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Dynamic instability of flying head slider and stabilizing design for near-contact magnetic recording

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ABSTRACT

The dynamic instability of a flying head slider is described, and a design guideline is presented for a slider that can stably fly at a height of less than 5 nm. The current use of shrouded Rayleigh step-bearing slider has been a good way to increase air-bearing stiffness and damping while reducing meniscus adhesion and friction forces, but does not have enough ability to achieve a small flying height less than 5 nm. On the basis of meniscus interfacial force theory, I proposed a spherical pad slider that is inherently stable in the near-contact regime and that has high durability against intermittent contact, which is necessary for future high-density magnetic recording. This design concept is being partly realized by thermal flying height control technique.

1. Introduction

Since the introduction of perpendicular magnetic recording in 2004, the bit areal density of hard disk drives has been increasing at an annual rate of about 40%. During the transition from longitudinal to perpendicular recording, efforts to reduce the flying height (FH) to less than 10 nm encountered a crucial problem—slider instability [1]. Bouncing vibration occurred at a FH of several nanometers and often continued until the nominal FH was increased to 10 nm. Thus, the hysteresis of the bouncing vibration prevented the FH from being reduced to less than 10 nm [2,3]. This slider instability was partly overcome by adopting shrouded Rayleigh step air-bearing design [4]. Another difficulty in reducing the FH was decreasing the static FH variations due to radial position, temperature, altitude, and fabrication and assembly tolerances. The introduction of thermal FH control (TFC) greatly reduced these variations [5]. This control technique uses an electric heater to create a thermal protrusion near the read/write element, enabling the FH to be adjusted in-situ. It is estimated that TFC can reduce the nominal FH by ~2 nm by compensating for variations in the FH. In addition, the partial protrusion of an air-bearing surface (ABS) reduces the interfacial force between the slider and disk, resulting in improved slider stability. Adding a shrouded step bearing and TFC has enabled the nominal FH to be reduced to ~5–6 nm.

In this paper I overview the innovation of techniques developed over the last several years for reducing the FH, focusing on slider instability problem, and then propose a design concept for achieving inherently stable flying at a low FH (less than 5 nm) for future high-density magnetic recording. In Section 2, I introduce our group's experimental and theoretical investigation of unstable slider vibration and discuss design guidelines for stable flying at a low FH less than 5 nm. In Section 3, I describe several slider designs proposed for improving the dynamic stability of a flying head slider. In Section 4, I describe the basic design concept of a spherical pad slider that I proposed before the emergence of TFC technique. It is aimed at achieving an inherently stable, highly durable head slider for near-contact recording, which is necessary for achieving a 1 Tb/in^2 recording density. In Section 5, I summarize the present state of flying head sliders and mention future key technologies.

2. Interfacial force, instability of slider, and design of stable flying head slider

2.1. Features of flying head slider instability

I will first explain the typical features of the touchdown (TD) and takeoff (TO) of a pico-slider [6]. Fig. 1(a) schematically shows the ABS of a typical pico-slider. Fig. 1(b) shows the amplitude characteristics of the slider vibration measured at point A in Fig. 1(a) for both decreasing and increasing ambient pressure. The dashed line represents the nominal FH at the head position numerically calculated using the Reynolds equation. The actual height may be ~1–2 nm less. The amplitude is expressed as the rms value of the bouncing vibration. Bouncing vibration occurred at heights more than 5 nm. Once severe unstable vibration occurs,

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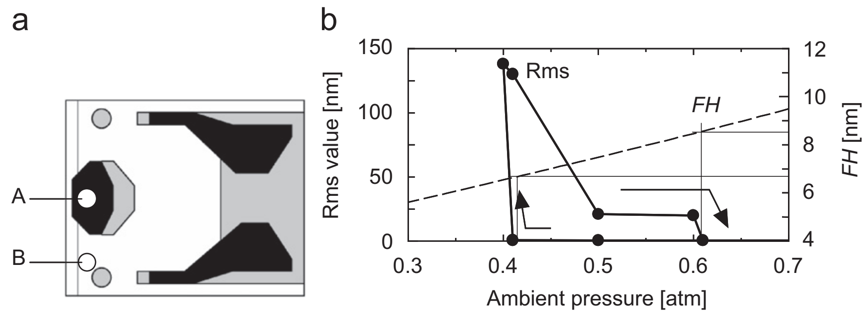

Fig. 1. ABS of pico-slider tested (A: trailing center, B: trailing side) and amplitude characteristics at A during TD and TO [6]: (a) air-bearing surface; (b) rms value of vibration and FH versus ambient pressure.

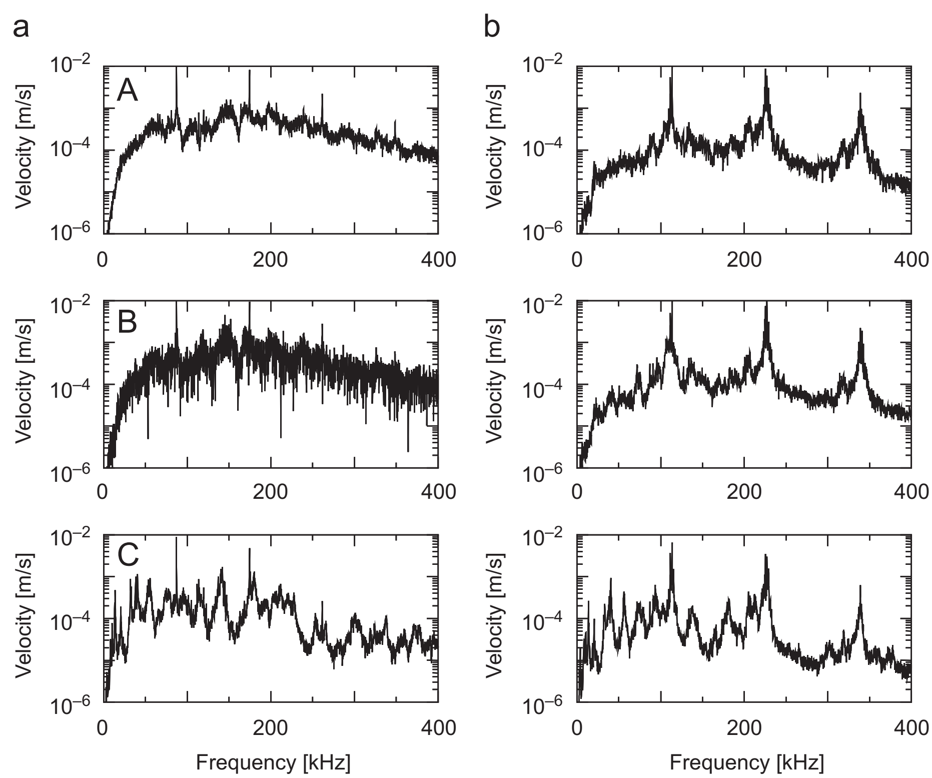

Fig. 2. Frequency spectra of measured velocity of bouncing vibration (a) immediately after TD and (b) immediately before TO measured by LDV at (A) trailing center, (B) trailing side, and (C) suspension [6]: (a) touchdown (0.45 atm); (b) takeoff (0.58 atm).

it continues even at a larger nominal FH. The beginning and ending of the bouncing vibration are called TD and TO. The heights immediately before TD and immediately after TO are termed TD height (TDH) and TO height (TOH), respectively.

Fig. 2 shows the frequency spectra of the measured velocity of the bouncing vibration of the slider at the trailing center (A), trailing side (B), and suspension (C) immediately after TD and immediately before TO. That for the suspension was measured near the back of the slider's leading edge. The dominant frequency was slightly less than 100 kHz, which is close to the lower pitch mode frequency of a slider/air-bearing system. The bouncing vibration is unstable vibration of the slider/air-bearing system due to the interfacial force between the slider and magnetic disk. Experiments demonstrated that a slider flying stably when the pressure is below the TO pressure will exhibit bouncing vibration if a disturbance is applied. Therefore, we cannot use a flying head slider below the TOH. This was the most difficult problem to overcome in achieving a FH of less than 10 nm. A number of researchers have investigated bouncing vibration since 2001 [7–12]. Xu et al. [11] showed that texture on the slider can prevent severe unstable bouncing vibration. Li et al. [12] showed that slider vibration occurs at FHs above the intermittent contact height and that this phenomenon is related to lubricant pickup by the slider.

The TD phenomenon is often attributed to van der Waals force [13–15] as many think that meniscus formation is not possible during bouncing vibration at 100 kHz on a spinning disk. Considering the experimental results of Li et al. [12], we established a theory of interfacial force caused by meniscus formation in the toe-dipping regime and performed dynamic analysis on a flying head slider using a simple two-degree-of-freedom (2-DOF) model [3,6,16–18]. We also experimentally investigated the dynamic adhesion force that occurs when a spherical slider collides with a magnetic disk [19,20].

Fig. 3 shows the motion velocity of a spherical glass slider when it bounced on a stationary magnetic disk under four lubricant conditions [19]. The slider had a curvature radius of 1 mm and a relatively rough surface ($R_a = 1.71$ nm, measured in a $1\times1\,\mu m^2$ scan area). The roughness of the disk was 0.52 nm,