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Review Article

Sensing and Identification of Nonlinear Dynamics of Slider with Clearance in Sub-5 Nanometer Regime

Gang Sheng

Department of Mechanical Engineering, University of Alaska, Fairbanks, AK 99775, USA

Correspondence should be addressed to Gang Sheng, gsheng@alaska.edu

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This paper provides an overview of the problems pertaining to the sensing and identification of nonlinear dynamics of slider with clearance in sub-5 nanometer regime. This problem is complex in nature because the nonlinear dynamics of slider in sub-5 nanometer clearance regime involves different sources of nonlinear, nonstationary, and uncertainty characteristics. For example, the involved forces such as air-bearing force, intermolecular force, and contact forces are all nonlinear. The complex interface interaction with mobile lubricant makes the slider response be nonstationary. Furthermore, the interfacial parameters are available only by assumptions in the sense of statistics. Most of the reported studies either focused on physics-based simulations by using assumed interfacial parameters or focused on experimental characterization. The issues of the sensing and identification of the nonlinear dynamic properties of slider in nanometer clearance regime will be discussed with an aim at illustrating the promising approaches for improving the correlation between test data and physics-based simulations.

1. Introduction

Reducing the spacing between magnetic head and magnetic disk media is critical to enabling further increased recording density of magnetic disk drives. The development of head-disk interface technology has been focused on slider dynamics. Pushing the areal density toward 1–10 Tbit/in^2 requires the magnetic spacing down to sub-3 nm level, which requires clearance down to sub-nanometer.

There is a large body of literature devoted to modeling, simulations, and experimental characterization of slider dynamics with clearance in the regimes from sub-10 nanometer to nanometer. However, the research in the correlation between test data and physics-based simulations has been very limited. This paper aims to present an introductory review of this challenging field. The paper starts with a brief description of the problem, the factors affecting uncertainty and nonlinear dynamics of sliders, the state of the art, and current status with the practical limitations and the challenges faced in the studies related to nonlinear dynamics of slider in nanometer clearance regime.

The complexity of interface slider-disk interaction and the uncertainty of interface parameters have made the quantitative prediction of slider response by using physics-based simulation a difficult task. This is similar to the conventional problem of the quantitative prediction of friction for a given interface, which has been elusive. Although physics-based models and numerical tools are available for modeling specific types of nonlinearity of slider dynamics, a systematic investigation of the uncertainty of the formulations and resolutions of the inverse problems for nonlinear dynamics of slider has never been addressed in the literature. On the other hand, there are many experimental characterizations of slider dynamics in sub-10 nanometer regime, but most of the experimental analysis falls in conventional Fourier transform framework that is not suitable for characterizing complex nonlinear systems in principle.

This article will review and illustrate the issue of the numerical analysis correlation and updating using tested results. On one hand, conducting numerical simulation using physics-based models with assumed interface parameters has been a common practice; on the other hand, dealing with nonstationary, nonlinear phenomena encountered in experiments has been bypassed due to its challenging characteristics, which is reflected by the fact that only Fourier transform approach has been used to interpret the test data of the sliders with thermal flying height control (TFC). Nevertheless, improving slider performances requires accounting for the true, nonstationary, nonlinear, and uncertainty nature of slider dynamics and, therefore, it can be predicted that the field of conventional slider dynamics analysis will increasingly involve nonlinearity and uncertainty as air-bearing surface (ABS) designs and interface are increasingly being optimized. When test is performed, slider-disk interface is usually tested and analyzed under the assumption that the behavior remains linear in the frequency range of interest. This fundamental assumption makes it possible to interpret data in the frequency domain because signals measured can usually generally be found with periodic natural modes of air-bearing. On the other hand, analyzing nonlinear systems using Fourier transforms would theoretically require the addition of higher-dimensional kernels. Another drawback is that most transformations, such as Fourier transforms and wavelets are essentially linear tools, which has a theoretical limitation at analyzing nonlinear data with linear techniques.

To understand the literature in this area, it is convenient to examine the following relatively distinct elements documented by the literature: (1) nonlinear dynamics of slider in sub-10 nanometer clearance regime, (2) dynamics of TFC slider in sub-5 nanometer clearance regime, and (3) detection and identification of nonlinear dynamics in general area. After having reviewed the literature in the above three aspects, the author will try to offer some future perspectives by illustrating the promising approaches used to improve the correlation between test data and physics-based simulations of slider dynamics.

2. Nonlinear Dynamics of Slider in Sub-10 nm Clearance Regime

The success of HDDs has been partly due to the technical progress of R/W head-disk interface. The physical slider-to-disk minimum spacing was about 100 nm in 1992 and was about 12 nm by 2002. The nonlinear phenomena and features of slider dynamics in sub-10 nm clearance regime are very rich. There are many models developed to explain the theories associated with these phenomena and features. The characteristics of nonlinearities have been investigated due to their significance. Nonlinearities in slider dynamics occur in two ways: (1) system continuum such as air-bearing film, lubricant film, and solid; and (2) along the interface boundaries during friction or the transition from contact to noncontact. Besides nonlinear phenomena, nonstationary phenomena, such as mobile lubricant transfer, also occur along interface boundary. The nonlinear effects in interface include air-bearing nonlinearity, intermolecular force, electrostatic force, solid contact, lubricant contact, friction, meniscus, and topographic effect. Besides the above mentioned nonlinearities, other nonlinear effects may coexist; for example, thermal actuation control of the TFC slider may cause a change of system nonlinear properties.

The nonlinear characteristics of air-bearing film have been experimentally characterized and analytically quantified [1–8]. The nonlinear properties could be quantified as power law of polynomial form or exponential form, by using the simulation of generalized Reynolds equation [3, 7]. The linear properties of air-bearing and contact force were identified using linear frequency response function approach [9–13]. There was no research published on the nonlinear identification using testing data.

The contact-induced nonlinearities of air-bearing slider have also been characterized [14–32]. The latest research includes two- to three-dimensional motion of sliders contacting media, the bouncing vibrations of partial contact air-bearing sliders, using the generalized Reynolds equation modified with the Fukui-Kaneko slip correction, and a slip correction for the contact situation. The adhesion, contact, and friction are also comprehensively considered [27–32].

The dynamics of sub- 5 nm air-bearing sliders in the presence of electrostatic and intermolecular forces have been widely investigated [33–50]. The intermolecular forces (van der Waals forces), electrostatic forces, and lubricant meniscus forces could be sufficiently strong to be considered only when clearance is below 5 nm. They are often called short range forces. Generally, short range forces appear as suction forces (or negative force) mainly in the sub-5 nm to nm regime. They give rise to negative stiffness and therefore could cause flying instabilities of a slider. Typical average roughness of slider air-bearing surface and disk surface is in the sub-nanometer level for current hard disk products, and the intermolecular forces are very strong if the clearance is also small. When the surfaces are considered as smooth, the intermolecular forces of a slider can be as large as hundreds of mN [35, 50]. Electrostatic forces are caused by the electrostatic charge between the slider and the disk [49].

The intermolecular force could be bigger between rougher surfaces. In sophisticated analysis, the adhesive force has been studied by the approach of continuum-based modeling and both the adhesion force and the contact force are obtainable by the improved models relevant to sub-5 nm interfaces [40–46]. The continuum-based models consider not only the surface roughness but also the elastic and plastic deformations. Specifically, the lumped parameter single- or two-degree-of-freedom models, three state nonlinear dynamic models including the normal dynamics of the slider, and asperity-based contact and adhesive models have been developed and coupled together to predict the performance of ultra-low (e.g., 3 nm) flying sliders.

Existing research has concluded that the intermolecular force can be changed by changing either surface energy or nominal contact area or roughness/mean asperity radius. The direct approaches to reduce intermolecular force include getting the slider FII-treated [51] and use of spherical pad slider design [48].

There are still certain questions needing further clarification, such as whether the forces are over counted if considering both intermolecular force and contact force between slider and disk at the same time, in other words, whether contact force is already included in intermolecular force to some sense.

The unique effects of slider-lubricant interaction and the associated nonlinearity have been characterized [52–71]. Dynamic lubricant meniscus force was once idealized as in the static case [19, 20], in which the disk velocity is not considered. In static case, the meniscus force behaves as a suction force. A more complex model employs the lattice Boltzmann method to calculate the dynamic case [66], which shows that lubricant behaves as a lift force. Even though the force direction (suction force or lift force) in the dynamic case was not in agreement until now, it is widely agreed that the existence of lubricant will block part of the airflow through the interface, and the air-bearing pressure will be weaker due to such blockage. Due to the relatively high speed between slider and disk, the meniscus force, if any, is a dynamic meniscus force. The shear rate of the molecularly thin lubricant can be as high as 2×10^{10} 1/s when disk velocity is 24 m/s and lubricant thickness is assumed to be about 1 nm. At very high shear rates, the lubricant is more like a semisolid instead of liquid. When the shear rate of lubricant exceeds a critical value, the viscosity decreases as shear rate continues increasing. Indirect investigation of dynamic lubricant meniscus force was conducted by studying the hysteresis between the takeoff and the touchdown of a full flying slider. It is reported that the hysteresis is related to the lubricant thickness and the percentage of mobile lubricant [54–56]. In general, thicker lubricant leads to lower takeoff speed and lower touchdown speed, or lower takeoff pressure and lower touchdown pressure. The possible explanation is that the lubricant may influence the Hamaker constant for the intermolecular force, and therefore the takeoff and touchdown performances are changed, despite the argument of the effect of dynamic meniscus force.

The behavior of lubricants on disk under the effect of flying slider air-bearing has been studied extensively in [52, 57–61], in which the appearance of lubricant moguls and ripples as a slider flies above a particular disk track is reported. Lubricant moguls and ripples are observed to form and they change in frequency and amplitude, following the slider dynamics. Ripples are found to match the slider pitch motion while moguls follow the disk topography. The wash-boarding effect can cause increased slider flying height modulation of up to a few nanometers. The slider motion and lubricant thickness modulation appear to build on each other. Both lubricant moguls and ripples are observed where their amplitudes first increase and then decrease with increasing flying time. At the same time, the slider displacement also follows the same time dependence. Both ripples and moguls cause increased slider displacement, and ripples can be much more detrimental due to the periodic nature of the feature. Lubricant thickness and mobility and texturing are all found to affect the slider dynamics significantly.

The effect of lubricant on the nonlinear vibrations of sliders has been characterized in [4, 53, 64]. It has been illustrated that thicker lubricant increases slider vibrations. The motion of the slider in the vertical, pitch, roll, off-track, and down-track direction due to slider-lubricant interactions was found to be consistent, and an identical frequency component of vibration could occur for all degrees-of-freedom. It is claimed that there exists a critical clearance between the flying head and the disk in a hard disk drive, below which significant lubricant transfer from the disk to the slider takes place [71].

The topographic effects of disk on slider dynamics have been studied [72–74]. As the clearance or the flying height between slider and disk is reduced to nanometer level, slider and disk topographies can significantly affect the vibrations and stability of slider. The ratio of slider motion to disk topography could be affected by the topography of the disks used. The roughness of the disk affects the magnitude of the adhesion forces and hence the stability of the slider. The texturing of the disk could reduce the effect of intermolecular forces by reducing the area over which intermolecular forces act.

3. Dynamics of TFC Sliders in Sub-5 Nanometer Clearance Regime

The physical spacing reached about 5 nm in 2006, a spacing below which the short distance forces, such as intermolecular force, begin to play substantial roles. In order to lower the transducer further, TFC sliders have been employed in air-bearing sliders since 2007. TFC slider employs a heating element integrated in the thin film transducer structure. When power is supplied to this element, the slider thermally expands locally in a way that protrudes only a small region around the read-write transducers to move it closer to the disk. Because of the smallness of the close-approach region the destabilizing forces are minimized. With this invention the slider-disk clearance has been moved down to nanometer level. Such a system has been proven to be feasible based on preliminary research and development at various laboratories. The critical questions related to stability, reliability, wear, and lubricant displacement and transfer have been addressed [75–100]. This kind of sliders in application is capable of attaining the clearance of nanometer level. However, the interaction between the TFC slider surface and disk surface could result in bouncing, lube-pickup, and slider instability. It has been experimentally verified that TFC sliders have unstable bouncing vibrations when the slider actuation power is beyond a certain critical point called "touchdown". Such unstable behaviors have been the focus of numerical investigations and experimental characterizations using various approaches [94–100]. During thermally induced contacts, the vibrations of TFC slider measured using laser Doppler vibrometry increase with disk roughness and lubricant thickness [89]. The fly-ability and durability of the TFC sliders at sub 1-nm clearance are characterized [94]. In the simulation using 1, 2, or 3-DOF models including intermolecular interaction, contact, and friction, the unstable vibrations of TFC sliders have been attributed to adhesive forces and improper interfacial parameters [97–100]. As the interfacial adhesive effects are associated with several factors, a further question is how the interfacial parameters (such as the work of adhesion at the head-disk interface, and roughness parameters) affect this adhesive instability found in both experiments and simulations. The investigations have been made to identify the optimal clearance and light contact conditions, which minimizes both the clearance and the flying height modulation [99, 100]. The simulations suggest certain light contact regime with reduced bouncing vibrations and low stresses. However, still the lack of fundamental understanding of the slider-disk interaction mechanisms, for example, the light contact or surfing status of TFC slider has been argued [95].

4. Detection and Identification of Nonlinear Dynamics

The treatment of nonlinear dynamics problem has been considered of kind subjective because there are many analytical methods available, but there is no general approach to characterize input-output relationships in nonlinear dynamics systems. Next, we illustrate the test-nonlinear analysis correlation problem that appears in between the tested data of the real system and the simulation data obtained with the physics-based model. One method of obtaining an efficient representation for a nonlinear slider system is to create a parametric model of the system by using physics-based simulation [3, 7], then to correlate this parametric model with measurement data taken from the real slider system. In this case, the parametric equation of the motion of a slider can be written as

$$[m]\{\ddot{x}(t)\} + [k(p,t)]\{x(t)\} = \{F(t)\} \tag{1}$$

in which $x(t)$ is the slider vibration displacement. $[k(p,t)]$ is nonlinear stiffness matrix due to the nonlinear effect of air-bearing film, intermolecular force, electrostatic force, lubricant contact, solid contact, and so forth, and $\{F(t)\}$ is function of time due to disk morphology effect. Usually, the number of the degree-of-freedom used for analysis could be one, two, or three. In (1), the stiffness depends on parametric variables $\{p\}$ which express the parametric nature of the model representations [3, 7]. The model updating is the procedure by which these variables $\{p\}$ are optimized to minimize the distance between test data and numerical simulations. $\{p\}$ is the function of slider and interface physics parameters, as such the assumed interface physics parameters could be finally optimized and could be used for refined and more accurate simulation.

We assume that time-domain and displacement response of slider $\{x_{\text{test}}(t)\}$ are obtained by testing real slider system, and $\{x_{\text{sim}}(t)\}$ is simulated displacement response. Since our objective is to generate a refined and more accurate parameters/physics model, the natural test-analysis correlation metrics to consider are distances between test and simulation data. We define residue vectors as

$$\{R(p,t)\} = \{x_{\text{test}}(t)\} - \{x_{\text{sim}}(t)\}. \tag{2}$$

Then the computational procedure for optimizing $\{p\}$ consists of the following steps.

(1) For a parametric model defined by a parameter variable $\{p\}$, the slider response is simulated via numerical integration of (1).

(2) Residues (2) are calculated at prescribed degree-of-freedom and time samples.

(3) The following cost function $J(p)$ is minimized using an optimization algorithm:

$$J(p) = ||R(p,t)|| + \alpha||p - p_0||. \tag{3}$$

It represents the 2-norm (Euclidean norm) of the residue vectors. It includes a minimum change term, or regularization term, which helps in reducing the numerical ill-conditioning characteristic of inverse problems. From an engineering point-of-view, it simply means that an optimum design $\{p\}$ is sought after that brings the least possible change to its original parameter variables $\{p_0\}$.

The optimization procedure in step (3) involves multiple model simulations since time-domain responses must be calculated to evaluate the costs $J(p)$ for various parameter variables $\{p\}$.

Finally, the identified parameter variables $\{p\}$ can be further used for interface physics parameters identification through physics-based simulations.

The identification of system models through the use of experimental data has received considerable attention owing to the increased importance given to the accurate prediction of the response of dynamics systems [101–120]. Many nonlinear identification methods have been proposed, in which the relatively popular ones include the following: Volterra and Wiener series, spectral analysis and the reverse-path formulation, nonlinear autoregressive moving average models, the restoring force method, the describing function methods, direct parameter estimation, Hilbert transforms, wavelet transforms, and neural networks.

The historic assumption that the affect of nonlinearity on slider dynamics is negligible is not true at all in the nanometer clearance regime. Actually, all of the current simulations on slider dynamics have used nonlinear physics models. However, all of the related experimental characterizations have used Fourier transform or wavelet transform to interpret data [1, 2, 5, 6, 92, 93]. There are certain limits in these applications as the obvious gap between the simulation and experiment exists. There are some published works on the linear identification of slider system [9–13]. The experiment-based nonlinear identification of slider dynamics remains a void.

The experimental investigations of transient dynamics of sliders have been widely conducted using laser Doppler vibrometer (LDV) signal, acoustic emission (AE)/PZT signal, and read/write signal. The analyses of nonstationary and nonlinear signals of slider dynamics have been implemented by using Fourier analysis-based time-frequency analysis (TFA) and wavelet transformation (WT) in HDDs area by industry and university labs [1, 2, 5, 6, 92, 93]. For slider dynamics in nanometer clearance regime, the effects of air-bearing, intermolecular adhesion, contact and lubricant effect, as well as other factors yield nonlinear responses. Moreover, the short and consecutive or intermittent contacts of the slider with lubricant/asperity/defect on disk render the slider responses to have nonstationary characteristics. Hence, the desired time-frequency analysis methods for slider vibration signal analysis should have the capability of dealing with nonlinearity and have fine resolutions both in time domain and in frequency domain. Due to the fundamental assumption of linearity in Fourier analysis, the TFA is not suitable to deal with nonstationary and nonlinear signal in principle. TFA-based nonlinear analysis could give artifacts or even incorrect results for nonstationary and nonlinear signals. The wavelet methods may also prove inadequate because, although wavelet is well suited for analyzing data with gradual frequency changes, its nonlocally adaptive approach causes leakage. WT adopts a nonlocally adaptive approach in the calculation, which leads to an inevitable leakage of the energy in frequency vicinities. This leakage can spread frequency energy over a wider range, removing definition from data and giving it an overly smooth appearance. The WT has inherent problems of large computational time and fixed-scale frequency resolution. The computing of continuous wavelet transform is somewhat time consuming and is not suitable for large size data analysis. Due to the limitation of Heisenberg-Gabor inequality, the wavelet transform cannot achieve fine resolutions in both time domain and frequency domain simultaneously. Therefore, although the wavelet transform has good time resolution in high-frequency region, it may be unable to separate impacts in time domain if the time intervals between consecutive impacts are often too small. In the last decade, Hilbert-Huang transform (HHT) has been successfully developed for processing nonlinear and nonstationary signals, and it has been widely applied in science and engineering [104–107]. This method does not require the limitations of linearity required by the Fourier transform and the extension. Moreover, in many tested cases, the HHT gives results much sharper than the wavelet. HHT-based processing consists of two main elements: empirical mode decomposition (EMD) and Hilbert spectral analysis. The EMD phase generates the intrinsic mode functions (IMFs) from the signal, and the Hilbert spectral analysis generates a "time-frequency-energy" representation of the signal, based on the IMFs. EMD is a method of decomposing a nonlinear and nonstationary signal into a series of zero-mean amplitude-modulation frequency-modulation components that represent the characteristic time scale of the observation. This is done by iteratively conducting a sifting process.

A comprehensive review of nonlinear identification of dynamics in general area can be found in [103]. The most commonly used nonparametric methods employ the higher-order frequency response function method (Volterra series) and the restoring force-surface or force-state mapping method [108–116]. The higher-order frequency response function method needs high computational cost, may have convergence problems, and is unable to describe multi-valued responses. The restoring force-surface approach requires simultaneous measurements of the input excitation and output response, which is not suitable for slider dynamics. Most of the parametric identification methods are time-domain based, which have the advantages of requiring less time and effort for data acquisition than some frequency-domain techniques and being suitable for the identification of strongly nonlinear systems. Frequency-domain techniques include approaches based on the backbone curve and limit envelope, curve-fitting experimental frequency and force-response data points, the harmonic balance method, and methods exploiting nonlinear resonances [117–120]. Frequency-domain techniques avoid the efforts of differentiation and observability of small terms but require more theoretical effort and are generally applicable to weak nonlinear systems.

Despite the substantial progress attained in the general area of nonlinear dynamics identification in last decade, previously there was no work published pertaining the nonlinear identification of dynamics of air-bearing slider.

5. Future Perspective

Pushing recording density toward tera-bit per square inch and beyond from current status requires reducing flying height or clearance to nanometer regime. The dynamics of slider in nanometer clearance regime have been considered one of the core technologies that might carry HDDs industry through the next decade. A number of studies on slider dynamics have been carried out and are still being pursued at various academic and research laboratories all over the world to explore the underlying mechanisms of this complex problem. Currently, there are many efforts using simulation or testing method to understand complex slider dynamic phenomena such as light contact or lubricant contact for which there are some disparities in interpretation of the results and postulating findings. After having had deep understanding about the underlying physics of the slider-disk interface, it is natural to define and classify properly the interactions patterns between slider and disk and use system identification techniques to identify them by using testing data. Despite the extensive research in the field, the development of efficient approach for nonlinear identification remains a void.

Over last several years researchers have made substantial contributions to slider dynamics in nanometer regime (with focuses on TFC slider) by developing two distinct tracks:

(1) comprehensive simulation using a physics-based model;

(2) experimental characterization using LDV, AE, read/write signal, and other tribological tests such as friction, thermal asperity, and lubricant/surface characterizations.

Previously, using the approach of track (1) researchers were able to demonstrate the qualitative effects of slider design and interfacial parameters on slider dynamics and instability and to derive general guidelines for stable interface design.

However, there are still some issues in the physics model-based simulation, such as the selection of air-bearing equations, the determination of nominal or effective contact area, the determination of interfacial parameters and the model selection of contact and adhesion between the slider and disk in partial contact, the quantifying of interfacial lubricant, and the treatment of the coupled heat transfer and air-bearing within the slider-disk interface. Examples of such issues include the following.

(i) How to select appropriate air-bearing models to properly include the real effects in interface such as the air shear at the extremely high shear rates and its effects on the disk lubricant. How to justify various nanoheat transfer models for modifying the air-bearing calculations. How to treat the coupling of heat transfer and air-bearing change as the results of thermal deformation, space change, and cooling effect.

(ii) How to determine Hamaker constant or surface energy for a specific system in application. The intermolecular force can be quantified by rigor physics formulation, but the accurate determination of Hamaker constant in a lubricated interface is difficult due to the feature of nonuniform Hamaker function distribution and the uncertainty of real lubricant distribution. The surface energy could have big difference by three times subject to the lubricant existence on slider. The lubricant build-up and thickness on real slider is usually difficult to predict.

(iii) How to properly select surface parameters to implement contact model and friction model. The intermolecular forces could be due to the adhesions of noncontacting asperities, lubricant-contacting, and solid contacting, which has been incorporated into generalized Reynolds equation in previous simulation. In these works, the subboundary lubrication model, has been used, which is a multiasperity model, that is, it first obtains the forces at a single asperity, then assumes a statistical distribution of the asperities, and integrates to get the total force. As such, a lot of conventional assumptions regarding contact mechanics have to be used to quantify the system, such as the nominal contact area, the area density of asperities, the asperity height, radius of asperity summit, standard deviation of combined asperities, the probability density function of asperity heights, normal distribution with a standard deviation, the separation between the reference plane, and the mean plane of asperity heights. The statistical distribution of asperity heights has to be assumed, which determines how many asperities are in a certain contact-regime (noncontacting, lubricant-contacting, or solid-contacting) at a specific flying-height. This should be retreated for non-Gauss distribution asperity encountered in real disk [60].

All of these render the results of simulation to tend to be qualitative instead of quantitative for the dynamics prediction of real slider systems. The situation is similar to the physics-based simulation for friction prediction of real interface. If these problems are solved or improved, and stable and reliable head-disk interface with light contact could be better designed and implemented, then the further success of interface for magnetic recording will have been achieved. As such, the experiment-based identification is indispensable to quantify a real system and to determine a system parameter for simulation/design.

In experimental characterization using the approach of track (2), LDV, AE, and read/write signal and other tribological testing such as friction, thermal asperity, and lubricant/surface characterizations has been widely applied. Conventionally, slider dynamics is detected by laser Doppler vibrometer (LDV) and acoustic emission (AE) sensor. AE sensor measures the elastic stress waves generated by contact vibration and LDV directly measures slider body vibration and they are basically consistent [5]. Read-back signal from reader has also been used for slider contact dynamics detection [80]. It is noted that the nonlinear identification based on AE signal only gives an approximate results. AE signal could be inherently assumed to be approximately equivalent to slider vibration signal. Actually the AE signal is proportional to slider vibrations. AE sensor measures the elastic stress waves generated by contact vibration, which could be complicated by the interfacial effects, boundary conditions, and systems. As such, the background noise is high in AE signal. However, once stand waves (such as resonance mode of air-bearing or slider body mode) is established, its signal-to-noise ratio increases remarkably and accordingly AE signal becomes sensitive enough to show these resonant peaks in its spectrum. Generally, LDV is more sensitive than AE does. For major slider resonant mode and its harmonics of nonlinearity, LDV and AE frequency spectra are consistent. Recent experimental studies on TFC slider during actuation also show that LDV is more sensitive than AE does, whereas both AE and LDV could capture the dominant mode such as pitch mode and its harmonics.

It is noted that the multiple harmonics could always exist in reader signal regardless of the vibration being nonlinear or linear, which is due to the nonlinear properties of reader function. To illustrate this, we assume that the reader clearance has pure sinusoidal variation, $d(t) = d(0) + d_0 \sin \omega t$, and the wave length is λ. According to Wallace equation, head signal can be represented as

$$S_d(t) = S_0 e^{-2\pi d(t)/\lambda} = \sum_{i=1,2,\ldots} S_i \sin(i\omega t + \varphi_i), \qquad (4)$$

which suggests that even a pure harmonic modulation in reader clearance could cause multiple harmonics in the read signal. This suggests that the multiple harmonics in recorded read signal are different from the multiple harmonics in LDV or AE signal that reflects the nonlinear vibrations of the system.

Previously, by using the approach of track (2), researchers were able to characterize bouncing vibrations of slider. However, most of those experiments only directly observed and reported the phenomena of the contact and bouncing vibrations of TFC slider in nanometer clearance regime (touchdown or lubricant-contact/light contact phase). Some works on experimental characterization of TFC slider dynamics have used Fourier transform to interpret data, but the recorded nonlinearity information (e.g., the higher-order harmonics of air-bearing modes in [94, 95]) has not been exploited. There has a lack of detailed and direct correlation between testing results and simulated results to interpret involved nonlinearity. The experimental data are all treated in the context of Fourier analysis. The detailed interpretation of nonlinear, nonstationary vibrations of sliders from experimental data has not been explored, despite the fact that most of the simulation indicates the possible bouncing instability due to the nonlinear effect of adhesion and contact.

The recent implementation of the contemporary nonlinear identification methods offers some promising approaches to identify certain core parameters of slider dynamics in sub-5 nanometer clearance regime by using experimental data [121–125]. In [121], the nonstationary and nonlinear response of sub-10-nm clearance air-bearing slider induced by a bump contact is recorded using laser Doppler vibrometer (LDV) and studied using FFT, power spectrum density, spectrogram, and Hilbert instantaneous spectrum analysis. When the response amplitude is relatively large, TFA plot can reveal fundamental frequency and harmonics of nonlinear vibrations with a relatively low resolution. As the response amplitude is relatively small, TFA plot is unable to identify the detailed frequency modulation of nonlinear system. The research demonstrates that the response of air-bearing slider in instantaneous contact exhibits nonstationary and nonlinear properties which can be identified using Hilbert instantaneous spectrum. The interpretation based on Fourier analysis and its extension in time-frequency domain could lead to inaccurate results due to their limitation in resolution and linearity assumption. In principle, due to their fundamental limitations, FFT, power spectrum density, and TFA could lead to some artifact and/or misrepresentation of the nonstationary and nonlinear signal. In [122], the AE signal due to the response of TFC slider in thermal actuated touchdown process is used to identify system parameters and the effect of intermolecular forces. The responses of TFC slider in thermal actuated touchdown process exhibit nonlinear properties of multiple harmonics, which have been widely recorded by using LDV and AE sensors [80, 94, 95]. The work in [122] proposed a nonlinear parameter identification approach that is based on the multiple harmonics in the slider response and the derived higher-order frequency response functions. To obtain higher-order frequency response functions, the parametric model of slider dynamics is used. The case study shows that during slider thermal actuated touchdown process, the slider vibration exhibits weak nonlinearity in which the vibration is dominated by air-bearing mode. In over-push or saturated process after touchdown, the slider response is found to be linear and nonstationary due to intermittent light impact/contact. The work in [123] proposed another nonlinear parameter identification approach that is based on the Hilbert spectra of the response signals from both testing and simulation. This approach uses difference of Hilbert spectra as cost function instead of using response difference. This approach can be implemented by either using parametric model or using physics-based simulation with assumed parameters. The parameters are identified through minimizing cost function. In [124], HHT analysis is employed to investigate PZT signal of glide head. HHT-based results show that slider-defect interaction process consists of multiple consecutive contacts which are gradual loading and unloading process associated with both amplitude modulation and frequency modulation of slider body response. The peak frequency of power spectrum density of some decomposed components has well correlations with the natural mode frequency of the slider body based on finite element analysis. These frequencies from power spectrum density only represent the superposed "instantaneous frequencies" of a real slider vibration. The approach of the combination of power spectrum density of decomposed signal and Hilbert spectrum is more effective than conventional time-frequency analysis and Wavelet transform for identifying spectrum signature of slider contact dynamics, which exhibit nonstationary and nonlinear dynamics properties. The work in [125] proposed to use artificial neural network to map the varied spectrum patterns of the slider response in nanometer clearance regime from simulations and existing testing database, which offers an efficient tool for experimentalists to design laboratory test and conduct parameter identifications.

6. Concluding Remarks

The authors have attempted to present a broad picture of the current state of knowledge in the field of the sensing and identification of slider dynamics, with a specific focus on nonlinear identification. The present overview is focused to draw the attention of research and academic community towards the fundamentals of identification by providing a review on the important reported work.

Based on the work reviewed in this article, the following are recommended future research avenues:

(a) advance the state of the art in the application of LDV, AE sensor, and read/write signal to effectively detect nonlinear dynamics of slider in nanometer clearance regime, by applying advanced approaches such as HHT to treat the signal of slider responses; explore the dynamic behavior and spectrum signature of nonstationary and nonlinear vibration of slider in complex dynamic process such as touchdown and lubricant-contact/light contact;

(b) implementing and applying nonlinear identification techniques; develop suitable verification and validation approach for dealing with experimental data and simulation results; explore in-depth understanding on various nonlinearities, so as to specify and develop an efficient approach to better interpret nonlinearity in experimental data and improve correlations between testing and simulation;

(c) the combination of the above two will allow researchers to properly employ measured data to identify parameters/update model to make their prediction be more accurate and quantitative and will also help experimentalists to design laboratory test system to better support validation studies.

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