# Air Bearing Dynamic Stability on Bit Patterned Media Disks

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**Abstract**

Bit Patterned media (BPM) recording is one of the potential technologies to be used in future disk drives in order to increase the areal density to 5 Tbit/in$^2$. But one of the main obstacles for BPM is to achieve dynamic stability of the air bearing slider at the head-disk interface (HDI). In this paper we first use a direct simulation method to check the accuracy of our previously developed Homogenization Reynolds equation solution. After confirming the accuracy it is then implemented to study the slider's flying attitude on BPM disks. Then we investigate the system's parameters using a system identification method by simultaneously solving the equations of motion of the slider and the Homogenization Reynolds equation. We observe that the first pitch mode frequency of the air bearing increases with increase of pattern groove area ratio and pattern height. And the stiffness decreases when the pattern groove area ratio or pattern height increases. We conclude that a partially planarized BPM is preferred in order to maintain the dynamic stability of the HDI.

## Introduction

In BPM recording the individual recorded bits are stored on distinct nano-scale magnetic islands in order to overcome the bit thermal stability problems caused by continuously increasing the areal density in hard disk drives beyond a stability limit. A few research works have been reported on the simulation of the slider's flying characteristics over a BPM disk. Gupta et al. [1] applied the Homogenization method to simulate the static problem of the HDI with a BPM disk. Li et al. [2] investigated the flying characteristics of air bearing sliders over BPM disk using a direct simulation method. The above researches showed the effect of the pattern height and pattern area ratio on the slider's flying height. However, they were all analyzed for steady conditions. Li et al. [3] studied a slider's dynamics when it flies over a BPM disk, and they showed that a Taylor Expansion Homogenization method is an economical and accurate method for the BPM air bearing problem. Myo et al. [4] used the direct Monte Carlo method to study the air bearing characteristics on BPM, and they found that the bearing forces are reduced with increase of bit depth and total recess area ratio. Knigge et al. [5] performed experiments on a disk with a half normal media zone and a half patterned zone. They found similar results for the relationship between the flying height change and the pattern parameters.

Li et al. [6] studied slider dynamics on a BPM disk with different pattern types on the data and servo zones. It was found that the effects of the bit aspect ratio and pattern arrangements can be ignored, and the flying characteristics during transition between the two zones depend on the pattern height and pattern area ratio. Hanchi et al. [7] investigated the effect of discrete track pattern orientation shifts at data-servo transitions on air bearing dynamic flying stability, and they found that the orientation shifts between data and servo sectors could give rise to perturbations in flying height. The dynamic characteristics of a slider flying over various servo patterns was studied in Li et al. [8]. They showed that the air-flow field is disturbed and causes flying amplitude modulation during the transitions.

A system identification method applying the CML Dynamic Simulator with modal analysis was first proposed for the analysis of the dynamic characteristics of air bearings by Zeng et al. [9]. An improved method based on [9] that employed the multiple input/multiple output orthogonal rational fractional polynomial method to estimate the modal parameters was presented by Zeng et al. [10]. However, little work has been done to investigate the dynamic stability and system parameters of the air bearing between sliders and BPM disks.

In this study we first perform a direct simulation method to check the accuracy of the Homogenization Reynolds equation. Then a system identification method that involves simultaneously solving the equations of motion of the slider and the Homogenization Reynolds equations is used to obtain the system's parameters.

## Numerical Modeling

The model of a slider flying on a BPM disk that is defined by uniformly distributed cylinders on a flat disk is show in Fig. 1. The bit pattern parameters are shown in Fig. 2, in which h is the pattern height, $\varepsilon$ is the wavelength and d is the diameter. So the area of one bit island is $\pi d^2/4$.

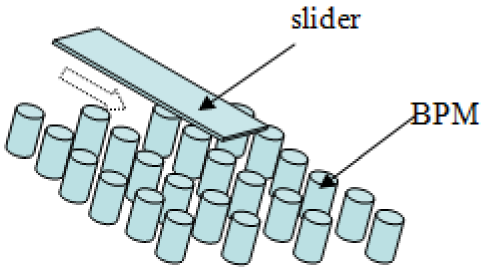


Fig. 1 Depiction of a slider flying on a BPM disk

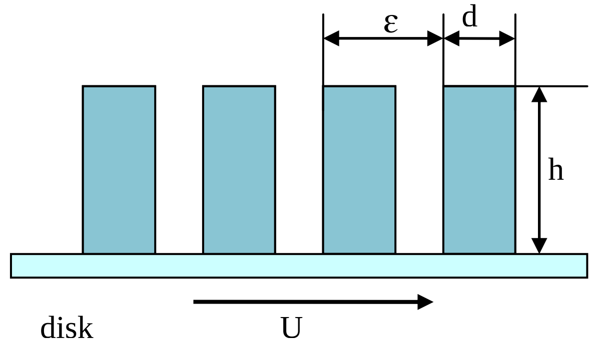


Fig. 2 Parameters of BPM

Assume the slider is a rigid body that vibrates near its steady state position, so the governing equations for the motion of the slider vibrating in 3 DOF can be expressed as:

$$m\frac{d^2z}{dt^2}+c_z\frac{dz}{dt}+k_z z = f_z(t)+\iint_A (p-p_s)dA \qquad (1)$$

$$I_\theta\frac{d^2\theta}{dt^2}+c_\theta\frac{d\theta}{dt}+k_\theta\theta = f_\theta(t)+\iint_A (p-p_s)xdA \qquad (2)$$

$$I_\beta\frac{d^2\beta}{dt^2}+c_\beta\frac{d\beta}{dt}+k_\beta\beta = f_\beta(t)+\iint_A (p-p_s)ydA \qquad (3)$$

In Eqns (1)-(3), $m,\ I_\theta\ \ and\ \ I_\beta$ are the mass and inertia moments of the slider; z, ɵ and β are the slider's vertical displacement (from the steady state) at the slider's center, its pitch and roll; $k_z,\ k_\theta,\ k_\beta,\ c_z,\ c_\theta\ \ and\ \ c_\beta$ are stiffness and damping coefficients of the 3-DOF model of the suspension in the three directions. $f_z(t),\ \ f_\theta(t)\ \ and\ \ f_\beta(t)$ are external excitation forces. $p$ and $p_s$ are pressure profiles in the vibration state and steady state, governed by the Homogenization Reynolds equation developed in [3]:

$$\nabla_x\cdot\left[\underline{\underline{A}}^*\nabla_x P_0\right]-\nabla_x(P_0\underline{\underline{\Theta}}^*)=\sigma\frac{\partial(P_0\overline{H})}{\partial T} \qquad (4)$$

where the homogenization coefficients are:

$$\underline{\underline{A}}^* = \begin{pmatrix} \overline{\overline{QPH^3(1+\frac{\partial\omega_1}{\partial y_1})}} & \overline{\overline{QPH^3\frac{\partial\omega_2}{\partial y_1}}} \\ \overline{\overline{QPH^3\frac{\partial\omega_1}{\partial y_2}}} & \overline{\overline{QPH^3(1+\frac{\partial\omega_2}{\partial y_2})}} \end{pmatrix} \tag{5}$$

$$\underline{\underline{\Theta}}^* = \begin{pmatrix} \Lambda_x(\overline{H}+\overline{\overline{QPH^3\frac{\partial\chi_1}{\partial y_1}}})+\Lambda_y\overline{\overline{QPH^3\frac{\partial\chi_2}{\partial y_1}}} \\ \Lambda_x\overline{\overline{QPH^3\frac{\partial\chi_1}{\partial y_2}}}+\Lambda_y(\overline{H}+\overline{\overline{QPH^3\frac{\partial\chi_2}{\partial y_2}}}) \end{pmatrix} \tag{6}$$

Here Q is the flow factor assuming the Fukui and Kaneko [11,12] correction and P, H and T are the dimensionless pressure, spacing and time. $\underline{\Lambda}$ is the bearing number vector and σ is the squeeze number. The functions $\omega_1$, $\omega_2$, $\chi_1$ and $\chi_2$ are 1-period solutions of the following local problems:

$$-\nabla_y\cdot(QP_0H^3\nabla_y\omega_i)=\nabla_y\cdot(QP_0H^3\underline{e_i}) \tag{7}$$

$$-\nabla_y\cdot(QP_0H^3\nabla_y\chi_i)=\nabla_y\cdot((H_0-(1-\frac{\sigma}{\Lambda})H^D)\underline{e_i}) \tag{8}$$

By simultaneously solving the equations of motion of the slider (1-3) and pressure equation (4) we obtain the vibration responses of the slider for given disturbances, and using the system identification method [10], we can get the air bearing system's parameters.

## Simulation Results and Analysis

### (1) A direct calculation for checking the Homogenization method

We first use the CML Dynamic Simulator [12] to check the Homogenization Reynolds equation simulation results. In this direct method, the bit patterns are defined as cylinder-formed waviness. Because of the computing limitation, the pattern sizes in this simulation are chosen to be on the order of µm. While using the Homogenization method, the pattern sizes are chosen to be on the order of tens of nm.

Fig. 3 shows a comparison of the simulated steady flying height using the direct method and the Homogenization method. From this figure we see that the spacing change tendency with change of pattern height and pattern area ratio is almost the same for these two methods except there is an offset of spacing. The simulated flying height using the direct method is slightly higher than the simulated flying height using the Homogenization method. Since the direct method uses a pattern size much larger than the pattern size used in the Homogenization method we also investigated the effect of the pattern size on the simulated steady flying height using the direct method; the results are shown in Fig. 4. In this simulation we studied the case with PH=0.75 and AR=0.25. We selected three different pattern sizes: 100 μm, 10 μm and 5 μm respectively. The right figure of Fig.4 is a partial zoom in of the left figure. The simulation results show that the average minimum spacing decreases as the pattern size decreases. We see that when the pattern size used in the direct method is reduced (approaching the real pattern size) the calculated flying height moves in the direction of the flying height calculated by the Homogenization method. Thus we can say, with some assurance, that the direct method guarantees the accuracy of the Homogenization method. Since the direct method takes approximately three hours for a simulation while the Homogenization method takes only about 0.5 hour we use the Homogenization method to do the rest of the dynamic simulations.

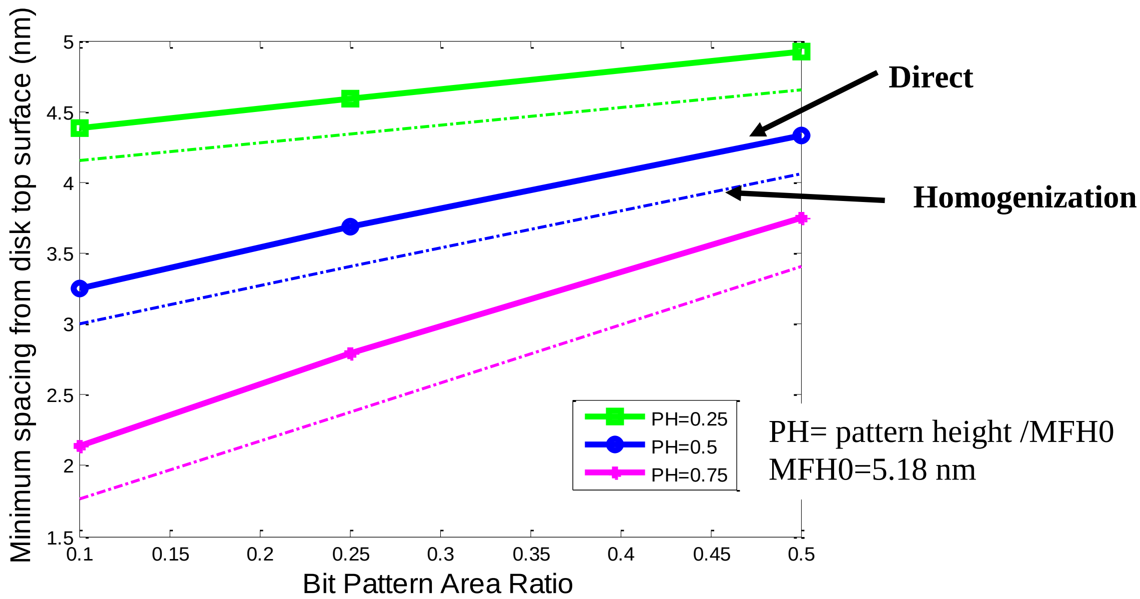


Fig. 3 Comparison of steady flying height for direct method and Homogenization method

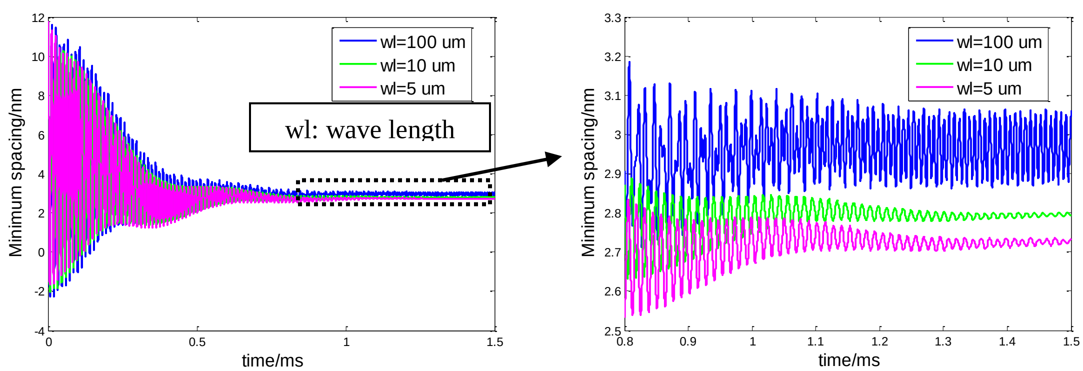


Fig. 4 pattern size effects on simulated flying height for direct method

## (2) Slider dynamic stability

In this section we investigate a slider's dynamic stability on various pattern designs. The ABS design studied in this section is shown in Fig.5. We first use the Homogenization method to obtain the slider's steady flying height on different pattern designs, the results of which are shown in Fig. 6. This figure shows that the minimum flying height decreases with increase of groove area ratio (1- $\pi d^2/4$, refer Fig. 2); the flying height also decreases with increase of pattern height. The results also indicate that the minimum flying height is smaller if the pattern height is higher or the groove area ratio is larger.

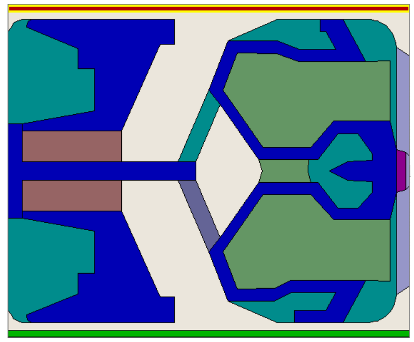

Fig. 5 ABS design

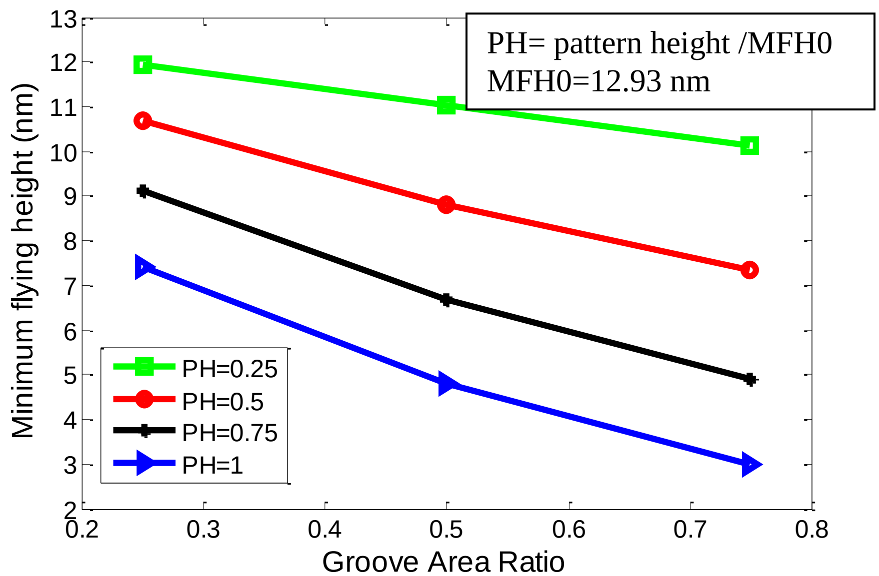


Fig. 6 The slider's steady minimum flying height on various pattern designs

Next we use the system identification method [10] to obtain the air bearing system parameters such as stiffness, mode shape, mode frequency, etc. In order to study the bit pattern effects on the system parameters we first study the case when the slider is flying over a smooth disk. The mode shapes and their corresponding frequencies are shown in Fig. 7, which shows that the first mode (numbered 1) is a pitch mode with frequency 177 kHz and its nodal line is close to the trailing edge; the second mode is a roll mode with frequency 188 kHz with its nodal line located almost at the slider center line; the third mode is nearly a pure pitch mode with frequency 362 kHz and its nodal lines is close to the leading edge.

Then we studied the frequency and stiffness changes with the changes of pattern height and pattern area. The frequencies (kHz) of the first pitch mode are listed in Table 1, in which each row has different groove area ratios and each column has different pattern heights. To show the results more clearly, we plot the first two rows in the top figure of Fig.8 and plot the first column in the bottom figure. These results show that the first pitch mode frequency increases with increase of groove area ratio, and also increases with increase of pattern height. As shown in Fig.6, the minimum flying height decreases with increase of groove area ratio and pattern height. And the first pitch mode nodal line is close to the trailing edge where the minimum clearance occurs. So the increase of the first pitch mode frequency can be considered as an effect of further compression of the air film at the trailing edge. Referring back to Table 1, we see there are three frequencies, which are emphasized by bold font, that don't follow the frequency increasing tendency. As shown in Fig. 9 the stiffness decreases as groove area ratio or pattern height increase. And continuous increase in the pattern height or groove area ratio leads to a negative stiffness which means that instability appears under these conditions. This indicates that a partially planarized patterned media is required in order to improve the dynamic stability of HDI.

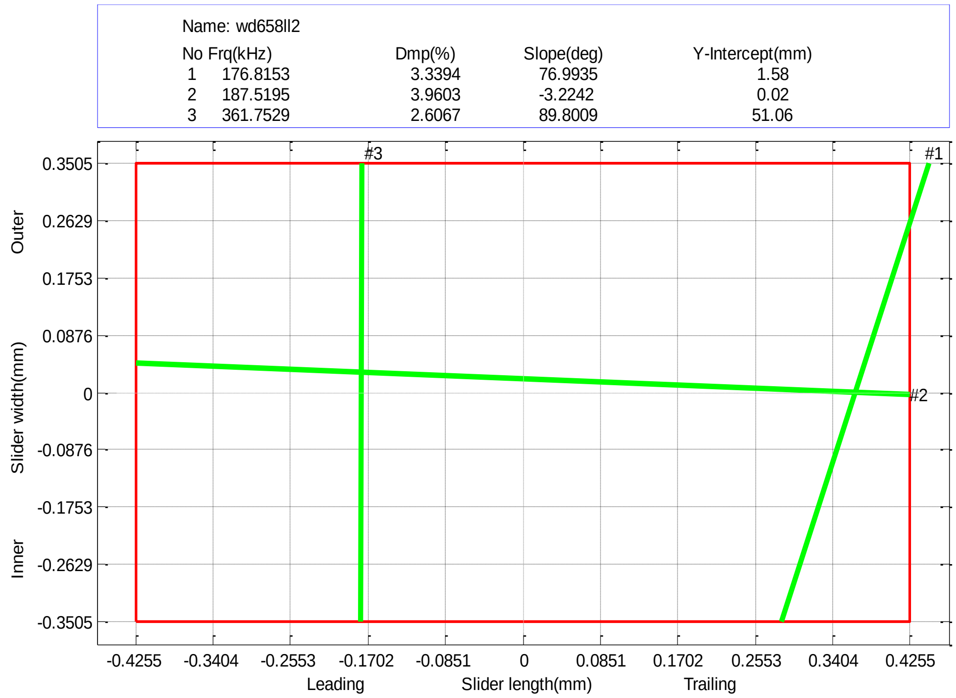


Fig. 7 Results when the slider is flying on a smooth disk

Table 1 First mode frequencies on BPM disks

| PH \ G AR | 0.25 | 0.5 | 0.75 |
|---|---|---|---|
| **0.25** | 177.671 | 178.471 | 179.062 |
| **0.5** | 178.517 | 179.265 | 179.742 |
| **0.75** | 179.102 | 179.445 | **173.839** |
| **1** | 179.516 | **177.427** | **167.496** |

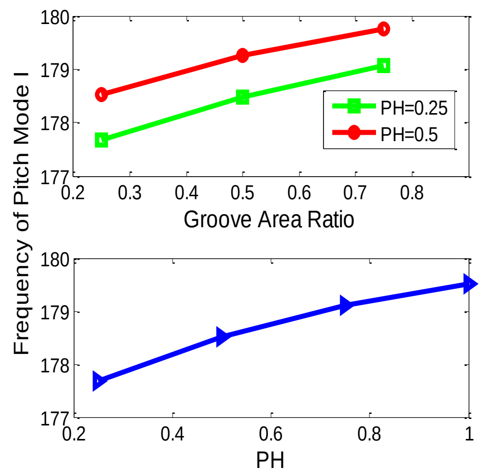


Fig. 8 First mode frequencies on BPM disks

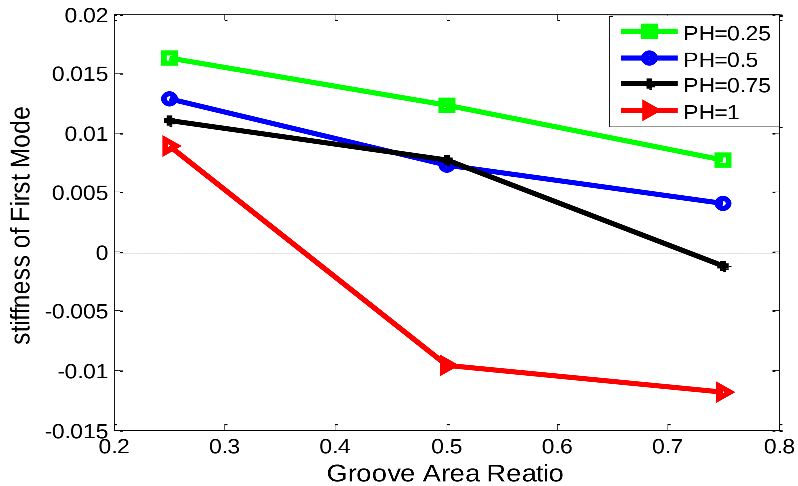


Fig. 9 First mode stiffness on BPM disks

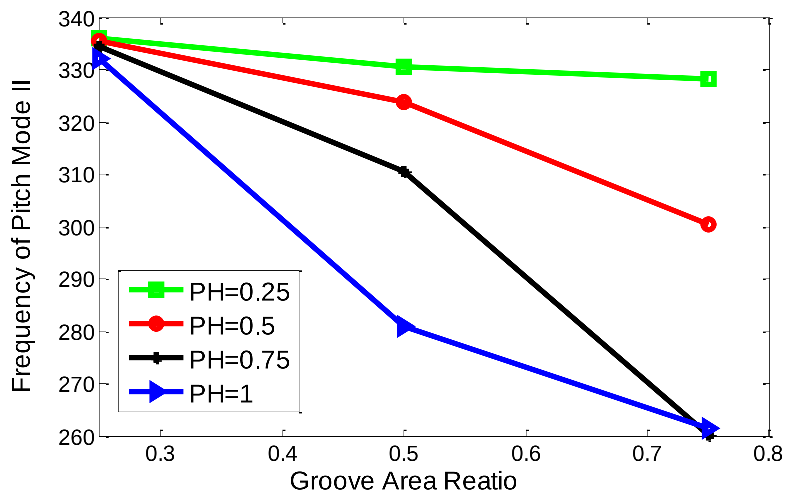


Fig. 10 Third mode frequency on BPM disks

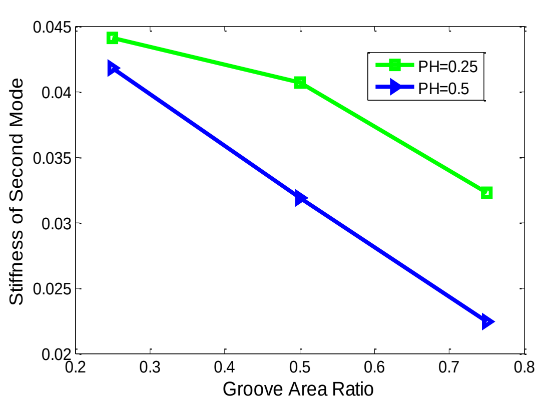


Fig. 11 Second mode stiffness on BPM disks

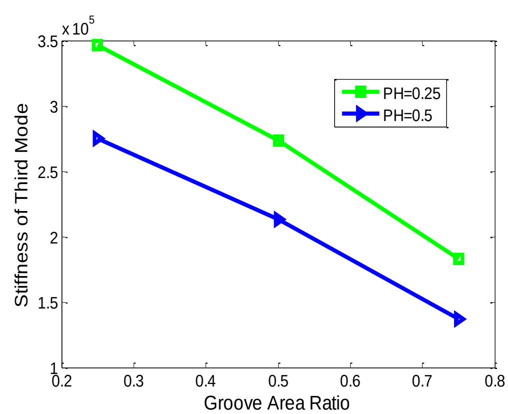


Fig. 12 Third mode stiffness on BPM disks

Fig. 10 shows that the frequency of the third mode decreases with increases of groove area ratio and pattern height. As the third mode nodal line is close to the leading edge, which has a relatively large minimum flying height, the effect of compression of the air film is not so obvious in this case. The decrease of frequency may indicate a decrease of stiffness. Figs. 11 and 12 show the stiffness of the second and third modes when the slider is flying on different pattern designs. The results show that the stiffness decreases as groove area ratio increases and also decreases as pattern height increases. These results also indicate that a partially planarized pattern media is needed in order to maintain a steady HDI.

**Conclusion**

We first used a direct method to study the slider's steady flying height over various bit pattern media disks and compared the results with those from the much less computation intensive Homogenization method to guarantee the accuracy of the latter method. Having found satisfactory confirmation and since the Homogenization method can significantly save computing time, we used this method to do the HDI dynamic stability investigation.

We then used the system identification method to study the air bearing system's stiffness, mode shape and frequency when the slider flies over different BPM disks. It was found that the first pitch mode frequency slightly increases with increase of groove area ratio and pattern height, which can be explained as the effect of further compression of the air film at the trailing edge. The stiffness decreases as groove area ratio or pattern height increases. Since negative stiffness can be realized for certain values of area ratio and pattern height we conclude that a partially planarized patterned media is needed in order to guarantee the dynamic stability of the HDI.

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