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Mechanism and Machine Theory 41 (2006) 1230–1242
Mechanism and Machine Theory
www.elsevier.com/locate/mechmt

Nonlinear dynamics of sub-10 nm flying height air bearing slider in modern hard disk recording system

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Received 25 May 2004; received in revised form 21 October 2005; accepted 11 November 2005
Available online 9 January 2006

Abstract

This paper presents an experimental and analytical study of nonlinear dynamics of air bearing slider in modern hard disk recording system. Proximity recording sliders used for commercial hard disk drive were deployed for the experimental investigation. Flying height oscillation signal of the sliders in various proximity regimes (nano-meter level) were measured by using ultra-precision laser doppler vibrometer (LDV), and processed by using Matlab for time–frequency analysis and phase plot analysis. From the experimental results, it was found that two kinds of nonlinear oscillations exist in the system: the slider–disk contact-induced nonlinearity and the air bearing inherent nonlinearity. Primary resonance, superharmonic resonance and subharmonic resonance due to the nonlinearity were observed. A numerical–analytical model incorporating the nonlinear features of both slider air bearing oscillation and slider contact vibration was developed to quantitatively estimate spectral signatures. Direct numerical simulations were also carried out to simplified model to obtain phase plots. The analytical and numerical results agree with the experimental results well. It was shown that both the contact vibration and air bearing oscillation render the system to exhibit complex nonlinear features. Particularly, phase plots can be used to identify the slider–disk contact vibration and air bearing nonlinear oscillation, the former is characterized by "sharp corner" when the non-contact phase transferring to contact phase, and latter is characterized by "smooth corner" due to stiffness–softening feature of air bearing.

Keywords: Computer hard disk drive; Nonlinear dynamics; Tribology; Data storage

1. Introduction

Hard disk drive is one of key components in computer. In the development of modern hard disk drive that is currently targeting on a density of 200 Gb/in^2, it is widely believed that the air bearing slider with 5 nm flying height should be employed together with super smooth disk. However, such a low spacing interface faces a great challenge of the instability of air bearing slider due to the unavoidably contact-induced nonlinearity and the inherent nonlinearity of air bearing system. A thorough understanding of both slider air bearing dynamics

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doi:10.1016/j.mechmachtheory.2005.11.002

and slider contact dynamics is crucial to the successful design and implementation of proximity recording interface. Suzuki and Nishihira [21] investigated the actual flying characteristics of proximity slider by experiments. Donovan and Bogy [2], Hayashi et al. [4], Liu et al. [8] and Menon [9] investigated the contacts and vibrations in proximity recording interfaces. Peck et al. [16] studied frequency characteristics of air bearing by using FFT analysis of slider response. Bogy et al. [1], Zeng et al. [26] conducted theoretical and experimental modal analysis of different slider air bearing. Wahl et al. [24], Hu et al. [5] investigated the dynamic characteristics of proximity recording slider in time domain. Harrison et al. [3] investigated the dependence of resonance frequencies on the proximity conditions by using experiments and a simplified model. Ono et al. [12,13] presented extensively numerical analysis on bouncing vibrations of a single and two-DOF contact slider model on a harmonic wavy disk surface. Sheng and Liu [18,20] presented a theoretical analysis of contact vibrations of slider with partial contact air bearing. Voights and Doan [23], Suzuki [22] observed the vibrations and severe instability phenomena of proximity recording sliders. Ruiz and Bogy [19] alerted that the slider air bearing exhibits highly nonlinearity as the stiffness depends on the flying height. Menon and Boutaghou [10] revealed strong nonlinear behavior of air bearing slider in the transient process of passing bump by using time–frequency analysis. Knigge et al. [6] studied contact behavior of nano and pico glide slider and proximity recording slider by using joint time–frequency analysis, and they illustrated the highly nonlinear behavior of air bearing in transient process. Generally, time domain analysis provides rigorously results for case study, whereas frequency domain study is more convenient to draw the spectral signature of the air bearing system and to combine numerical and experimental techniques together to draw dynamic parameters. However, there have been lack of a comprehensive understanding of the spectral signatures of slider air bearing system in the proximity recording regime, but it is obviously helpful for further developing proximity recording slider interface. This topic is investigated widely recently, but the basic features have not been clarified as the different nonlinearities and different disturbances may take place simultaneously in the interfaces. This paper proposes a new approach to characterize the nonlinearities of slider–disk interface with sub-5 nm flying height, which enables to clearly clarify the contact-induced nonlinearity and air bearing inherent nonlinearity.

In this paper, the nonlinear dynamics behaviors of slider air bearing in the proximity recording regime were studied experimentally, numerically and analytically. Proximity recording sliders were used in the experiments. Flying height modulation signal of sliders in various proximity regimes were obtained and processed for time–frequency analysis. In the experiments, resonance with fold and fractional frequencies of the natural frequency as well as primary resonance were recorded. A numerical–analytical method was presented to quantify the spectral properties of the nonlinear fluctuation of air bearing and contact vibration of slider in the proximity recording regime. From the rigid dynamics equation of slider and the generalized Reynolds equation of air bearing, stiffness and damping matrices were numerically derived by implementing dynamic perturbation to the air-bearing equation under Laplace transformation, and solving the resultant boundary value problem. By using quasi-dynamic loading method, by which a variation to the steady equilibrium displacements of pitch and vertical modes is attained by applying different virtual inertial loads, the changes of stiffness and damping matrices as the variation of displacements were calculated numerically. A nonlinear analysis reveals that the air bearing system possesses softening features. Finally, a simplified equation in conjunction with slider–disk interference was applied to quantify the vibrations of the slider in the proximity recording regime. The derived nonlinear system could exhibit primary, sub-harmonic and superharmonic resonance. On the other hand, a comprehensive solutions include preliminary resonates, nonlinear normal modes, sub-harmonic resonance, superharmonic resonance, are given to the system contact vibrations. Even though the air bearing nonlinear oscillation and contact nonlinear vibration share many similar nonlinear properties, it is found that these two different nonlinearities have a distinctive nonlinear feature associated with them: contact vibration has ''sharp corner'' in phase plot whereas non-contact has ''smooth corner'' in phase plot.

2. Theoretical considerations

2.1. Characterization of nonlinear fluctuation of air bearing slider by a numerical–analytical approach

We suppose that the equation characterizing the pressure distribution, $p(x, y)$, between a slider and disk surface is governed by generalized Reynolds equation