on slider at higher altitudes contribute to this efficiency increase. This study is of practical importance for improving heater and ABS design to reduce HDD sliders' sensitivities to altitude changes.

INTRODUCTION

The ever-increasing demand for higher areal density in hard-disk drives has pushed the magnetic spacing to sub-5nm. Among the technologies driving sliders to fly lower, the TFC technology has become the most popular one [1]. As illustrated in Fig. 1, the slider is locally heated by an imbedded heater near the read-write transducers. The heating generates a thermal deformation in the slider body and results in a protrusion over the air bearing surface (ABS). Thus the original FH at read-write transducers can be reduced as much as several nanometers.

However, with this reduced spacing, the read/write transducers potentially can be degraded or even damaged due to contact with the disk induced by the FH variations related to several factors, such as the external environmental conditions, dynamic disturbances, manufacturing tolerance, etc [2]. Efforts have been made to address the issues of these effects [3-7]. Yet none of these studies covers the case of the altitude sensitivity of the thermally actuated sliders.

In this paper, we focused on the altitude effects on TFC sliders. We applied a numerical approach and compared the results with drive level testing data. More specifically, we calculated and compared the heater-induced pole tip protrusion

(H-PTP), flying-height, actuation efficiency and the pushback factor at different altitudes. In further we studied the mechanisms that cause the variations of the FH actuation by TFC between different altitudes.

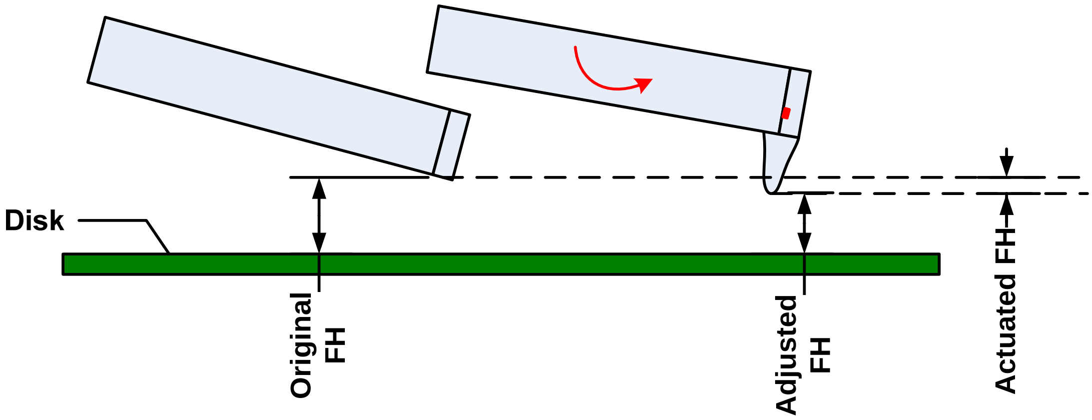

Fig.1 Illustration diagram for the thermal flying-height control of sliders. FH at read-write transducers is adjusted by the thermal protrusion induced by TFC heating.

NUMERICAL APPROACH

Model and Solution

The approach used in this analysis includes numerically solving a model that integrates two sub-models, one is the ANSYS finite element based model for the TFC heater that calculates the protrusion on the ABS due to the Joule heating, and the other is finite volume based model for calculating the air bearing spacing and pressure distribution so to generate the cooling of the air bearing on the TFC heater. To accomplish the solution, an iteration procedure is required between the two sub-models that exchanges input-output data mutually [8]. A flowchart illustrating this process is shown in Fig.2.

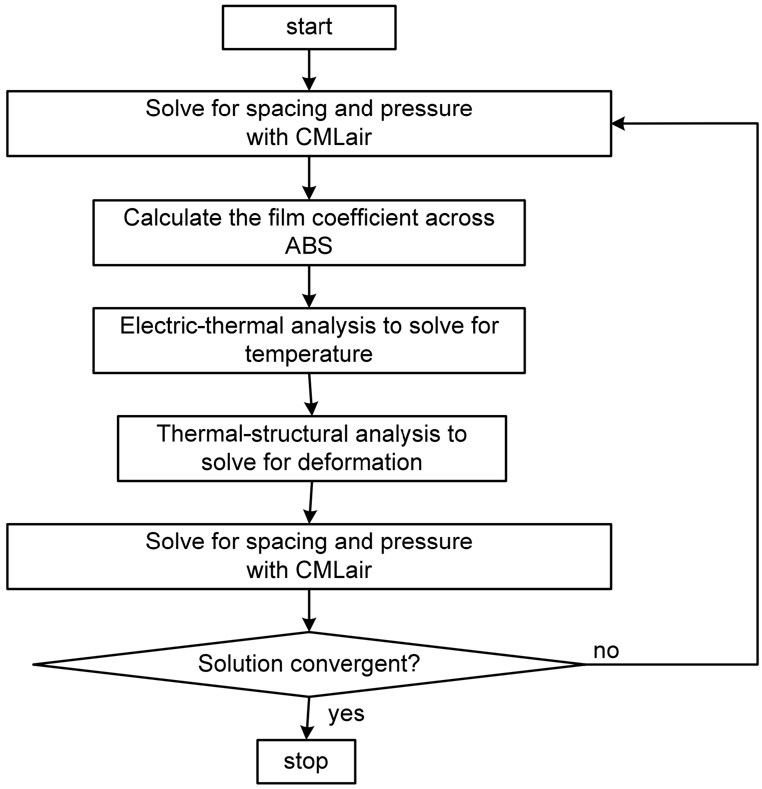

Fig.2 Flowchart for the iterative approach of TFC simulations

More specifically for the iteration, we first use CMLair, an air bearing solution software developed by Berkeley [11], to solve the generalized Reynolds equation to obtain the air bearing pressure and spacing fields. With these results, we calculate the air bearing cooling effects with or without the deformation due to heater actuation using the following heat transfer model [9]:

$$q = \frac{k}{h + 2b\lambda}(T_s - T_d) \tag{1}$$

where, k is the thermal conductivity of air and is taken as *0.0261W/(m·K)* at 25°C, h is the spacing between the slider and disk at a local point, λ is the mean free path of air molecules in the air bearing and taken as *68.6nm* at 25°C and 1 atm, T_s and T_d are temperatures of the slider and the disk, respectively. Here T_d is set to be 25 °C and T_s is varying with location. The coefficient b is defined by:

$$b = \frac{2(2-\sigma)\gamma}{\sigma_T(\gamma+1)\mathrm{Pr}} \tag{2}$$

where, $\sigma_T=0.9$ is the thermal accommodation coefficient, $\gamma=1.4$ is the specific heat ratio for air, and Pr=0.707 is the Prandtl number for air at 25°C,.

Second we solve for the ABS deformation due to the TFC heating. In this step, we conducted an electric-thermal analysis by applying voltage across the pads of the TFC heater that generates Joule heating and deforms the slider. The cooling effects on the ABS from the air bearing are included as the thermal boundary conditions in this analysis by taking the disk temperature as the ambient temperature. After obtaining the temperature distribution over the slider body, a thermal-structural analysis follows to calculate the displacement field in the slider body. Based on the deformation results, the protrusion on the ABS surface is calculated and included in the next round of flying-attitude calculations of the slider air bearing. Such a process is continued until the variation in flying-height is less than 0.05nm. Once the criterion is reached, the slider's flying attitude is determined so is the FH actuation at the read/write transducers.

Experimental verification of the model

To verify the model, we ran a series of experiments and compared the simulation results with the test data. These experiments utilized the measurement of the read-back signal of the magnetic head in commercial drives operating in an altitude chamber. The read-back signal was converted to the spacing or FH changes under the reading transducer by applying the Wallace spacing loss theory [12]. The chamber pressure can be set to different values (altitude related) so the FH or spacing under the reading transducer can be obtained for selected altitudes. Fig. 3 shows a comparison of the simulated FH loss vs. the measured data. Actuation powers are normalized with respect to a mean actuation power V_{mean}. For these results, a femto-sized slider (0.85×0.70×0.23mm) with an ABS design as shown in Fig. 4 was used in both simulation and experiments. The comparison shows that the actuation efficiency is higher at an altitude of 10kft than at sea level. The agreement between the simulations and experiments indicates the effectiveness of this approach.

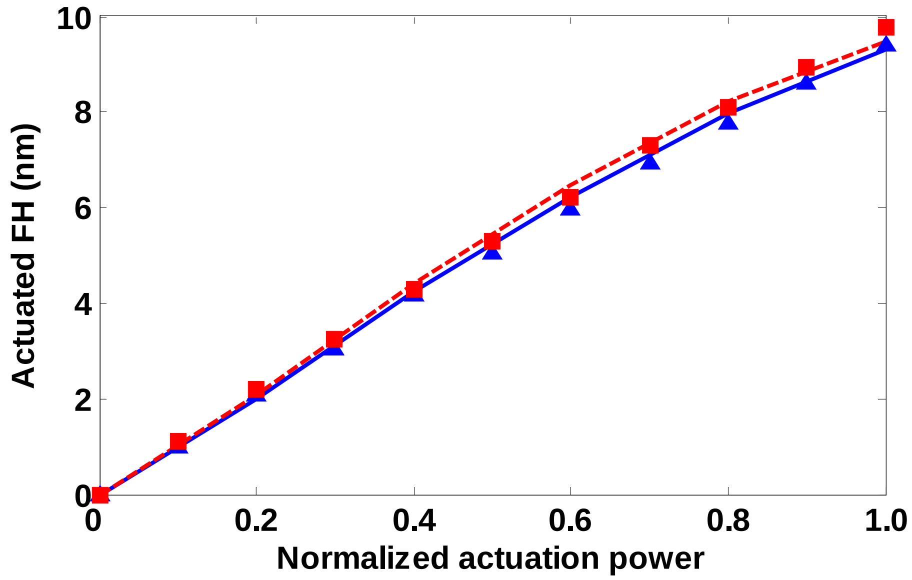

Fig. 3 Actuated FH at different actuation powers: a comparison of simulation and experiment results

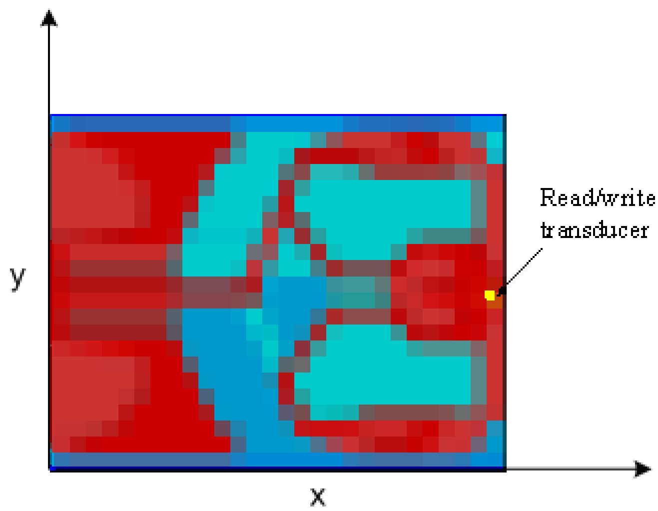

Fig. 4 Slider ABS design: different colors represent different etched recessions up to 2μm for this design. Read/write transducer located at the central trailing edge.

RESULTS AND ANALYSIS

Effects of altitude on thermal protrusion

To determine the mechanism of the actuated FH variation at altitudes, a series of simulations with identical ABS (Fig. 4) and heater design were carried out. As stated earlier, the altitude can affect H-PTP through the air bearing cooling which is defined in equation (1). Figure 6 shows the deformation along the y-centerline of the ABS at sea level, 2km, and 5km. Obviously the protrusion increases as the altitude increases.

It implies that the cooling effect is reduced at higher altitudes since the heater design is the same so is the actuation power. If further considering the cooling effects within the protruded area, as shown in Fig.6, the heat transfer coefficient at the transducer location drops for the 4km case, which indicates that the cooling is weaker when the altitude is higher. This is consistent with the higher protrusion results observed in Fig.5.

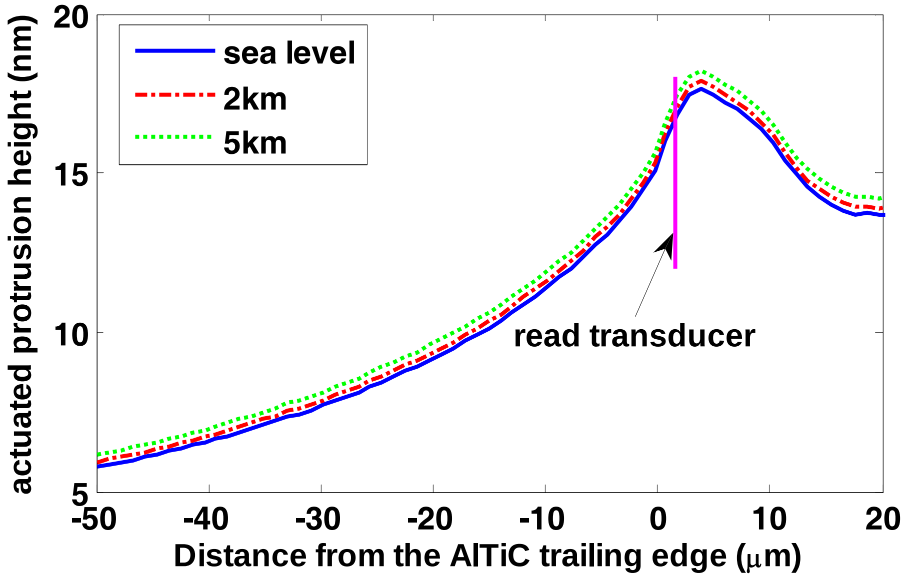

Fig. 5 Protrusion under 100mW TFC heating at different altitudes

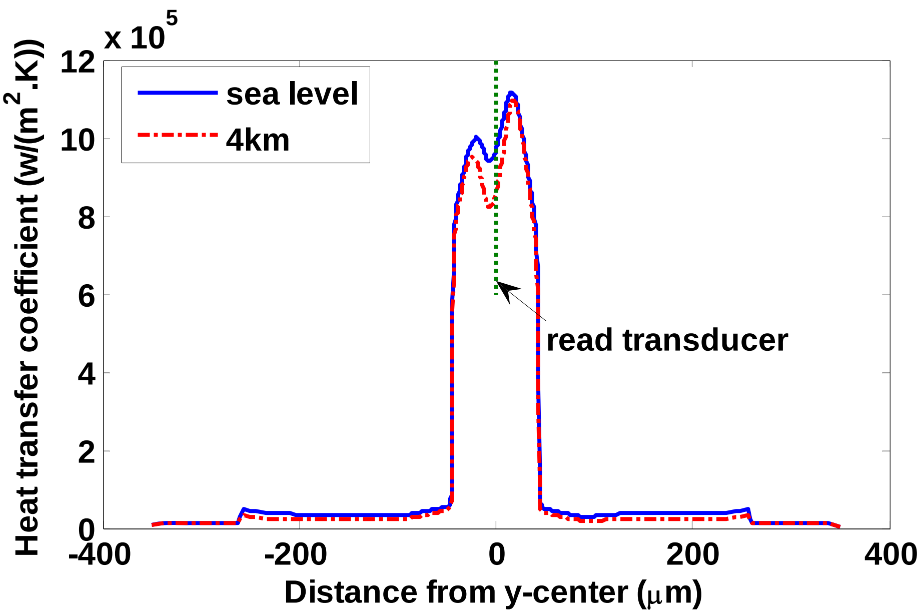

Fig. 6 Comparison of heat transfer coefficients for the sea level case and the 4km case: heat transfer coefficients along $x=x_{transducer}$ under 100mW TFC heating

According to equation (1), there are two factors that contribute to the air bearing cooling: the local air bearing spacing and the mean free path of the air. Both of them vary with altitude changes. Since the local air bearing spacing at the protruded area is smaller (usually, not always) at higher altitudes that tend to enhance the heat transfer, as predicted by the model, it is reasonable to expect that the mean free path plays an important role in reducing this heat flux. To address the altitude effect on mfp, we adopted the model of the US standard atmosphere, which describes the relationship between mean free path and pressure as follows [10].

$$\lambda = \frac{2^{1/2} \cdot R^* \cdot T}{2\pi \cdot N_A \cdot \sigma^2 \cdot P} \tag{3}$$

where, $R^*=8.31432\times10^3 N\cdot m\ /\ (kmol\cdot K)$ is the gas constant, $T=298.15K$ is the ambient temperature, $N_A = 6.02213\times10^{23}$ is the Avogadro constant, σ=3.65×10^{-10} is the effective collision diameter of the mean air molecules, P is the pressure at a local point in the air bearing.

According to equation (3), the mean free path is inversely dependent on the pressure. Fig.7 shows that the pressure around the transducer is reduced at higher altitude. Referring to Eq. (3), such a pressure reduction increases the mean free path and thus decreases the heat transfer from the slider to the disk, which gives an inverse effect from the air bearing spacing change in altitude. For this ABS design, the change in FH at the protruded area is small compared with the change of mfp term. Thus, the pressure related mfp plays a greater role which leads to the increased protrusion shown in Fig.5.

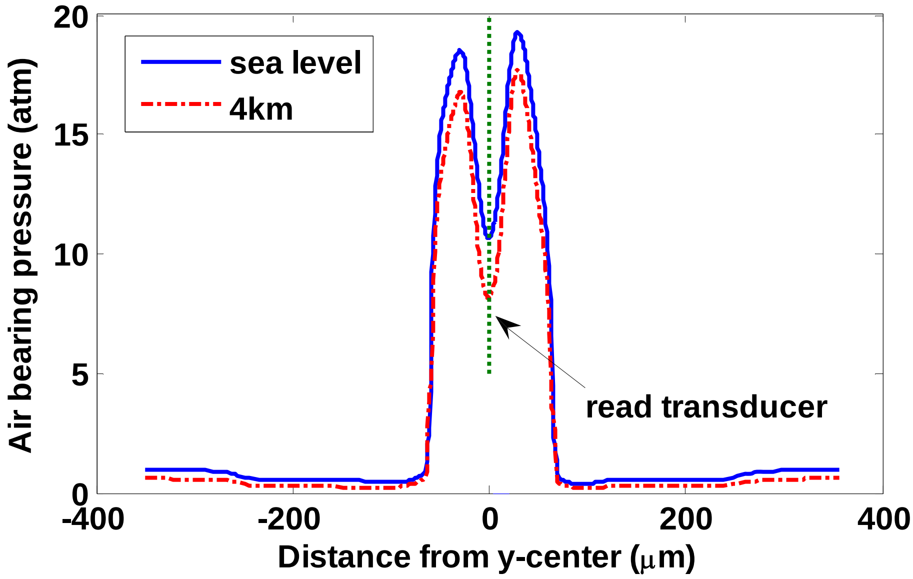

Fig. 7 Air bearing pressure for the cases of sea level and the 4km altitude: pressure measured along $x=x_{transducer}$ under 100mW TFC heating. Y-center is in the middle of the slider width in y-direction (refer to Fig. 4).

Effects of altitude on the pushback

FH change caused by the Joule heating of the TFC heater is usually not the same as the TFC protrusion itself. This is because when the TFC is switched on, it heats the slider body and deforms the ABS, which changes the air bearing pressure and tends to lift the slider's FH to regain the air bearing to balance the forces from suspension. The lifted FH compensates certain amount of TFC protrusion and thus shortens the actual FH adjustment. We use FH actuation ratio to describe this phenomenon, which is defined as:

$$FH\ actuation\ Ratio = \frac{FH\ change\big|_{read\ transducer}}{protrusion\big|_{read\ transducer}} \quad (4)$$

This ratio addresses the capability of the FH adjustment by TFC and was also called the "FH actuation efficiency" by some authors [5]. Its value is usually smaller than 1. Its complimentary part pushback factor is defined as:

$$pushback = 1\text{-}FH\ actuation\ Ratio \quad (5)$$

which represents the capability of the slider to be lifted by the TFC protrusion. Note that the pushback has relations with both the air bearing's cooling effect and force changes induced by TFC. To maximumly separate them so to study their individual contributions, we apply the protrusion profile obtained at sea level on the slider that flies at sea level and 4km respectively. As shown in Fig. 8, the pushback factor goes up with increasing actuation powers, and experiences higher values at sea level than at altitude given the same protrusion. This is because the pressure change due to the TFC protrusion is smaller at altitude than at sea level, so it requires smaller FH lift to re-gain the air bearing to balance suspension force at altitude [5]. If we substitute the sea level protrusion with the original 4km protrusion for the 4km case, we get the pushback that consists of the contributions from both the pressure change and air bearing's cooling. The curve for this case (dash-dot line) is located right between the solid one and the dashed one, which indicates that the less cooling at the 4km altitude increases TFC protrusion, leading to higher pushback amplitude.

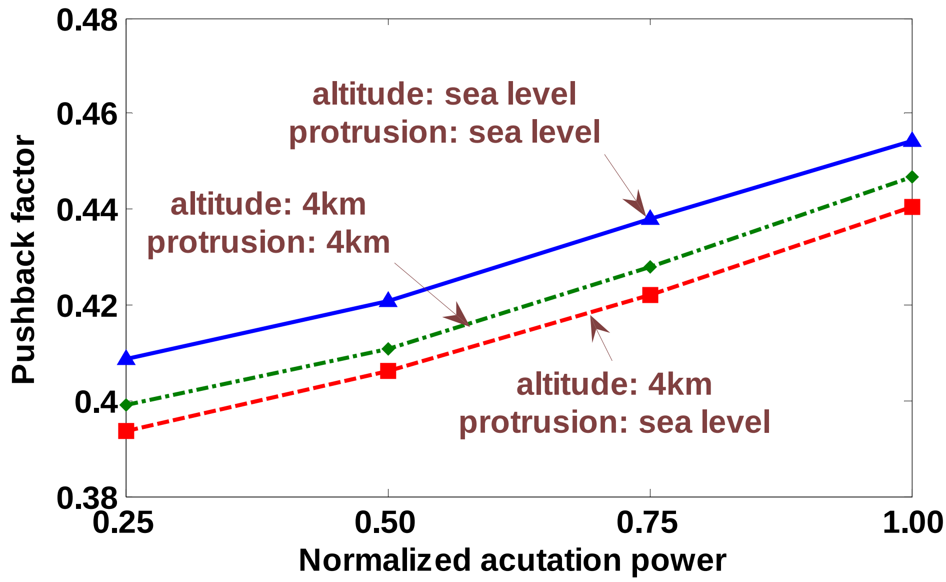

Fig. 8 Effect of altitude on the pushback factor: a comparison of the pushback factor for the cases (i) the slider is flying at sea level with the protrusion obtained in the sea level case; (ii) the slider is flying at 4km with the protrusion obtained in the 4km case; (iii) the slider is flying at 4km with the protrusion obtained in the sea level case.

Since the pushback effect is associated with the change of air bearing force, we can check its sensitivity to the altitude by tracking the change of air bearing forces under different TFC protrusions. To realize it, we fix the slider at certain attitude, say 12nm for FH at center trailing edge, 90μrad for pitch and 0 for roll, and protrude the TFC amplitudes using different heating powers. As shown in Fig. 9, the air bearing force at sea level increases faster with actuation power than at the 4km case. It implies that the slider that is combined with a suspension tends to fly higher in order to compensate the increased air bearing force, and this leads to a larger pushback and lower efficiency in the sea level case.

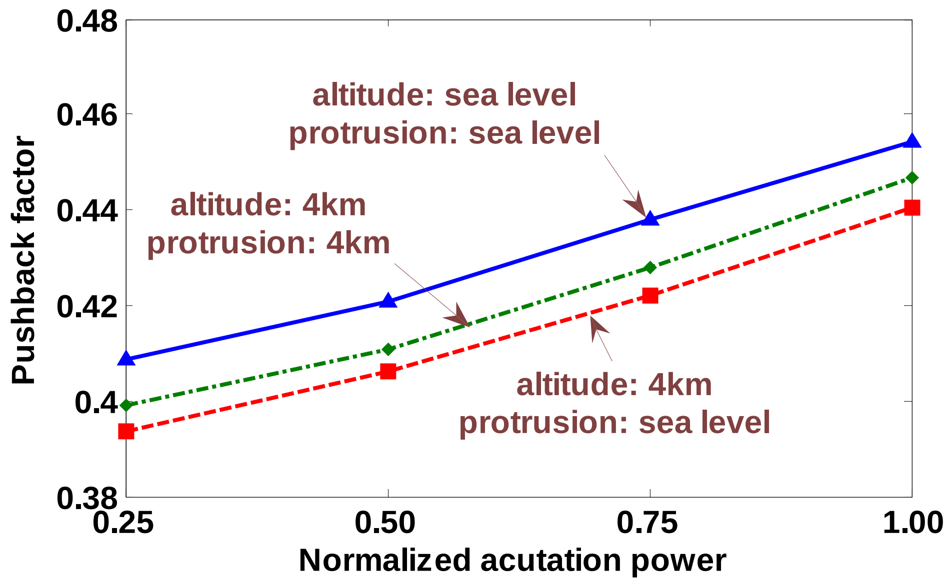

Fig. 9 Effect of altitude on the air bearing force: a comparison of the change in air bearing force for the cases (i) the slider is flying at sea level with the protrusion obtained in the sea level case; (ii) the slider is flying at 4km with the protrusion obtained in the 4km case; (iii) the slider is flying at 4km with the protrusion obtained in the sea level case.

<u>The dominating factor in actuation efficiency variation</u>

As analyzed above, at increased altitude, the pressure change under the ABS induces variations in both the ABS cooling and air bearing forces. The enlarged protrusion and less pushback can both contribute to the increase in actuation efficiency. To understand the role of the two effects, we compare the actuation efficiency for the same ABS in the following four cases: (a) the slider flying at sea level with the protrusion at sea level; (b) the slider flying at sea level with the protrusion at 4km; (c) the slider flying at 4km with the protrusion at sea level; (d) the slider flying at 4km with the protrusion at 4km. A comparison between (a) and (b) reveals how much the variation in protrusion alone affects the actuation efficiency. A comparison between (a) and (c) tells us the effects of the slider lift change due to altitude change. The difference between (a) and (d) is the combined effects of these two.

As illustrated in Fig. 10, for this ABS design, both factors influence the actuation efficiency. Since this is a nonlinear system, we can not quantify the amount each factor contributes to the actuation efficiency change. However, by the closeness between curves (b) and (c), it can be concluded that for this ABS design, the two factors have roughly equivalent effects.

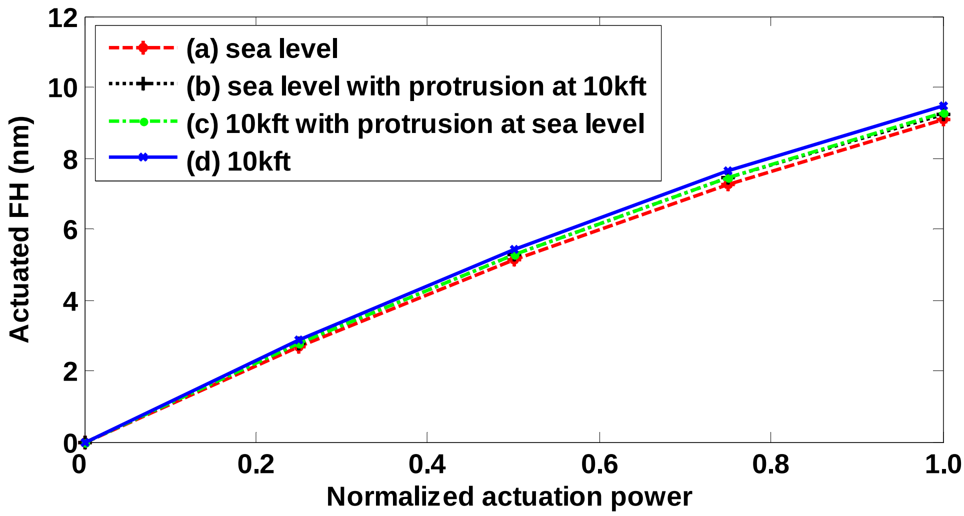

Fig. 10 Effects of altitude on actuated FH: (a) the slider is flying at sea level with the protrusion obtained in the sea level case; (b) the slider is flying at sea level with the protrusion obtained in the 10kft case; (c) the slider is flying at 10kft with the protrusion obtained in the sea level case; (d) the slider is flying at 10kft with the protrusion obtained in the 10kft case

Conclusion

The effect of altitude on thermally actuated sliders was investigated numerically and experimentally. Both the simulations and experiments indicate that the actuated FH is larger at increased altitude. It is found through simulations that such an efficiency increase is due to the increased protrusion and less pushback at the protruded area. The former one is mainly caused by the reduced cooling due to pressure change. The latter one is associated with the smaller slider lift at higher altitude. These results are of practical importance for heater and ABS design in order to reduce the sliders' sensitivities to altitude and thus improve the HDI stabilities under ambient condition changes.

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