Channel Modeling and Detector Design for Dynamic Mode High Density Probe Storage

Naveen Kumar, Pranav Agarwal, Aditya Ramamoorthy and Murti V. Salapaka

***Abstract*— Probe based data storage is a promising solution for satisfying the demand for ultra-high capacity storage devices. One of the main problems with probe storage devices is the wear of tip and media over the lifetime of the device. In this paper we present the dynamic mode operation of the cantilever probe that partially addresses the problems of media/tip wear. A communication system model which incorporates modeling of the cantilever interaction with media is proposed for the system. We demonstrate that by using a controllable canonical state space representation, the entire system can be visualized as a channel with a single input which is the tip-media interaction force. A hypothesis testing formulation for bit-by-bit detection is developed. We present three different classes of detectors for this hypothesis test. In particular, we consider two different cases where statistics on the tip-medium interaction are available and not available. Simulation results are presented for all these detectors and their relative merits are explored.**

I. Introduction

In recent times, the explosive growth of the personal computer industry and the Internet has created the demand for ultra-high capacity storage devices. The ubiquitous use and increased demands of consumer electronics (e.g. pen drives and MP3 players, digital cameras) and the Internet is driving the need for high density data storage devices. Demands of a few Tb per in.^{2} are predicted in the near future. Commercially used data storage techniques are primarily based on magnetic, optical and solid state technologies. However all these technologies are reaching fundamental limits on their achievable areal densities. Magnetic storage suffers from the super-paramagnetic effect that limits the minimum size of a magnetic domain. Optical devices are limited by the wavelength of the utilized laser and solid state devices are limited by the minimum size of a transistor that can be created.

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A promising high density storage methodology, that is the focus of this paper utilizes a sharp tip at the end of a micro cantilever probe to create (or remove) and read indentations (see [13]). The presence/absence of an indentation represents a bit of information. The main advantage of this method is the significantly higher areal densities that are possible. Recently, experimentally achieved tip radii near 5 nm on a micro-cantilever were used to create areal densities close to 4 Tb/in^2. The areal density in this method is primarily limited by the tip geometry. The effective area of the tip that interacts with the media can be made considerably smaller with technologies such as carbon nanotube attachments (see [1], [3]) that have the promise to yield sub-nanometer small features. Thus, unlike the previous storage technologies, the fundamental limit of areal densities possible is far from being reached.

A particular realization of a probe based storage device that uses an array of cantilevers is provided in [4]. However, there are fundamental drawbacks of current probe based devices (including [4]) that are related to the static mode operation. In static mode, the cantilever is analogous to a gramophone needle (cantilever tip) of the gramophone player that moves due to the topography of the record (media) i.e. the cantilever is in continuous contact with the medium. The information content is present in low frequency in this case. However, it can be shown experimentally that the system gain at low frequency is very small. Therefore, in order to overcome measurement noise at output, the interaction force between tip and medium should be large which degrades the medium and probe over time and significantly reduces reliability.

The problem of tip and media wear can be partly addressed by using dynamic mode operation but the conventional dynamic methods, though gentle on the medium, are too slow to be useful in data storage applications. In the dynamic mode operation given in this paper, the cantilever is forced sinusoidally using a dither piezo. The oscillating cantilever interacts with the medium intermittently as it gently taps the cantilever and thus the lateral forces are reduced which decreases media

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wear drastically. Other advantages of this scheme such as high resolution are discussed later in more detail.

The primary objective of a probe based data storage system is ultra-fast detection of topographic features on the media as against determining the height of the feature (which is useful in nano-imaging applications). In the ultra-fast detection task, the exact topographic profile of a particular feature is not as much of a concern as distinguishing the presence or absence of the feature. However, as density increases, the readback signal suffers from increase in noise and linear/nonlinear distortions. This makes data detection more difficult, and requires increasingly powerful detection techniques. Data detection can be improved by increasing the tip-medium interaction force but it increases tip and medium wear and reduces the reliability of system. Thus, what we really want are low-complexity detectors that have a low probability of error at a given tip-medium interaction.

In this paper the dynamic mode operation that utilizes high quality factor probes (for enhanced resolution and smaller forces) that yields two orders higher read speeds (compared to existing dynamic mode techniques) is presented. The problem of modeling the data storage unit as a communication system and the design of efficient detectors for the channel model are discussed in detail. We pose the problem of detecting the presence/absence of the tip-medium interaction as a hypothesis testing problem. The problem is first posed as a composite hypothesis test where prior statistics on the tip-medium interaction force are not available. Next, we obtain statistics of interaction forces from a realistic Simulink model of the system that models the inherent nonlinearities in the system. We then develop detectors that utilize this prior information. Simulation results are presented for all the detectors and their relative merits are explored.

The paper is organized as follows. In Section II the physical model of the probe based data storage system is presented. Section III deals with the problem of designing and analyzing the data storage unit as a communication system and finding efficient detectors for the channel model. Section IV reports results from simulation and Section V summarizes the main findings of this paper and provides the conclusions and future work.

II. Physical modeling

The main components of a probe based high density data storage device are analogous to that of an atomic force microscope (AFM) (see Figure 1(a)) reported in [2]. The components are (1) a microcantilever probe that has a sharp tip at one end. The supported end can be forced using piezoelectric material (termed the dither

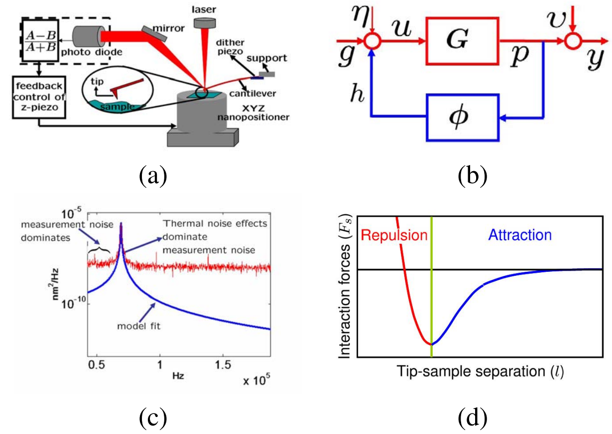

Fig. 1. (a) Shows the main components of a probe based storage device. (b) Shows a block diagram representation of the cantilever system G being forced by white noise (η), tip-media force h and the dither forcing g. The output of the block G, the deflection p is corrupted by measurement noise υ that results in the measurement y. Tip media force $h = \phi(p)$. (c) shows an experimentally obtained thermal spectra (setting $g = h = 0$ in the block diagram shown in (b)) that demonstrates that the thermal response of the cantilever is discernable only near the resonant frequency of the cantilever. (d) shows the typical tip-media interaction forces of weak long range attractive forces and strong repulsive short range forces.

piezo). (2) The detection system that consists of a laser that is incident on the tip end of the cantilever. The incident laser is reflected into a split photodiode that provides a voltage signal proportional to the difference in the laser power incident on its different halves. (3) The control system that takes the measured signal as input and provides the control signal to the nanopositioning device and possibly the cantilever support. (4) The nanopositioning device which provides the capability of positioning the media with respect to the cantilever probe in the lateral x and y directions and the vertical z direction.

A. *Models of cantilever probe, the measurement process and the tip-media interaction*

The cantilever is a flexure member and the first mode approximation is given by the spring mass damper dynamics described by

$$\ddot{p} + \frac{\omega_0}{Q}\dot{p} + \omega_0^2 p = f(t), \;\; y = p + \upsilon, \qquad (1)$$

where $p,\ f,\ y$ and υ denote the deflection of the tip, the force on the cantilever, the measured deflection and the measurement noise respectively whereas the parameters ω_0 and Q are the first modal frequency (resonant frequency) and the quality factor of the cantilever respectively. The quality factor characterizes the energy losses to the surrounding environment.

The input-output transfer function with input f and output p is given as $G = \frac{1}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}$. The cantilever model described above can be identified precisely (see [9]). Viewing the cantilever as a filter proves crucial for channel modeling purposes.

The interaction force between the tip and the media (h) depends on the deflection p of the cantilever tip. Such a dependence is well characterized by the Lennard-Jones like force that is typically characterized by weak long-range attractive forces and strong short range repulsive forces (see Figure 1(d)). Thus the probe based data storage system can be viewed as an interconnection of a linear cantilever system G with the nonlinear tip-media interaction forces in feedback (see Figure 1(b) and note that $p = G(h + \eta + g)$ with $h = \phi(p)$); see [11]).

B. Currently employed probe based data storage method and the dynamic mode operation

All of the current probe based data storage efforts (primarily by IBM, Zurich Research Labs) employ the static mode operation (see [13]). In the static mode, the signal content (the information in h) is primarily present in a frequency range much below the resonant frequency of G. Note that the deflection measurement is given by $y = G(h + \eta) + v$ as in static mode there is no dither forcing g. As the magnitude of $|G(j\omega)|$ away from resonance is very small, the force h has to be large so that Gh overcomes the measurement noise v particularly the $\frac{1}{f}$ part in v (in the low frequency domain $|G\eta| << |v|$ and therefore measurement noise, and not the thermal noise η, is the main limiting factor). The large force h required by the static mode leads to more wear. Another reason for enhanced wear is that the cantilever drags along in the lateral directions (analogous to the gramophone needle scratching the record). An abundance of experimental data under various operating conditions on media and tip wear is available (see [12]).

The problem of wear can be partly addressed by using the dynamic mode operation. In the dynamic mode the cantilever is forced sinusoidally using the dither piezo ($g = \gamma \sin \omega_0 t$). In the absence of any other force, the deflection $p = Gg$ of the cantilever will be sinusoidal with amplitude $|G(j\omega_0)|\gamma$. The tip-media force alters this motion and the media characteristics can be gleaned from the observed changes in the cantilever motion. This operation effectively shifts the information about the media to a frequency range centered near the resonance of the cantilever filter G (see [5]). As presented earlier, in this frequency range the $\frac{1}{f}$ noise is not effective and the gain $|G(j\omega_0)|$ is large. The output is $G(h+\eta)+v$ and η has to be overcome by the signal with $|G\eta| >> |v|$ in the relevant frequency range (see Figure 1(b)). As the thermal forcing is white with variance $\sqrt{2k_BTc}$ (k_B, T and c are the Boltzmann constant, temperature and damping factor $\frac{\omega_0 m}{Q}$ with m the effective mass of the cantilever) that is small, the force signal resolution is limited by η. It is evident that the magnitude of the smallest force that can be resolved in dynamic mode varies as $\sqrt{\frac{1}{Q}}$ and higher the quality factor, better the resolution. As smaller forces can be resolved, the tip-media interaction forces can be small thus reducing the force on the media and tip. This can lead to smaller wear. Another important reason for lesser wear is that in dynamic mode the oscillating cantilever interacts with the media intermittently as it gently taps the cantilever and thus the lateral forces are reduced. It is therefore the preferred mode of imaging soft medias like biological material and polymers [14].

C. Information source model

The simplest model of the tip-media interaction is obtained when the media's influence on the cantilever tip is approximated by an impact condition where the position and velocity of the cantilever tip instantaneously assume a new value (equivalent to resetting to a different initial condition). This is satisfied in most typical operations because in the dynamic mode, the time spent by the tip under the media's influence is negligible compared to the time it spends outside the media's influence [10]. Indeed typically the oscillation amplitudes range from 10-80 nm whereas the tip-media interaction is effective from 2-5 nm separations and lower separations.

III. Channel model and detectors

In this section, we present our modeling of the cantilever as a communication system and the design of efficient detectors for the channel model.

The cantilever system has a long impulse response. For achieving *channel equalization* with low complexity we need to shorten the impulse response. The shortening of an impulse response can be achieved by using the technique presented in [8] where observers are employed for the purpose of imaging. The observer framework also provides a means of canceling the effect of the dither forcing at the output.

Under the spring-mass-damper model of the cantilever, a state space representation of the filter G can be obtained as $\dot{\overline{x}} = A\overline{x} + Bf,\ y = C\overline{x} + v$ where $f = \eta + g$ (assuming no media forces h) and A,B and C are given by,

$$A = \begin{bmatrix} 0 & 1 \\ -\omega_0^2 & -\omega_0/Q \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 1 \end{bmatrix},\ C = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{2}$$

Based on the model of the cantilever an observer to monitor the state of the cantilever can be implemented

[6]. The observer dynamics and the associated state estimation error dynamics is given by,

$$\overbrace{\begin{array}{rcl}\dot{\hat{\overline{x}}} & = & A\hat{\overline{x}} + Bg + L(y-\hat{y}); \hat{\overline{x}}(0) = \hat{\overline{x}}_0, \\ \hat{y} & = & C\hat{\overline{x}},\end{array}}^{Observer}$$

$$\overbrace{\begin{array}{rcl}\dot{\tilde{\overline{x}}} & = & A\overline{x} + B(g+\eta) - A\hat{\overline{x}} - Bg - L(y-\hat{y}), \\ & = & (A-LC)\tilde{\overline{x}} + B\eta - L\upsilon, \\ \tilde{\overline{x}}(0) & = & \overline{x}(0) - \hat{\overline{x}}(0), e = y - \hat{y} = C\tilde{\overline{x}} + \upsilon.\end{array}}^{State\ Estimation\ Error\ Dynamics}$$

where L is the gain of the observer, $\hat{\overline{x}}$ is the estimate of the state $\overline{x}$ and g is the external known dither forcing applied to the cantilever. The error in the estimate is given by $\tilde{\overline{x}} = \overline{x} - \hat{\overline{x}}$, whereas the error in the estimate of the output y is given by e. It can be shown that under the presence of the noise sources η and υ, the error process e approaches a zero mean wide sense stationary stochastic process in steady state. The error process is white if the Kalman gain is used [8].

The discretized model of the cantilever dynamics is given by

$$\begin{array}{r}x_{k+1} = Fx_k + G(g_k+\eta_k) + \delta_{\theta,k+1}\nu\ , \\ y_k = Hx_k + \upsilon_k, k \geq 0\ ,\end{array} \quad (3)$$

where the matrices F, G, and H are obtained from matrices A, B and C and $\delta_{i,j}$ denotes the dirac delta function. θ denotes the time instant when the impact occurs and ν signifies the value of the impact. The impact is modeled as an instantaneous change or jump in the state by ν at time instant θ. When a Kalman observer is used, the profile in the error signal due to the media can be pre-calculated as (see [8]),

$$e_k = y_k - \hat{y}_k\ = \Gamma_{k;\theta}\ \nu + \gamma_k\ , \quad (4)$$

where $\{\Gamma_{k;\theta}\ \nu\}$ is a known dynamic state profile with an unknown arrival time θ defined by $\Gamma_{k;\theta} = H(F - L_K H)^{k-\theta}$, for $k \geq \theta$. L_K is the Kalman observer gain and $\{\gamma_k\}$ is a zero mean white noise sequence which is the measurement residual had the impact not occurred. The statistics of γ are given by, $E\{\gamma_j\gamma_k^T\} = V\delta_{ij}$ where $V = HP_{\tilde{\overline{x}}}H^T + R$ and $P_{\tilde{\overline{x}}}$ is the steady state error covariance obtained from the Kalman filter that depends on P and R which are the variances of the thermal noise and measurement noise respectively. Thus determining when the cantilever is "hitting" the media and when it is not, can be formulated as a binary hypothesis testing problem with the following hypotheses,

$$\begin{array}{rcl}H_0 & : & e_k = \gamma_k, k = 1,2,...,M \\ H_1 & : & e_k = \Gamma_{k,\theta}\nu + \gamma_k, k = 1,2,...,M\end{array}$$

If the system is treated like a communication channel where there exists a front-end timing recovery unit, the time of the hit i.e. θ is known quite accurately. Therefore for the purposes of this hypothesis test, it can be assumed that θ is known. For simplicity we set $\theta = 1$. Thus, under H_1, the innovation signal becomes

$$\bar{e} = \Gamma\nu + \bar{\gamma} \quad (5)$$

where $\bar{e} = [e_1\ e_2 \dots e_M]^T$,$\bar{\gamma} = [\gamma_1\ \gamma_2 \dots \gamma_M]^T$ and $\Gamma = [H\ H(F - L_K H) \dots H(F - L_K H)^{M-1}]^T$ and $V \times I$ denotes error covariance matrix of $\bar{\gamma}$ where I stands for $M \times M$ identity matrix. In (5) ν has two components i.e. $\nu = [\nu_{pos}, \nu_{vel}]$ and it signifies magnitude of impact. Essentially the impact is modeled as an instantaneous change in the state by ν at time instant θ.

A. Reformulation of state space representation

It is to be noted that although we have modeled the cantilever system as a spring-mass-damper model (second order system with no zeros and two stable poles)(see (1)), the experimentally identified channel transfer function that is more accurate in practice has right half plane zeros that are attributed to delays present in the electronics. Given this scenario, the state space representation used in [8] leads to a discrete channel with two inputs as seen above because the structure of B is no longer in the form of $[0\ 1]^T$. However, source information enters the channel as a single input as the tip-medium interaction force. Thus the problem can be reformulated as one of a channel being driven by a single input by choosing an appropriate state space representation. For the state space model used to derive the hypothesis given above, it is known that the pair (A, B) is controllable which implies there exists a transformation which will convert the state space into a controllable canonical form such that $B = [0\ 1]^T$. Note that this kind of structure of B will force the discretized model (3) to be such that one component of ν is equal to 0 i.e. $\nu = [0, \nu_{vel}]^T$ where ν_{vel} is some value of ν. With B chosen as above, the entire system can be visualized as a channel that has a single source and following hypothesis is obtained,

$$\begin{array}{rcl}H_0 & : & \bar{e} = \bar{\gamma} \\ H_1 & : & \bar{e} = \Gamma_0\nu_{vel} + \bar{\gamma}\end{array} \quad (6)$$

where Γ_0 is given by $\Gamma = [\Gamma_1\ \Gamma_0]$. In this paper, the above hypothesis with one parameter is used. This simplifies the detector structure and analysis substantially.

B. Detector Design and Analysis

We now present the different detectors that we have developed for the hypothesis testing problem in (6). For this purpose we used a high fidelity Simulink model that mimics the experimental station that provides a qualitative as well as a quantitative match to the experimental data. This model incorporates a Lennard-Jones like nonlinearity (shown in Figure 1(b)) together with the cantilever transfer function that is identified experimentally. There is a means to introduce bit profiles and to simulate the media interaction with the cantilever. The output of the nonlinear block gives statistics on the tip-media force which in turn provides statistics on ν.

Note that ν is a measure of the tip-medium interaction force and as such it is difficult to experimentally verify this nanoscale force accurately. Therefore we first present detectors that do not assume any prior distribution on ν i.e. we treat the problem as a composite hypothesis test and develop Neyman-Pearson like detectors for it.

1) Locally Most Powerful (LMP) Test: The tip-media interaction force contains attractive and repulsive forces. From model simulations, we have observed there is a hit on media, the repulsive force dominates in tip-media interaction force and the sign of ν is always same for all hits. This information can be used to develop a locally most powerful (LMP) test for hit detection. In case of LMP, the likelihood ratio can be easily derived in closed form and is given by [7],

$$l_{lmp}(M) = \bar{e}^T V^{-1} \Gamma_0.$$

The decision rule in this case is defined as, $l_{lmp}(M) \lessgtr_{H_1}^{H_0} \tau_1$ where τ_1 is LMP threshold. Probability of false alarm is given by,

$$P_F \quad = \quad \mathcal{Q}\left(\frac{\tau_1}{\sigma}\right),$$

where $\mathcal{Q}(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} exp(-\frac{x^2}{2}) dx$, $\sigma = \sqrt{\Gamma_0^T V^{-1} \Gamma_0}$ and τ_1 is LMP threshold.

2) Generalized Likelihood Ratio Test (GLRT): In [8], the GLRT is developed for a model which has ν containing two parameters. Unlike the two parameters model, the likelihood ratio can be computed easily for one parameter model and is given by,

$$l(M) \quad = \quad l_{lmp}^2,$$

where l_{lmp} is likelihood ratio for LMP case. The decision rule in this case is given by, $l(M) \lessgtr_{H_1}^{H_0} \tau_2$ where τ_2 denotes GLRT threshold value. From likelihood ratio, we have

$$P_F \quad = \quad 2\mathcal{Q}\left(\frac{\sqrt{\tau_2}}{\sigma}\right),$$

where $\sigma = \sqrt{\Gamma_0^T V^{-1} \Gamma_0}$ and τ_2 is GLRT threshold.

3) Bayes Detector: Simulations from the model can be run for a large number of hits in order to gather statistics on the discretized output of nonlinearity block which models the tip-media force. The discretized output is multiplied by discretized B of state space to obtain the statistics for ν.

We modeled the histogram in Figure 2(d) by a Gaussian pdf with the appropriate mean and variance. The hypothesis test in (6) now contains $\nu_{vel} \sim N(\alpha, \lambda^2)$. By simple calculation, it can be shown that likelihood ratio is,

$$l(M) = \bar{e}^T V^{-1} \mu' + \frac{1}{2} \bar{e}^T V' \bar{e} - \bar{e}^T V' \mu'$$

where $\mu' = \Gamma_0 \alpha$ and $V' = \frac{\Gamma_0 \Gamma_0^T}{(\frac{V^2}{\lambda^2} + V \Gamma_0^T \Gamma_0)}$. Matrix V' has rank 1 which means $l(M)$ has sum of $M+1$ Gaussian terms and one Gaussian square term. It is hard to compute probability of detection and false alarm in closed form in this case.

IV. Simulation Results

In order to see the performance of all detectors, simulations are performed with cantilever parameters obtained from experimental data. The parameters of simulation are, first resonant frequency of the cantilever f_0 = 63.15 KHz, quality factor Q =206, the value of forcing amplitude $|G(jw_0)|\gamma = 24nm$, tip-media separation is 28 nm, discretized thermal and measurement noise variance are 0.1 and .001 respectively. We used a topographic profile where the medium height alternated between high and low. The high and low regions denote the bit '1' and '0' respectively. The simulation was performed with the above parameters using the Simulink model described previously. Tip-media interaction were varied by changing the height of media corresponding to bit '1'. The innovations were obtained at the output of the observer for different tip-media interaction. The innovation signal was passed through all the three detectors for hit detection. For these results we assumed that the correct sampling instants were known to all the detectors. In practice, this can be justified if there is a front end timing recovery unit that allows this synchronization. Developing timing recovery units is part of future work.

In Figure 2 we have plotted the probability of misdetection (denoted P_{MD}) vs. probability of false alarm (denoted P_F) for all the detectors. It is clearly observed that LMP and Bayes gives less probability of misdetection than GLRT. For example, in case of 1.5 nm tip-media interaction and $P_F = 1.9 \times 10^{-3}$, P_{MD} for Bayes, LMP and GLRT are 2.3×10^{-3}, 2.72×10^{-3} and 1.27×10^{-2} respectively (see Figure 2(b)). Figure 2

TABLE I

MINIMUM PROBABILITY OF ERROR FOR DIFFERENT TIP-MEDIA INTERACTION FOR DIFFERENT DETECTORS

Tip-media Interaction (nm)	Minimum Prob. of error		
	Bayes	LMP	GLRT
1.3 nm	3.5×10^{-3}	3.5×10^{-3}	5.8×10^{-3}
1.5 nm	1.5×10^{-3}	1.5×10^{-3}	2.8×10^{-3}
1.7 nm	8.9×10^{-4}	9.1×10^{-4}	1.5×10^{-3}

shows that P_{MD} decreases for a given value of P_F for all detectors if the tip-media interaction is increased. The intuition behind this result is that hits become harder on media if tip-media interaction is increased which makes detection easier. The minimum probability of error for all tip-media interaction for all detectors are given in Table I. It is clear that the minimum probability of error also decreases as the tip-media interaction increases. The Bayes detector is the best detector among all detectors in term of minimum probability of error.

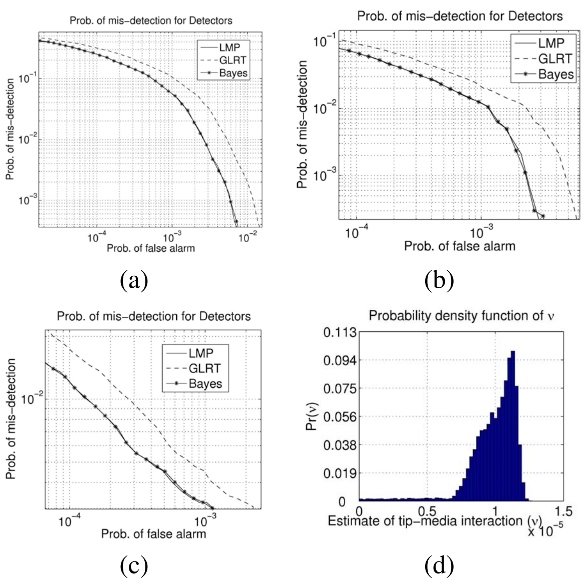

Fig. 2. Probability of mis-detection vs probability of false alarm for (a) 1.3 nm tip-media interaction. (b) 1.5 nm tip-media interaction (c) 1.7 nm tip-media interaction (d) Probability density function of the estimate of tip-media interaction force (ν) obtained from 1.5 nm tip-media interaction data.

V. CONCLUSIONS AND FUTURE WORK

We presented the dynamic mode operation of a cantilever probe and demonstrated its applicability to a high-density probe storage system. The system is modeled as a communication system by modeling the cantilever interaction with media. A controllable canonical state space representation of the entire system makes it possible to visualize the system as a communication channel with a single input. Efficient detectors like LMP, Bayes and GLRT are proposed for hit detection for different levels of tip-media interaction. Simulation results show that LMP and Bayes detectors have a lower probability of mis-detection compared to the GLRT detector. However, the Bayes detector requires prior information on impact parameter (ν) which makes this detector implementation more complex. Due to low probability of error and low implementation complexity, the LMP detector is the most attractive detector in practice.

In this paper we have exclusively worked with data generated by a realistic Simulink model of the cantilever system. We are currently working on validating these results on real experimental data. Moreover, we have only addressed the problem of bit-by-bit detection at this time. There are a host of issues around improved channel modeling, efficient sequence detection and improved topographic profile selection that we shall present in future work.

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