Adaptive Feedforward Reference Design for Active Vibration Rejection in Multi-Actuator Hard Disk Drives

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Abstract—In December 2017, Seagate unveiled the Multi Actuator Technology to double the data performance of the future generation Hard Disk Drives (HDDs). This technology will equip drives with two Dual Stage Actuators (DSAs) each comprising of a Voice Coil Motor (VCM) actuator and a piezoelectric Micro Actuator (MA) operating on the same pivot point. Each DSA is responsible for controlling half of the drive’s arms. As both the DSAs operate independently on the same pivot timber, the control forces and torques generated by one can affect the operation of the other and thereby worsening the performance drastically. In this paper, a robust adaptive feedforward controller is designed as an add-on controller to an existing stabilizing feedback controller to reject the disturbances transferred through the common pivot timber by shaping the references to the VCM actuator and the total output of the dual stage system.

I. INTRODUCTION

In the recent years, hard disk drives (HDDs) have been replaced by solid state drives (SSDs) in most of personal computers regardless of their high cost. One of the most important reasons is that the data transfer rate of an SSD is much faster than that of an HDD. In 2017, Seagate unveiled its new multi actuator technology as a breakthrough that can double the data transfer performance of the future-generation hard drives for hyper-scale data centers. In a multi actuator drive, the read-write heads are split into two sets, an upper and a lower half, which can double the data transfer rate by having the upper and lower platter sets work in parallel. This technology will equip drives with two Dual Stage Actuators (DSAs) each comprising of a Voice Coil Motor (VCM) actuator and a piezoelectric Micro Actuator (MA) operating on the same pivot point.

The multi actuator setup brought some new challenges to the HDD’s controller design. Since both the DSAs operate on the same pivot point, the forces and torques generated by one actuator can affect the operation of the other DSA. The interaction of the two DSAs can be categorized into three basic scenarios. In the first scenario, both DSAs are in the track following mode, and it is expected that the interaction between the two actuators is negligible. In the second scenario, both the DSAs are in seek mode. In this mode, the coupling vibrational interaction is usually negligible compared to the large trajectories for both the DSAs. In the third scenario, one DSA is in seek mode and the other DSA is in track following mode. Under this scenario, the seeking DSA will impart disturbance in the form of vibration to the track following DSA, which drastically hampers the performance of the track following DSA.

Recently, a data-driven control design approach [6], [7] to suppress the vibrations generated by the seeking DSA has been applied to a multi actuator drive. The data-driven controllers are robust to the variations in the plant models. However, a common controller might not be the optimal controller for each individual HDD as there might be variations in the plants. To address this issue, an adaptive feedforward reference design technique is developed in this work. The proposed technique takes advantage of both feedforward and feedback control structures. A set of feedback controllers are designed to stabilize the closed-loop system and decoupled the dual-stage actuator as well. A feedforward controller can adapt its parameters to attenuate the imparted coupling disturbance before it affects the tracking error. This work utilizes the reference design for track seeking controllers developed in [3] to shape the total output of the dual stage system. Since the track seeking architecture is already built inside the HDD, adding the current adaptive control strategy to the HDD would be simple. A pretraining strategy to prevent the MA’s output from exceeding its stroke limits during the adaptation process is also presented.

II. CONTROL ARCHITECTURES FOR DUAL STAGE ACTUATORS

A. Feedback Control Structure

Fig.1 shows a block diagram of the dual-stage controller design using sensitivity decoupling method [2]. \(G_v\), \(G_m\) represent the actual plants of the VCM and MA respectively. \(K_v\) and \(K_m\) are the Single-Input Single-Output (SISO) controllers for the VCM and MA plants respectively. \(\hat{G}_m\) is the feedforward plant estimate of MA. \(H\) represents the
disturbance cross transfer function from the seeking DSA to
the track following DSA which takes in the input of the VCM
of the track seeking DSA \((u_{v,c})\) and produces the disturbance
d on the output of the track following DSA. The signals \(r_o\)
represents the runout, \(e\) represents the position error signal
(PES), \(u_v\) represents the control input to the VCM, \(u_m\)
represents the control input to the MA, \(y_v\) represents the
output of VCM, \(y_m\) represents the output of MA, \(y_t = y_v + y_m\)
represents the total output produced by both the actuators
and \(y\) represents the actual output of the dual stage
system along with the disturbance. The overall sensitivity
transfer function from \(r_o\) to \(e\) can be calculated as
\[
S = \frac{1}{1 + G_vK_v + G_mK_m + G_vK_v\hat{G}_mK_m}
\]
\[
= \frac{1}{1 + K_vG_v + 1 + K_mG_m}
\]
\[
\bar{G}_m = G_m + \frac{K_vG_v(\hat{G}_m - G_m)}{1 + K_vG_v}
\]
The MA has high frequency uncertainties and hence the
estimated model of the MA \((\hat{G}_m)\) is a good approximation
of the actual MA plant \((G_m)\) in the low frequency region. As a
result \(\hat{G}_m\) will be very close to \(G_m\) in those low frequency
regions. In the high frequency regions, the term \(K_vG_v\)
is relatively small as the VCM actuator is not active in that
region. Consequently, any difference between \(G_m\) and \(\hat{G}_m\) at
high frequency regions will be decreased by the \(K_vG_v\) term
and hence \(G_m\) will also be a good approximation of \(\hat{G}_m\)
at high frequency regions. Therefore, the overall sensitivity
of the dual-stage actuation in 1 can be approximately decoupled
as the multiplication of the actuators’ sensitivity transfer
functions
\[
S \approx S_vS_m
\]
where
\[
S_v = \frac{1}{1 + K_vG_v}
\]
\[
S_m = \frac{1}{1 + K_m\hat{G}_m}
\]
B. Feedforward Reference Design Structure
The feedback control structure for track following shown in
the previous section has been extended to track seeking in
[3]. In this structure, the reference trajectories to be followed
by the read-write head of the DSA and the VCM actuator
are designed to minimize the output of the MA as it has
small stroke limits. Fig. 2 shows a block diagram of the
feedforward reference design structure. In this structure, \(G_v\)
represents the estimate of the VCM plant. \(\hat{G}_v^{-1}\) and \(\hat{G}_m^{-1}\)
are the zero phase plant inverses used in Zero Phase Error
Tracking Control (ZPETC) [11]. The signals \(r_v\) represents
the reference signal to VCM and \(r\) represents the reference
to the total output of the dual stage system. The signals
\(e_v = r_v - e\) and \(e_t = r - e\). Various signals and overall
transfer functions can be easily obtained by simplifying the
block diagram. Let \(r_{os} = Sr_o\) and \(d_s = Scd\) be the signals
obtained by filtering the runout and disturbance signals
through the sensitivity transfer function respectively. The
PES in the presence of disturbance can be obtained from
the block diagram as
\[
e = r_{os} - d_s + R_{r_{v}\rightarrow e}r_v + R_{r_{t}\rightarrow e}\ (7)
\]
where
\[
R_{r_{v}\rightarrow e} = S(G_m\hat{G}_m^{-1} - G_v\hat{G}_v^{-1})
\]
\[
R_{r_{t}\rightarrow e} = -S(G_m\hat{G}_m^{-1} + G_vK_v + G_mK_m + G_vK_v\hat{G}_mK_m)
\]
Here \(R_{r_{v}\rightarrow e}\) denotes the transfer function from \(r_v\) to \(e\) and
\(R_{r_{t}\rightarrow e}\) denotes the transfer function from \(r\) to \(e\). If \(G_v\hat{G}_v^{-1}\) ≈
1 and \(G_m\hat{G}_m^{-1}\) ≈ 1, then \(R_{r_{v}\rightarrow e}\) is close to zero and \(R_{r_{t}\rightarrow e}\) is
close to negative unity.
\[
R_{r_{v}\rightarrow e} \approx S(1 - 1) = 0
\]
From (1) and (9)
\[ R_{r\to e} \approx -S(1 + G_v K_v + G_m K_m + G_v K_v \hat{G}_m K_m) \]
\[ = -1 \quad (11) \]
Furthermore, the PES can be approximated by
\[ e \approx -d_s - r + r_{os} \quad (12) \]
It can be seen that if the total reference signal \( r \) is designed to be equal to \(-d_s\), the PES can be minimized. To achieve this, the disturbance \( d_s \) needs to be known. This motivates the design of an adaptive controller to estimate this signal.

It must be noted that the high frequency uncertainties arising because of the approximations made do not cause issues with implementations as the disturbance signals do not contain high frequency components as the seek signals have low frequency components.

III. ADAPTIVE CONTROL STRUCTURE

In this section, an adaptive controller \( C \) will be designed to estimate the signal \( d_s \) and compensate for it. This design utilizes the feedforward reference design structure presented in the previous section. While estimating \( d_s \), it is also essential to respect the stroke limits of MA and hence the references will be chosen in such a way that the MA’s output is minimized. The output of MA \( (y_m) \) can be obtained by simplifying the block diagram in fig. 2 as

\[ y_m = -G_m \hat{G}_m^{-1} r_v + (G_m \hat{G}_m^{-1} + G_m K_m) r + G_m K_m (r_{os} - d_s + R_{r\to e} r_v + R_{r\to e} r) \quad (13) \]

Again, if \( G_v \hat{G}_v^{-1} \approx 1 \) and \( G_m \hat{G}_m^{-1} \approx 1 \), the following approximation can be obtained for \( y_m \),

\[ y_m \approx -r_v + (1 + G_m K_m) r + G_m K_m (r_{os} - d_s - r) \]
\[ = -r_v + r + G_m K_m (-d_s + r_{os}) \quad (14) \]

With the optimal filter \( C^* \), the reference signal follows the negative value of the filtered disturbance.

\[ r \approx -d_s \quad (15) \]

By substituting (15) in (14), and by designing \( r_v \) as

\[ r_v = \hat{G}_m K_m r \quad (16) \]

we can obtain \( y_m \) as

\[ y_m \approx -\hat{G}_m K_m r + r + G_m K_m (-d_s + r_{os}) \]
\[ \approx \hat{G}_m K_m d_s - d_s + G_m K_m (-d_s + r_{os}) \]
\[ \approx -d_s + G_m K_m r_{os} \quad (17) \]

As the quantity \( G_m K_m r_{os} \) is very small, the MA will just have to track \(-d_s\) which is well within its stroke limits. Similarly, we can also obtain the output of VCM, \( y_v \) as

\[ y_v = r_o - e - d - y_m \]
\[ \approx r_o - (-d_s - r - r_{os}) - d - (-d_s + G_m K_m r_{os}) \]
\[ \approx r_o - r_{os} - d + d_s - G_m K_m r_{os} \quad (18) \]

It can be seen that the VCM takes care of rejecting most of the actual disturbance as the signal \( d \) explicitly appears in the expression for \( y_v \). The total output of the dual stage system \( y_t = y_v + y_m \) can be obtained as

\[ y_t = -d + r_o - r_{os} \quad (19) \]

The actual output of the dual stage system along with the disturbance would now be

\[ y = y_t + d = r_o - r_{os} \approx 0 \quad (20) \]

Having designed \( r_v \), the only task remaining is to make

\[ y \]

The block diagram shown in fig.3 can be simplified to the block diagram shown in fig.4. From fig.4, we can obtain the overall transfer function of the secondary path \( P_{\text{dual}} \) as

\[ P_{\text{dual}} = -(R_{r\to y} + R_{r\to y} \hat{G}_m K_m) \approx -1 \quad (21) \]

Therefore we can define an estimate of \( P_{\text{dual}} \) as \( P_{\text{dual}} = -1 \) to be used in the parameter adaptation algorithm. The convergence condition for the parameters in the adaptive controller \( C \) is stated in the following corollary.

**Corollary 1:** The controller \( C \) converges to a unique stationary point \( \hat{C} \) if \( F_s / H S \) is strictly positive real (SPR). Proof is given in [12].

3785
Controller Pretraining on the Single-Stage Actuator

As the MA has a stroke limit of only a few micrometers, the adaptive reference design should take into consideration its saturation properties during the entire parameter adaptation process. As discussed in the previous section, the output of MA follows the negative residual disturbance \((-d_s)\) and its absolute value remains small if the controller parameters are close to the stationary point. If the controller parameters are far from the optimal, the plant model of the MA becomes nonlinear and the parameter adaptation algorithm may diverge.

In order to get a good initial point for the adaptive controller in the DSA system, the controller is pretrained on the single-stage actuator system with the VCM. The entire parameter adaptation process is then separated into two stages: a pretraining stage and a fine-tuning stage. In the pretraining stage, the MA is turned off. The controller parameters are initialized with some random values and updated on the single-stage actuator system until they converge. In the fine-tuning stage, the MA is turned on again. The controller parameters are tuned for the DSA system on the most resent measurements. The block diagram of the adaptive feedforward control system with two switches.

Adaptive Feedforward Control System

used to turn on/off the MA, and switch 1 is used to adjust the transfer function of the secondary path such that the control parameters converge to the same stationary point in both the stages.

When the Switch 1 is on and Switch 2 is off, the system is running in the pretraining stage with a single-stage actuator. A simplified block diagram is shown in fig.6. In fig.6 $S_v$ denotes the closed-loop sensitivity function of the single stage actuator, which is given by

$$S_v = \frac{1}{1 + G_v K_v}$$  \hspace{1cm} (22)$$

$\tilde{R}_{rv \rightarrow y}$ denotes the transfer function from $r_v$ to $y$, which is given by

$$\tilde{R}_{rv \rightarrow y} = S_v (G_v \hat{G}_v^{-1} + G_v K_v)$$

$$= \frac{G_v \hat{G}_v^{-1} + G_v K_v}{1 + G_v K_v}$$  \hspace{1cm} (23)$$

If $G_v \hat{G}_v^{-1} \approx 1$, then $\tilde{R}_{rv \rightarrow y} \approx 1$. The overall transfer function from $u_{c2}$ to $y$ in a single-stage actuator system is given by

$$\tilde{R}_{u_{c2} \rightarrow y} = S_u H + \tilde{R}_{rv \rightarrow y} (1 + K_m \hat{G}_m) CF_s$$

$$\approx \frac{H}{1 + G_v K_v} + (1 + K_m \hat{G}_m) CF_s$$  \hspace{1cm} (24)$$

Recall that the overall transfer function from $u_{c2}$ to $y$ in the dual-stage actuator system shown in fig.4 can be obtained as follows

$$R_{u_{c2} \rightarrow y} = SH + (R_{rv \rightarrow y} K_m \hat{G}_m + R_{rv \rightarrow y}) CF_s$$

$$\approx \frac{H}{1 + G_v K_v + G_v K_m + G_v K_v G_m K_m} + CF_s$$  \hspace{1cm} (25)$$

If there exists a controller $C$ that perfectly cancels the imparted disturbance for a single-stage actuator system and makes the transfer function $\tilde{R}_{u_{c2} \rightarrow y}$ equal to zero, then the transfer function $R_{u_{c2} \rightarrow y}$ is also close to zero. In other
words, the optimal control for the single-stage actuator system is close to the optimal controller for the dual-stage actuator system. Therefore, the pretrained controller parameters would be good initial points for the fine-tuning stage, and the output of the MA is kept within its stroke limits during the entire parameter adaptation process.

IV. RESULTS

The adaptive feedforward reference design presented was numerically implemented with realistic plant models for VCM, MA, disturbance cross transfer function \( H \) (shown in appendix) and 4\( ^{th} \) order FIR filter for the adaptive controller. The position error signal in single-stage mode and dual-stage mode are presented. Fig.7 shows the PES during the single-stage mode i.e., the pretraining stage. By using VCM only, the PES is reduced by 90%. The converged parameters are then used to initialize the controller parameters in the adaptation process for the dual-stage mode. Fig.8 shows the PES in the dual-stage mode which is within the desired limits. Comparing to the single-stage mode, the PES is reduced by 80% in the dual-stage mode. The standard deviation of position error signals is around 10nm and the maximum PES is kept below 20nm, which gives a large safety margin for read/write operation in the hard disk drives.

One of the practical issues in implementation of adaptive control algorithms on HDDs online is the limitation on the computational power on board. Hence, disturbances arising from higher order transfer functions cannot be compensated. Also, IIR filters are hard to implement as ensuring stability of the IIR filter at every instant needs projecting the adapted poles into the unit circle which is computationally very expensive for a HDD.

V. CONCLUSIONS

In this paper an adaptive feedforward control structure has been developed to learn and reject the disturbance process emanating from the dual stage actuator in the track seeking mode and affecting the dual stage actuator in the track following mode in a multi actuator hard disk drive. This control structure is designed as an add on controller to the already existing feedback control structure. The controller is designed as an FIR filter with unknown coefficients that are adapted to minimize the position error signal. A feedforward reference design structure has been used to make the adaptive controller robust to plant variations and to keep the output of the micro actuator within its stroke limits.

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APPENDIX

Fig. 9. Frequency responses for $G_v$, $\hat{G}_v^{-1}$ and $\hat{G}_v^{-1} G_v$

Fig. 10. Frequency responses for $G_m$, $\hat{G}_m^{-1}$ and $\hat{G}_m^{-1} G_m$

Fig. 11. Frequency responses for $\hat{S}, \hat{S}$

Fig. 12. Frequency response of the cross transfer function $H$

Fig. 13. Frequency response of filter $F_s$