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Servo Experiments for Modeling of Actuator and Windage Dynamics in a Hard Disk Drive

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Abstract

This paper presents the results of a parametric identification method for the modeling of the dynamics of a servo actuator and the windage disturbance present in a hard disk drive. The results are obtained with an identification method that is based on a recently introduced extended two-stage method which enables the estimation of low order complexity models of system and disturbance dynamics on the basis of closed-loop data. As a result, experimental data obtained under realistic servo conditions is used to find low order discrete time models that describe the actuator and windage disturbance dynamics at different locations on the hard disk.

1 Introduction

Hard disk drives (HDDs) are key components of current computers and other data-processing systems. A hard disk uses round, flat disks called platters, coated on both sides with a special media material designed to store data in the form of magnetic patterns [1]. The data is read and written to the disk by means of a read-write head mounted at the tip of a flexible suspension. The suspension is driven across the surface of the disk by a servo actuator which aligns the read/write head with the data tracks located on the surface of the disk.

The storage density and the rate at which data can be accessed play a role in the performance of the HDD. The storage density is limited by the ability of the recording head to resolve the different tracks and the accuracy of the servo mechanics to follow the track. Increasing the rotational speed of the HDDs can improve the access rate of the rotational storage devices.

As the rotational speed of HDDs increases, the external disturbances cause the track mis-registration (TMR) or run out errors, and limit the storage density performance of HDD. Thus, understanding of the effects of external disturbances becomes crucial in obtaining a reliable and high performance servo system for extremely high-density recording. Of these external disturbances, windage due to disk rotation is one of the most relevant but also poorly understood phenomena [2, 3]. The airflow caused by windage causes a mechanical disturbance by exciting the resonance modes of the head gimbal assembly (HGA), which produces non-repeatable runout errors that can only be controlled by a proper understanding and design of the servo system [4].

For the modeling of windage disturbance, computational flow models (CFM) in the HDD have been developed [5]. Although useful for the design of the disk drive housing, these models are too complicated to be used for servo control design. A stochastic approach based on open loop (uncontrolled) prediction error framework has been used to model the windage disturbance [6]. But to obtain models of both actuator and windage disturbance dynamics on the basis of closed loop (controlled) data is non-trivial and requires special attention. For the practical application of windage disturbance estimation, closed loop experiments are unavoidable to provide a stable control architecture for the VCM during experiments.

From a control point of view, estimating low order models for both the servo and disturbance dynamics is important in control design applications that focus on disturbance rejection. Several methods for low order model estimation on the basis of closed-loop data exist in the literature [7, 8, 9, 10, 11], but fail to address the simultaneous estimation of low order disturbance models that are relevant in disturbance control problems.

In this paper we use a extended two-stage estimation method [12] that can be readily applied to closed-loop servo data obtained from a hard disk drive. As a result, experimental data obtained under realistic servo conditions can be used to find low order discrete time models that describe the dynamics of the servo actuator and the frequency contents of the windage disturbance at different locations on the hard disk. The methodology is illustrated on data obtained from a Fujitsu hard disk drive where laser doppler vibrometer (LDV) windage disturbances are measured by using a transparent cover on the drive.

The outline of this paper is as follows. First some preliminary notations and experimental setting are given in Section 2. In Section 3 we shortly discuss the extended two-stage identification procedure used to model servo actutaor and windage dynamics. Section 4 presents the application to Hard Disk Drive, and Section 5 summarizes the conclusions of this paper.

2 Experimental setting

2.1 Closed-loop experiments

Due to the extreme miniaturization of the components, and the importance of the hard disk's role in the PC, the entire hard disk is manufactured to a high degree of precision. The main part of the disk is isolated from outside air to ensure that no contaminants get onto the platters, which could cause damage to the read/write heads. In order to obtain reliable and realistic experimental data to measure windage disturbance, the cover of the hard disk drive should be kept untouched. This has been done in the experimental data used for modeling purposes in this paper by altering the cover with a small plastic transparent aperture that is used to measure the read/write head position with a LDV. The schematic representation of the experimental setup is depicted in the right part of Figure 1, where it can be seen that the LDV measurement is fed back through an external controller. An additive reference signal $r(t)$ is applied for excitation and identification purposes.

In Figure 2, a block diagram of experiment configuration of hard disk drive is shown. Here $P_0(q)$ indicates the dynamics of the servo actuator that consists of voice-coil motor (VCM), E-block and suspension. The notation $H_0(q)$ is used to denote the spectral contents of external windage disturbance as seen in the LDV measurement of the Position Error Signal (PES). For experimentation purposes, the open-loop marginally unstable servo actutor is stabilized by the external controller $C(q)$. The controller used during the experiments is a

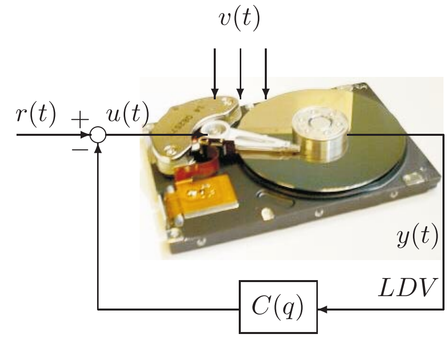

Figure 1: Experimental configuration of HDD and servo controller C for track following

(scaled) discrete time PD controller given by

$$C(q) = \frac{4.219 \cdot 10^5 q - 4.097 \cdot 10^5}{q - 0.1879} \tag{1}$$

where $C(q)$ is used only to stabilize the servo actuator during the experiments. Without such a controller, the open loop marginally unstable VCM drifts and LDV measurements are compromised.

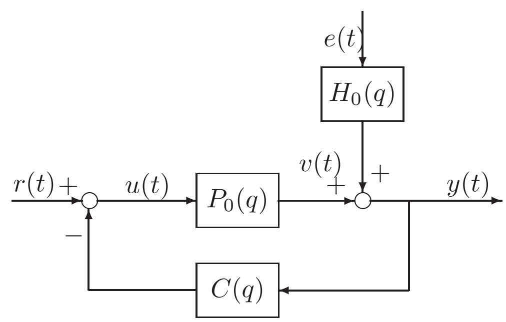

Figure 2: Closed-loop data generating system

2.2 Low order model estimation

In order to discuss the problem of estimating low order and control relevant models of the actuator dynamics and additive disturbance dynamics on the basis of closed-loop experiments, the feedback connection $T(P_0, C)$ of the unknown servo actuator plant P_0 and the known feedback controller C will be considered. The unknown plant P_0 refers to the dynamics of the actuator (VCM, E-block and suspension), whereas C is the known external controller used for experimental purposes. The feedback connection $T(P_0, C)$ is described in Figure 2 where the output $y(t)$ of the plant is fed back to the input $u(t)$ of the plant. Additionally, an additive disturbance $v(t)$ acts on the output of the plant which is modeled as a monic stable and stably invertible disturbance filter H_0 having a white noise input $e(t)$. The signal $v(t) = H_0(q)e(t)$ reflect the additional additive windage disturbance that is present in the HDD. We model the windage similar as in [6] as a filtered white noise signal, where $H_0(q)$ denotes the unknown spectral contents of the disturbance and $E[e(t)^2] = \lambda$ denotes the size of the noise. Given Figure 2, the data coming from the plant $P_0(q)$ and subjected to external reference signals $r(t)$ and additive disturbance $H_0(q)e(t)$ operating under closed-loop condition can be described as follows:

$$y(t) = P_0(q)S_{in}(q)r(t) + S_{in}(q)H_0(q)e(t) \quad (2)$$
$$u(t) = S_{in}(q)r(t) - C(q)S_{in}H_0(q)e(t) \quad (3)$$

where $S_{in}(q)$ is the input sensitivity function defined by

$$S_{in}(q) = \frac{1}{1 + C(q)P_0(q)}$$

Define $\bar{P} = P_0S_{in}$ and $\bar{H} = H_0S_{in}$, where $\bar{P}$ and $\bar{H}$ respectively denote the closed-loop servo actuator dynamics and closed-loop external windage disturbance dynamics. The notations $\bar{P}$ and $\bar{H}$ will be used to respectively indicate the closed-loop reference signal filter and the closed-loop disturbance filter later. With this definition, (2) can be rewritten into

$$y(t) = \bar{P}r(t) + \bar{H}e(t) \quad (4)$$
$$y(t) = P_0(1 - C\bar{P})r(t) + H_0(1 - C\bar{P})e(t) \quad (5)$$

Since the reference signal $r(t)$ and the windage disturbance $e(t)$ both act on the same servo actuator, the dynamics of the plant P_0 and H_0 will share the same main resonant modes of the E-block and suspension. On the basis of this rationale, an ARMAX model structure [13] is selected to model the common dynamics in servo actuator dynamics P_0 and windage induced vibrations H_0. An ARMAX model structure can be described by

$$\mathcal{M}: \quad y(t) = \frac{B(\theta, q)}{A(\theta, q)}u(t - nk) + \frac{C(\theta, q)}{A(\theta, q)}e(t) \quad (6)$$

where the model of the actuator dynamics is represented by $P_\theta(q) = \frac{B(\theta,q)}{A(\theta,q)}$ and the model of the windage disturbance dynamics is parameterized by $H_\theta(q) = \frac{C(\theta,q)}{A(\theta,q)}$ an share a common denominator to enforce the common resonance modes in actuator dynamics and windage induced vibrations. The parameter θ of the models P_θ and H_θ can be estimated by employing a least squares criterion [13]

$$\hat{\theta} := \arg\min_\theta V_N(\theta, Z^N) \quad (7)$$

$$V_N(\theta, Z^N) := \frac{1}{N}\sum_{t=1}^{N}\frac{1}{2}L^2(q)\varepsilon^2(t, \theta) \quad (8)$$

where $L(q)$ is a (user definable) data filter, and $\varepsilon(t, \theta)$ is the one step ahead prediction error.

In dealing with closed-loop data described in Figure 2, a major problem in approximate closed-loop identification of the actuator and windage disturbance dynamics is the correlation of the windage disturbance with any of the signals in the closed-loop. Estimating models for both actuator dynamics P_0 and windage disturbance dynamics H_0 is most important in control design applications that focus on windage disturbance rejection. Further, an explicit expression of the actuator dynamics $P_0(q)$ and windage disturbance dynamics $H_0(q)$ are needed to tuning the bias distribution of the actuator dynamics model $P_\theta(q)$ and the windage disturbance disturbance $H_\theta(q)$. A method which can handle the situation estimating both actuator and disturbance models on the basis of servo experiments is based on the extended two-stage method given in [12].

3 Extended two-stage method

3.1 Summary of the method

The extended two-stage method is an extension of the two-stage method [7], where the first stage is used to estimate high order models for filtering purposes. In the second stage, filtered signals are used for low order or low complexity model approximation. This method allows one to estimate both actuator dynamics and the dynamics of the windage induced disturbance simultaneously on the basis of closed-loop experimental data. The estimation can be done consistently or done in such a way that a control relevant approximation of the dynamics of the actuator and the windage induced disturbances is found.

The extended two-stage method is described by the following two steps:

1. In the first step, a standard open-loop identification of closed-loop actuator dynamics $\bar{P}$, and closed-loop windage disturbance dynamics $\bar{H}$ is performed on the basis of the closed-loop reference $r(t)$ and output position error signal $y(t)$ in (4). Using the estimated models $\bar{P}_*$ and $\bar{H}_*$, the closed-loop prediction error

$$\varepsilon_{cl}(t) = \bar{H}_*^{-1}\left(y(t) - \bar{P}_*r(t)\right). \quad (9)$$

is computed to obtain a realization of the (unfiltered white) noise present on the closed-loop data.

2. In the second step of the method, the estimated model $\bar{P}_*$ of closed-loop actuator dynamics $\bar{P}$ is used to create a filtered input $u_f(t)$ and a filtered prediction error $\varepsilon_f(t)$:

$$u_f(t) := (1 - C\bar{P}_*)r(t) \quad (10)$$
$$\varepsilon_f(t) := (1 - C\bar{P}_*)\varepsilon_{cl}(t) \quad (11)$$

using the knowledge of the feedback controller C. Subsequently, the signals $u_f(t)$ and $\varepsilon_f(t)$ according to (5) are used to estimate low order models P_θ of actuator dynamics and H_θ of windage disturbance dynamics by minimizing the two-norm of the output error

$$\varepsilon(t,\theta) = y(t) - [P_\theta(q)\ H_\theta(q)] \begin{bmatrix} u_f(t) \\ \varepsilon_f(t) \end{bmatrix} \quad (12)$$

that allows for a low order approximation of the open-loop actuator dynamics P_0 and external windage disturbance dynamics H_0.

3.2 Characterization of approximation

In case low order models P_θ and H_θ of actuator and windage dynamics are required for control design purposes, it is insightful to characterize the approximation being made during the estimation and modeling purposes. This can be done by studying the asymptotic frequency domain expression for the minimization of the 2-norm of the prediction error in (12). The frequency domain expression for the low order model approximation of P_0 and H_0 depends on the estimation results of the model $\bar{P}_*$ of the closed-loop actuator dynamics and the model $\bar{H}_*$ of the closed-loop windage disturbance dynamics in the first step of the method. In the most general case, when modeling errors are made in the first step, i.e. $\bar{P}_* \neq P_0 S_{in}$, $\bar{H}_* \neq H_0 S_{in}$, the following asymptotic bias expression is obtained.

Theorem 1 *Consider the first step in the extended two-stage method where estimates $\bar{P}_*$ and $\bar{H}_*$ satisfy*

$$\bar{P}_* \neq \bar{P} = P_0 S_{in}, \quad \bar{H}_* \neq \bar{H} = H_0 S_{in} \quad (13)$$

then for $N \to \infty$ the two-norm minimization of the output error in (12) is equivalent to

$$\min_\theta \int_{-\pi}^{\pi} \big[|(P_0 - P_\theta)S_{in} + (\bar{P}_* - \bar{P})(P_\theta C + H_\theta(1 - C\bar{P}_*)\bar{H}_*^{-1})|^2 \Phi_r(\omega) + |(H_0 - H_\theta)S_{in} + H_\theta(S_{in} - (1 - C\bar{P}_*)\bar{H}\bar{H}_*^{-1})|^2 \Phi_e(\omega)\big]\, d\omega \quad (14)$$

where P_θ and H_θ denote the models estimated in the second step of the extended two-stage method.

The frequency representation (14) shows the influence of model errors of $\bar{P}_*$ and $\bar{H}_*$ created during the first step of extended two-stage method on the estimates of low order models P_θ of actuator dynamics and H_θ of windage disturbance dynamics in the second step. Note that $\bar{P}$ and $\bar{H}$ are only used for filtering purposes and choosing a high order to estimate $\bar{P}$ and $\bar{H}$ in the first step does not influence the final results of the identification in the second step of extended two-stage method. So, if very accurate (high order) models of $\bar{P}$ and $\bar{H}$ are identified in the first step, i.e, $\bar{P}_* = \bar{P}$ and $\bar{H}_* = \bar{H}$, then (14) can be simplified to

$$\min_\theta \int_{-\pi}^{\pi} \big[|(P_0 - P_\theta)S_{in}|^2\, \Phi_r(\omega) + |(H_0 - H_\theta)S_{in})|^2 \Phi_e(\omega)\big]\, d\omega \quad (15)$$

Obviously, (15) is an explicit and tunable expression for the bias distribution of the asymptotic models P_θ and H_θ. In (15), it is easily observed that the difference $|\ P_0 - P_\theta|^2$ is weighted by the reference spectrum $\Phi_r(\omega)$ and the difference $|\ H_0 - H_\theta|^2$ is weighted by white noise spectrum $\Phi_e(\omega)$, while both are weighted by the input sensitivity function S_{in}. The implication of the approximation result in (15) is that a low order model P_θ of the actuator dynamics P_0 and a low order model H_θ of the windage induced disturbances H_0 is obtained by a frequency weighting that is dictated by the closed-loop experiments. This yields approximate models that are specifically tuned towards approximating the closed-loop behavior of actuator and windage dynamics and useful for control design purposes.

4 Application to Hard Disk Drive

4.1 Experiments and spectral analysis

The experimental setup indicated in Figure 1 is used to gather time sequences of external reference signal $r(t)$, input signal $u(t)$ and output position error signal $y(t)$. To analyze the effect of windage disturbance dynamics in the hard disk drive, experiments were conducted with the read/write head located at 3 different positions on the disk. The VCM was positioned via a feedback controller at the OD (outer diameter), the MD (middle diameter) and ID (inner diameter) of the platter.

For validating the parametric estimation results of actuator dynamics $P_0(q)$ and windage disturbance dynamics $H_0(q)$ with extended two-stage identification method, non-parametric estimates of $P_0(q)$ and $H_0(q)$

are needed, which can be obtained by a spectral analysis [13], and given by

$$\begin{aligned}\hat{P}(\omega) &= \hat{\Phi}_{ru}^{-1}(\omega)\hat{\Phi}_{ry}(\omega)\\ \hat{H}(\omega) &= \sqrt{(\hat{\Phi}_y(\omega) - \hat{\Phi}_{ry}^2(\omega)\hat{\Phi}_r(\omega))\hat{\Phi}_{ru}^{-1}(\omega)}\end{aligned} \tag{16}$$

where $\hat{\Phi}_{ru}(\omega)$ denotes an estimate of the cross-spectrum between reference signal $r(t)$ and input signal $u(t)$, $\hat{\Phi}_{ry}(\omega)$ denotes an estimate of the cross-spectrum between reference signal $r(t)$ and output position error signal $y(t)$. The $\hat{\Phi}_y(\omega)$ and $\hat{\Phi}_r(\omega)$ are estimations of the auto-spectra of output position error signal $y(t)$ and reference signal $r(t)$, respectively. It should be noted that $\hat{P}(\omega)$ and $\hat{H}(\omega)$ in (16) will only be used as a validation tool for the parametric models P_θ and H_θ being estimated with the extended two-stage method.

4.2 Application of extended two-stage method

First consider the case when the servo actuator is positioned at the OD (outer diameter) of the platter, and the reference signals $r(t)$, input signal $u(t)$ and output position error signal $y(t)$ are measured in a closed-loop experimental setting for identification purposes. In the first step of the extended two-stage method, a 17th order ARMAX model structure is selected to estimate the closed-loop actuator dynamics $\bar{P}$ and closed-loop windage disturbance dynamics $\bar{H}$ which are used for later filtering purposes. The minimization of the prediction error (9) leads to 12th order model estimates of the open-loop actuator dynamics P_0 and windage disturbance dynamics H_0 which are depicted in Figure 3 and Figure 4, respectively.

Figure 3 presents the amplitude plots of the spectral estimate of actuator dynamics P_0 (frequency domain plot) and the 12th order parametric model P_θ. Figure 4 shows the amplitude plot of non-parametric estimate of windage disturbance dynamics H_0 and 12th order parametric model H_θ. It can be observed that a good estimation of E-block resonance mode, torsion mode and sway mode is obtained in P_θ and H_θ that are parametrized in such a way that they share the same resonance modes of the E-block and suspension.

To further analyze the effect of windage disturbance dynamics in the hard disk drive, experiments were also conducted when the servo actuator was positioned at the MD (middle diameter) and ID (inner diameter) of the hard disk drive platter. Similar to the identification method of analyzing the data measured in the case when the servo actuator was located at the OD (outer diameter) of the platter, models P_θ and H_θ are obtained and compared for illustration purposes in Figure 5 and Figure 6.

Figure 5 and Figure 6 present the amplitude plot of 12th order parametric model P_θ and H_θ when servo actuator was located at the 3 different positions on the hard disk drive platter. From Figure 5, we can observe that the resonant modes of servo actuator dynamics remain the same, although experimental data was measured at different positions on the disk. On the other hand, it can be observed from Figure 6 that the position of servo actuator along the disk does change the dynamics of the windage disturbance dynamics. Obviously, the location of the resonance modes remain the same, as the dynamics of E-block and suspension do not change due to position changes, but the relative contribution of the resonance modes due to the windage disturbances changes. It can be observed that the excitation of the vibration mode of the main suspension sway mode at approximately 9 kHz becomes significantly larger at the OD of the disk.

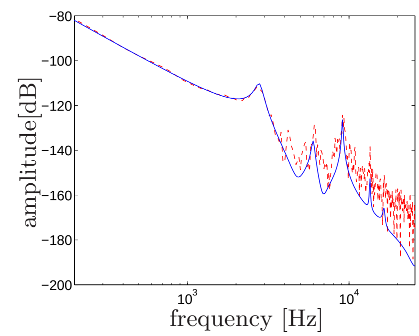

Figure 3: Amplitude Bode plot of spectral estimate of actuator dynamics P_0 (dashed) at OD and 12th order parametric model P_θ found by the extended two-stage method (solid).

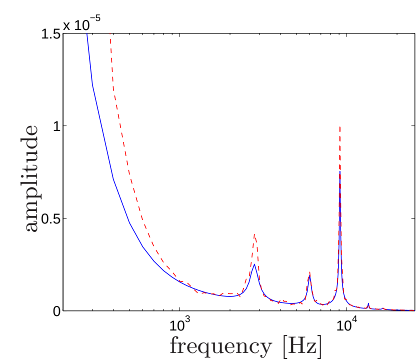

Figure 4: Amplitude Bode plot of spectral estimate of windage induced disturbance dynamics H_0 (dashed) and 12th order parametric model H_θ (solid) found by the extended two-stage method.

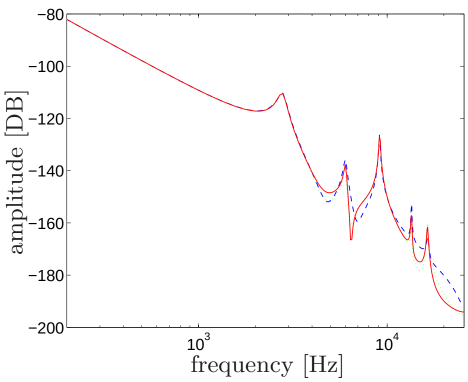

Figure 5: Amplitude Bode plot of the estimated 12th order parametric model P_θ of the servo actuator dynamics, when data is measured at different positions: outer diameter (dashed); middle diameter (dotted); inner diameter (solid).

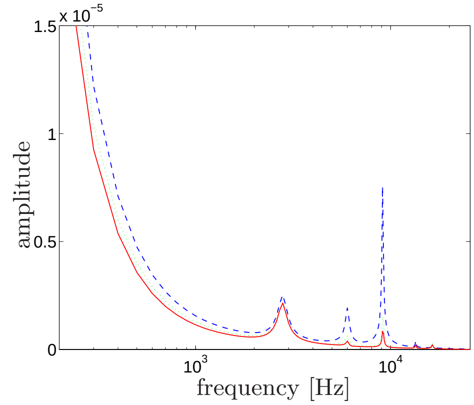

Figure 6: Amplitude Bode plot of estimated 12th order parametric model H_θ of the windage induced vibration dynamics, when data is measured at different positions: outer diameter (dashed); middle diameter (dotted); inner diameter (solid).

5 Conclusions

In this paper, a control relevant parametric identification scheme is applied to a Hard Disk Drive to obtain low order models of the actuator and windage disturbance dynamics. This is done by using a extended two-stage identification algorithm. In this method, a high order models are estimated in the first step for filtering purposes. In the second step, filtered signals are used to provide means for low order model approximation of both actuator and windage disturbance dynamics which can be used as a basis for the design of optimal low order servo controllers for windage vibration reduction in high track density recording.

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