Reduction of Flow-Induced Suspension Vibrations in a Hard Disk Drive by Dual-Stage Suspension Control

Arjan P. Teerhuis, Sandra J. M. Cools, and Raymond A. De Callafon

***Abstract*—A control design methodology is proposed to control an active dual-stage suspension for the reduction of flow-induced vibrations (windage) in a hard disk drive. The design of the controller uses dynamical models of both the suspension and the stochastic behavior of the windage to design a low third-order discrete-time feedback controller to reduce windage-induced track misregistration. Experimental results show that nonrepeatable runout errors due to windage are reduced by an order of a magnitude.**

***Index Terms*—Hard disks, optimal control, vibration control.**

I. Introduction

LARGE ROTATIONAL speeds in hard disk drives (HDDs) facilitate high-throughput data transfer but mechanical vibrations and air turbulence [1] will influence the storage capacity of the drive negatively. To reduce the effect of flow-induced vibrations, a preventive mechanical design can be used where the housing of the drive, the E-block and suspension, are evaluated on the sensitivity to flow-induced vibrations. Such a design requires an intricate aero-elastic model to understand the flow pattern in the drive and the interaction with the flexible mechanical components to predict the vibrations induced by the windage.

An alternative to this approach is to use an active suspension, such as a piezo-electric dual-stage actuator, to reduce flow-induced vibrations. Active suspension control has been shown to be very effective for vibration suppression [2], but for the design of optimal minimum variance control algorithms, explicit knowledge of the disturbance (windage) has to be taken into account in the control design. A well-tuned feedback design based on stochastic disturbance information provides better reduction of nonrepeatable run-out (NRRO) errors [3], [4], whereas control algorithms based on the repeatable nature of disturbances are successful for track following and track seeking in disk drive systems [5].

It is shown in this paper that a relatively simple quantitative stochastic model of the flow-induced vibrations can be used to design an optimal and low complexity control algorithm. To illustrate the effectiveness of an active suspension for windage disturbance rejection, only a controller for the active suspension is designed and it is shown that the effect of windage is reduced by an order of a magnitude.

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II. Modeling of Flow-Induced Vibrations

For the design of an optimal servo controller for active suppression of windage, the statistical and stochastic knowledge of the windage disturbance on the position error signal (PES) should be taken into account. Computational fluid models give detailed information on the turbulence patterns in a disk drive [6], but they do not describe the stochastic properties of the aero-elastic interaction between the air flow and the flexible suspension in the drive. A standard Prediction Error (PE) estimation technique [7], [8] can be used to model the effect of windage on an HDD suspension relevant for control design on the basis of actual experimental data.

For the experimental results in this paper, a laser doppler velocimeter (LDV) is used to the measure the relative slider position attached to a Hutchinson Magnum 5e suspension that is mounted on a fixed E-block arm in an open (without cover) drive with a rotational speed of 5400 r/min. For experimental modeling purposes, data is sampled at 40 kHz, but for controller implementation a smaller sampling frequency of 20 kHz will be used. A summary of the PE approach is presented here, for more details one is referred to [8].

In the PE framework, the relative slider position or PES $y(t)$ is described by $y(t) = G_0(q)u(t) + v(t)$, where $G_0(q)$ is used to denote the discrete time model of the suspension dynamics between PZT input $u(t)$ and PES output $y(t)$. The stochastic properties of the additive windage disturbance $v(t)$ are characterized by a filtering $v(t) = H_0(q)n(t)$ where $n(t)$ is a white noise with variance λ. The filter $H_0(q)$ denotes a stable and stably invertible monic noise filter that is used to represent the spectral contents of the flow-induced vibrations present in the PES $y(t)$.

Based on the information contained in N observations of the input/output data $\{u(t), y(t)\}$, $t = 1, \ldots, N$, discrete time models $G(q)$, and $H(q)$ of the unknown suspension dynamics $G_0(q)$ and noise filter $H_0(q)$ are estimated. This is done by constructing the prediction error

$$e(t,\theta) := H^{-1}(q,\theta)(y(t) - G(q,\theta)u(t)) \tag{1}$$

as a function of the parameters θ contained in the models $G(q,\theta)$ and $H(q,\theta)$. The models $G(q,\theta)$ and $H(q,\theta)$ are parameterized by an ARMAX structure [7]

$$G(q,\theta) = \frac{B(q,\theta)}{A(q,\theta)}, \quad H(g,\theta) = \frac{C(q,\theta)}{A(q,\theta)} \tag{2}$$

where $B(q)$ and $C(q)$ denote the numerator polynomial and $A(q)$ the common denominator of the IIR models. A common denominator $A(q)$ is used, as similar suspension vibration modes are expected to occur in the PES output $y(t)$ due to

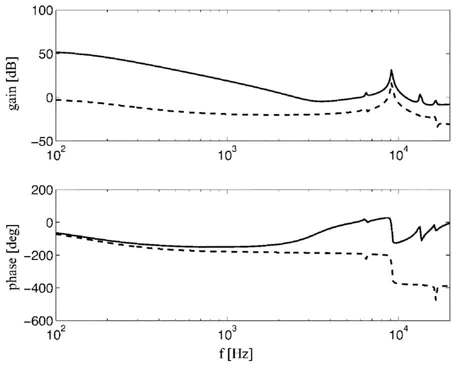

Fig. 1. Bode plot of estimated 12th-order discrete time models of windage-induced vibration dynamics H (solid) and mechanical suspension G (dashed).

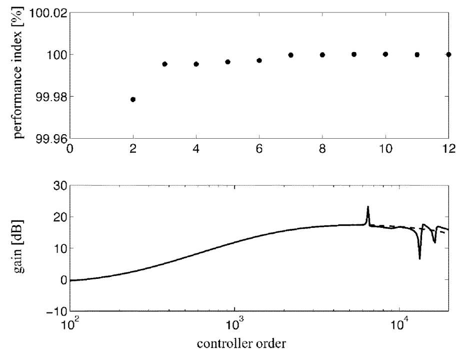

Fig. 2. (top) Performance index (7) in percentage when comparing the full (12th) order controller C to reduced-order controllers C_r. (bottom) Amplitude Bode plot of full order discrete time controller C (solid) and reduced (third) order discrete time controller C_r (dashed).

PZT excitation $u(t)$ and windage excitation $n(t)$. In the PE framework, the variance of the prediction error $e(t,\theta)$ in (1) is minimized to find an optimal parameter estimate $\hat{\theta}$.

On the basis of experimental data obtained at the outer diameter (OD) of the disk, consistent model estimates were obtained by choosing a twelfth-order model parameterization for $G(q,\theta)$ and $H(q,\theta)$ [8]. Measurements at the OD are used to model the windage disturbances as the OD is assumed to be the worst case position of the suspension with respect to windage disturbance [2]. A Bode plot of the discrete time models of the suspension dynamics G and the noise model H are given in Fig. 1. The models for G and H depicted in Fig. 1 will form a basis for the servo control design to suppress the flow-induced vibrations.

III. Active Control of Flow-Induced Vibrations

A. Control Design

Reduction of the windage-induced vibrations $v(t)$ on the PES $y(t)$ can be achieved by active control of the dual-stage suspension PZT input signal $u(t) = r(t) - C(q)y(t)$, where the signal $r(t)$ is used to denote an (optional) reference signal and $C(q)$ the digital feedback controller. The controller $C(q)$ uses the PES $y(t)$ to control the flexibilities in the suspension by increasing the damping of the resonance modes of the suspension and thereby reducing the variance of the PES $y(t)$ due to the windage disturbance $v(t)$.

The variance of the PES $y(t)$ due to the flow-induced vibrations $v(t) = H(q)n(t)$ is given by

$$E\{y(t)^2\} = \left\| \frac{H}{1+GC} \right\|_2^2 \lambda \tag{3}$$

and a straightforward minimization of the variance of $y(t)$ using the feedback controller C would lead to a high gain feedback controller. A feasible control design is obtained by including the (weighted) control signal $u_w(t) := W(q)u(t)$ in the controller computation by simultaneously minimizing the variance of the PES $y(t)$ and the variance of the weighted control signal $u_w(t)$

$$\min_C \left\| \begin{bmatrix} \dfrac{H}{1+GC} & \dfrac{WHC}{1+GC} \end{bmatrix} \right\|_2^2 \tag{4}$$

subjected to stability of the feedback connection of G and C.

The minimization (4) is a standard H_2 or weighted linear quadratic Gaussian (LQG) control design problem [9]. Compared to a standard LQG formulation, the optimal controller in (4) intuitively minimizes the variance of the PES $y(t)$ and the (weighted) control energy $u_w(t)$ by explicit knowledge of the suspension dynamics G and the disturbance dynamics H. Due to detailed knowledge of the disturbance dynamics, it can be noted here that the choice of a constant weighting filter $W(q) = c$ was used to construct a H_2-optimal controller that minimizes the variance of the PES $y(t)$ and the weighted control signal $u_w(t)$.

B. Controller Reduction

Models G and H in (2) are parameterized by a common denominator of order 12 and the choice $W(q) = c$ leads to the computation of an optimal controller C in (4) that has order 12. To facilitate the implementation of the digital controller, reduction of the controller complexity is required. Most controller reduction techniques are based on ad-hoc open-loop (balanced) reduction techniques. However, to ensure the performance of the feedback controller C_r, the variance of the PES signal $y(t)$ has to be monitored while reducing the controller.

With the variance of $y(t)$ given in (3), this can be done by posing the control reduction problem as a minimization

$$\min_{C_r} \left\| \frac{H}{1+GC} - \frac{H}{1+GC_r} \right\|_2^2 \tag{5}$$

where the difference between the closed-loop sensitivity functions is minimized. Although the minimization in (5) is nonconvex and intractable, in general, it can be written as a weighted additive difference

$$\min_{C_r} \left\| \frac{HG}{1+GC} \cdot \frac{1}{1+GC_r}(C - C_r) \right\|_2 \tag{6}$$

between the full-order controller C and the reduced-order controller C_r. As the full-order controller C, G, and H are known, the controller reduction can be approximated by a weighted open-loop balanced reduction. Alternatively, frequency responses can be computed and the computation of C_r in (6) can be approximated by a standard weighted frequency-domain curve fitting [10] of the frequency response

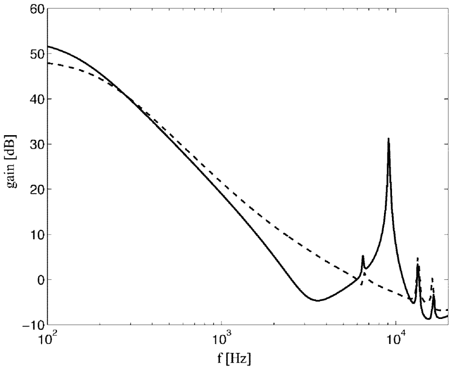

Fig. 3. Amplitude Bode plot of open-loop dynamics H (solid) and controlled windage dynamics $H/(1+GC_r)$ (dashed) with third-order controller C_r.

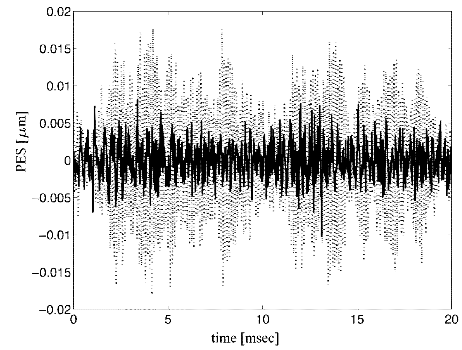

Fig. 4. Measured time histories of flow-induced vibration of slider position in an open drive without (dashed) and with control (solid) of dual-stage suspension using the third-order discrete time controller C_r.

of C. The weighting $(1/1+GC_r)$ can be updated iteratively with the estimate of a reduced-order controller C_r.

Although this approach does not guarantee convergence to a global minimum, nor the stability of the feedback of G and C_r, satisfactory results are easily obtained. This has been illustrated in Fig. 2 where the percentage of the performance index

$$\frac{\left\|\frac{H}{1+GC}\right\|_2^2}{\left\|\frac{H}{1+GC_r}\right\|_2^2} \tag{7}$$

is displayed when the controller C is reduced from a twelfth- to a second-order controller C_r. It can be observed that the third-order controller C_r has a performance index of 99.995% compared to the full twelfth-order controller C. As a result, hardly any performance degradation is obtained by reducing the twelfth-order controller to order three.

The effect of the designed reduced-order controller C_r can be illustrated when comparing the open-loop flow-induced vibration dynamics H with the closed-loop vibration dynamics $H/(1+GC_r)$. An amplitude Bode plot of both transfer functions is given in Fig. 3.

It should be noted that the designed controller C_r has not cancelled the sway resonance mode at 9 kHz. Instead, the dynamics of the suspension G, that also includes the sway mode, appears in the sensitivity function $H/(1+GC_r)$ and contributes to the reduction of the flow-induced vibrations. Although the controller C_r is not tuned to specifically dampen the sway mode of the suspension, the optimal design of the controller on the basis of windage disturbance information indicates the necessity to control the sway mode.

IV. Experimental Results and Conclusion

To illustrate the effectiveness of the windage reduction using an active suspension, the third-order controller C_r was implemented using LDV measurements of the PES to control the PZT elements of the dual-stage actuator, while the VCM actuator was fixed. Although LDV measurements are not available in a conventional HDD, the implementation of the controller is illustrative for the ability to reduce windage-induced disturbances on the basis of PES measurements.

To address the practical limitations on sampling requirements in a conventional hard disk, the discrete time controller coefficients are adapted to facilitate implementation using a sampling frequency of 20 kHz. Fig. 4 shows the PES of the system with and without control of the active suspension. It should be noted that the track misregistration without control is higher than expected from a conventional HDD at 5400 r/min, as the experiment is done with an open drive.

It can be seen that the third-order controller is able to reduce the effect of windage-induced vibrations significantly. Although the LDV measurement is used here for feedback purposes, practical implementation would require high-frequency sampling (20 kHz) of the PES signal. Alternatively, an additional measurement or sensor [11] can be used provide high sampling information to develop optimal servo controllers with the procedure mentioned in this paper.

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