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Design Approach for Hard Disk Drive Settle Performance Optimization

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Abstract: A design approach is presented for constrained optimization of feed-forward signal using closed loop impulse response. The approach is flexible and is possible to integrate easily with the existing controller structure. It is demonstrated that the approach does not need high order and precise description of the closed loop system.

Keywords: Parametric optimization; Controller constraints and structure; Industrial applications of optimal control.

1. INTRODUCTION

Hard disk drives present many challenges from the point of view of the control engineer. These are active field of research and large number of papers and patents is published every year on these topics. Hard disk drives require very high precision **tracking** in the presence of diverse external disturbances. A good practical overview on this topic can be found in Abramovitch et al. [1998]. In the same time, hard disk drives they must be able to **change the position** of the magnetic head very quickly and silently, see for example methods disclosed by Semba et al. [2007], Tremaine [1997]. It is well known, that these two main control problems are very difficult to solve simultaneously using purely linear feedback control methods, because of the well known fundamental limitations imposed by so called *Bode integral theorems*, see Lurie and Enright [2000] for introduction and Bode [1945] for the original work. One possibility to make a compromise between these contradictions is to use so called Two-Degree of Freedom Control, which involves feedback part and feed-forward part, as described among others in Astrom and Wittenmark [1996], Franklin et al. [1997]. The feedback part of the controller is used to ensure stability and robustness, while the feed-forward part is rather used to ensure desired input-output transient behavior and to eliminate the measurable disturbances. Because feed-forward is not part of the closed loop, it requires that the uncertainty is sufficiently reduced by the feedback part of the controller. In the same time, feed-forward does not affect the stability properties of the closed loop system and because of that it is possible to use many different approaches, for example including non-linear components or hybrid and discrete event systems in the feed-forward without much concern for stability. Nonlinear elements are used also in the feedback path. Since in general the non-linear controllers provide more degree of freedom in the feedback part and can potentially perform better, one widely used practical approach is to use so called *Composite Nonlinear Controllers*, which are composed of linear controllers and some logic to transition between them according to some rules. Each of the linear controllers can be regarded as local approximation to the globally optimal (non-linear) controller. See Lurie and Enright [2000], Chen et al. [2006].

Based on the open publications in scientific journals, papers and patents, hard disk drive industry is actively using both feed-forward and composite nonlinear controllers to ensure proper practical compromise between conflicting technical requirements. See Takaishi and Saito [2003, 2006].

2. HARD DISK CONTROLLER BASICS

2.1 Controller switching

The operation of hard disk drive servo controller can be divided in several main stages: **Seek** has to ensure quick and silent change of the position of the magnetic head from one track to another. The trajectory which is followed during this is critical to avoid exciting mechanical vibrations, which may slow down next stages and make large acoustic output. At the end of the seek, the hard disk head should be in certain neighborhood of the target track. This neighborhood is determined by imposing requirement on the phase-space coordinates - position and velocity. **Settle** has to ensure proper transition between the seek and tracking controller with minimum transient and acoustic output. During this stage, proper initialization of bias estimate should be performed; **Tracking** has to ensure proper disturbance rejection and magnetic track following. The controller is in this state for relatively long time, so

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linear optimal control theory is used to derive the proper controller taking into account the available information about disturbances.

2.2 *Reference trajectories*

In this work, we are not dealing with seek and tracking controller. We are interested in improving the settling performance. In fact, settling stage is the stage which can benefit most from feed-forward techniques, because this is the time when transient effects are most pronounced. As mentioned before, when using feed-forward, we have to assume that we know the plant sufficiently well to certain degree. This includes the properties of the plant in frequency domain, but also the initial conditions of the plant and feedback controller at the moment when settle mode is activated. In practice, even stronger assumption can be made about the states at least for seek length bigger than certain minimum.

Conjecture 1. Every time when settle mode is activated, the speed and velocity are repeatable independent on the seek length, while the remaining states of the plant differ with negligible small values.

One may wonder if this Conjecture 1 is reasonable. Here we will give brief explanation and example why this conjecture is valid in many cases. Traditionally seeks were performed using so called *Proximate Time-Optimal Servomechanisms (PTOS)* theory. See Workman [1987], Franklin et al. [1997], Chen et al. [2006] and Fig. 1. According to PTOS,

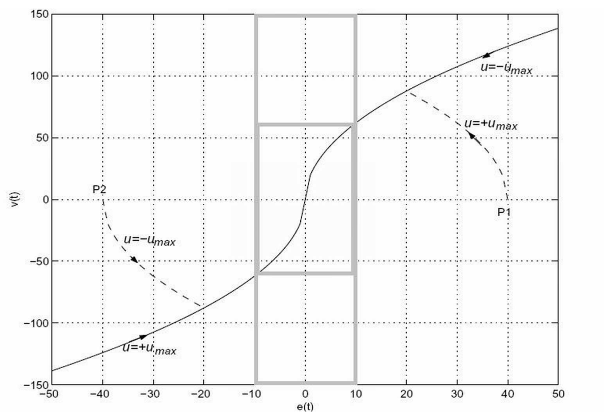

Fig. 1. Proximate Time-Optimal Servomechanisms

all seeks are performed by driving all possible initial states to certain pre-defined acceleration trajectory. The conclusion for PTOS is that seek trajectories enter the neighborhood of the target track from left or from right with same speed at same position. After that the controller mode is changed to *settle*. So Conjecture 1 holds true for PTOS if we disregard the higher order plant vibration modes.

PTOS above is used just as simplified example. It has weak points, mostly from the viewpoint of vibration and acoustics and this is exactly because it does not take into account higher order vibration modes. This is one of the reasons why it is not used in its pure form nowadays. Different companies nowadays follow different approaches, but without going into details, it is important to note that other smooth trajectories with same phase plane property as in Conjecture 1 may be designed, which do not excite the higher order vibration modes. If these reference trajectories are tracked with appropriately tuned feedback controller, then the actual plant can be designed to arrive always with same speed and position to enter settle mode and the remaining states will be negligible small because they were not excited during the seek.

2.3 *Uncompensated bias force*

As noted before, using feed-forward control requires sufficiently reliable model. Hard disk drives are subject to bias forces. These forces are nonlinear and have complex behavior such as hysteresis, direction dependence and others, see Eddy et al. [1997]. In practice they are compensated as much, as possible in a feed-forward fashion using lookup tables, but other more advanced methods are also explored by Huang and Messner [1998], Gong et al. [2002]. This compensation is not perfect and there is certain uncompensated bias, which has to be accounted by using integral control to get zero steady state tracking error. Integral control however leads to transients at first, which can be significant if the uncompensated bias value is big or if the settling controller is not appropriately tuned. The feed-forward signal can not solve problems associated with poorly known bias forces. However, it does not aggravate these issues. According to the principle of superposition, the transient effect of the uncompensated bias forces is superimposed on the transient effect of the reference and the transient of the feed-forward signals designed in this paper. Using (for example) optimal control methods, it is possible to tune the closed loop settling controller in such a way, so that the transient due to uncompensated bias only is in certain acceptable bounds when the value of the bias is also inside certain bounds. Tuning the settling feedback controller can be done only on the feedback loop by keeping down the input sensitivity function to ensure low sensitivity of the settling controller with respect to uncompensated input disturbances.

3. OPTIMIZATION OF SETTLING FEED-FORWARD WITH LEAST SQUARES AND IMPULSE RESPONSE

3.1 *Closed loop system description*

The assumed closed-loop structure is shown on Fig. 2. For

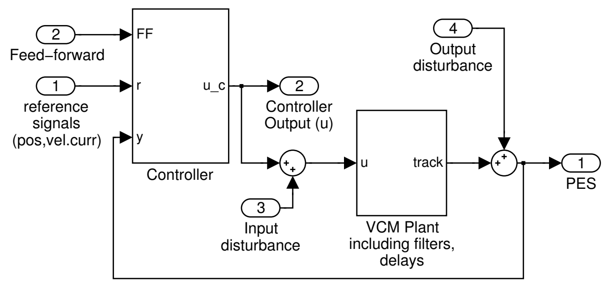

Fig. 2. Closed loop system during seek and settling mode

practical purpose we want to take into account:

(1) Controller output (u);
(2) Plant output (pes);
(3) Feed-forward input.

These transfer functions can be obtained analytically or experimentally (in frequency or time domain). The reference trajectories are generated off-line and have smooth properties, such as not to excite vibration modes during the seek and to arrive in the neighborhood of the target track according to Conjecture 1. The state observer on Fig.

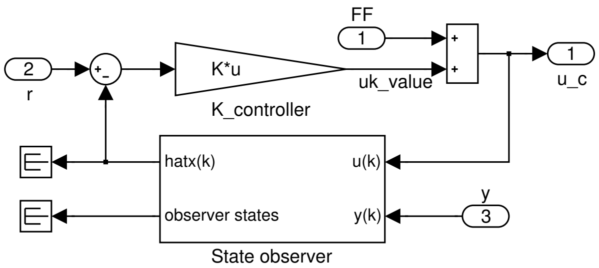

Fig. 3. State-space controller

3 may have different structure depending on the design objectives and limitations, but in all cases it uses some output feedback gains `L_observer`. The observer uses $y(k)$ and $u_c(k)$ data to calculate the state estimate $\hat{x}(k)$ or $\hat{x}(k+1)$. The gains `L_observer`, `K_controller` are changed depending among other things, on the controller mode – seek, settling, tracking and others. The feed-forward signal can be injected in many points - the position reference and the special feed-forward point after the controller gain, but before the $u_c(k)$ measurement. This is to avoid unnecessary excitation of observer dynamics with the feed-forward signal. Both points above differ only by a single gain from transfer function point of view, so theoretically it is not that important which one is used. Practically however they may have different advantages and disadvantages from implementation point of view. It is quite straightforward to obtain the MIMO transfer function corresponding exactly to the above diagrams. We are not interested in all the inputs and outputs from the Fig. 2 above. For our purpose we need only these two transfer functions

$$G_{cl} = \begin{bmatrix} G_{r_r,pes} \\ G_{r_r,u} \end{bmatrix}. \tag{1}$$

3.2 Convolution based I/O description

It is possible to calculate or measure directly the corresponding impulse responses H_{cl} of the transfer functions (1), the result is shown on Fig 4. One can represent the time dependence between r_r and the PES on one side and r_r and u on the other side using convolution of the impulse responses $H_{r_r,pes}$ and $H_{r_r,u}$ with r_r.

$$\begin{aligned} PES &= H_{r_r,pes} \star r_r \\ u &= H_{r_r,u} \quad \star r_r \end{aligned} \tag{2}$$

3.3 Matrix formulation

The calculation of the convolution sum in discrete time can be performed as follows. Construct the matrix containing the shifted impulse responses $r_r = H_{r_r,pes}$ like this:

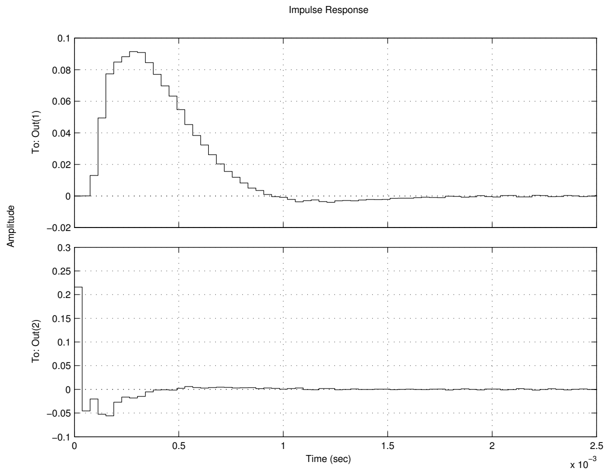

Fig. 4. Closed loop impulse responses $H_{r_r,pes}$ and $H_{r_r,u}$ corresponding to $G_{r_r,pes}$ and $G_{r_r,u}$

$$S_{pes} = \begin{bmatrix} H_1(0) & 0 & \dots & 0 \\ H_1(1) & H_1(0) & \dots & 0 \\ H_1(2) & H_1(1) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & H_1(n-2) \\ 0 & 0 & \dots & H_1(n-1) \end{bmatrix}, \tag{3}$$

where $H_1(.)$ is the corresponding element of the impulse response, the dimension of the S_{pes} matrix is $(n + N_{ff} - 1) \times N_{ff}$. The length of the impulse response is n and N_{ff} is the length of the feed-forward sequence we would like to generate. In the same way we can construct the impulse response matrix relating the reference input and the controller output $H_2 = H_{r_r,u}$.

$$S_u = \begin{bmatrix} H_2(0) & 0 & \dots & 0 \\ H_2(1) & H_2(0) & \dots & 0 \\ H_2(2) & H_2(1) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & H_2(n-2) \\ 0 & 0 & \dots & H_2(n-1) \end{bmatrix}. \tag{4}$$

It is easy to see, that using (3) and (4), the following matrix relation holds for the outputs and the inputs of the closed loop system G_{cl}

$$\begin{bmatrix} PES \\ U \end{bmatrix} = \begin{bmatrix} pes(0) \\ pes(1) \\ \vdots \\ pes(n + N_{ff} - 1) \\ u(0) \\ u(1) \\ \vdots \\ u(n + N_{ff} - 1) \end{bmatrix} = \tag{5}$$
$$= \begin{bmatrix} S_{pes} \\ S_u \end{bmatrix} \begin{bmatrix} r_r(0) \\ r_r(1) \\ \vdots \\ r_r(N_{ff} - 1) \end{bmatrix} = \begin{bmatrix} S_{pes} \\ S_u \end{bmatrix} R_r.$$

Using the matrix formulation above and assuming that we know the desired PES and U, it is possible to find the feed-forward sequence $R_r = \left[\, r_r(0) \; r_r(1) \; \dots \; r_r(N_{ff} - 1) \,\right]^T$, which would drive the outputs in PES to their desired values in some optimal way, while taking into account also the control output signal U. It sounds reasonable to assume the the number of columns in the matrix $\begin{bmatrix} S_{pes} \\ S_u \end{bmatrix}$ will be bigger than the length N_{ff} of our feed-forward sequence R_r , so the matrix problem will be overdetermined. This implies that we will have to search for some approximate solution, most probably in least square sense.

The controller output U is included in the matrix equation above, because we would like to take care of the energy and other properties of the controller output, resulting from the application of our feed-forward sequence. We may like to avoid too jumpy control output. To obtain appropriate compromise between satisfying requirements for *PES* and for U, we modify the above matrix equation and include a weighting coefficient u_{wght} for the controller output.

$$\begin{bmatrix} PES \\ Uu_{wght} \end{bmatrix} = \begin{bmatrix} S_{pes} \\ S_u \end{bmatrix} R_r = SR_r \qquad (6)$$

Up to this point, the problem can be solved as usual least square problem. In Matlab®, this can be done using the function `mldivide`.

It is possible to include and accommodate the available statistics about possible plant variations and uncertainty in the optimization by stacking more of the corresponding matrices in S vertically.

3.4 Constraining the control output

In practice we would also like to impose some additional restrictions on the matrix problem above. This transforms the problem into constrained least square problem. The corresponding Matlab function is part of the Optimization toolbox and is named `lsqlin`, which permits additional restrictions on the solutions of the form $A_{ne}R_r \leq b_{ne}$, $A_{eq}R_r = b_{eq}$, $lb \leq R_r \leq ub$, so the problem is transformed to create such matrices with appropriate structure. Using different structures, we will get solutions for the feed-forward satisfying different requirements. One example is to avoid overflows (too big values) of the controller output U. This can be represented in the following way. Define a matrix $L_u = \begin{bmatrix} S_u \\ -S_u \end{bmatrix}$ and the vector $l_u = \begin{bmatrix} Iu_{\max} \\ Iu_{\max} \end{bmatrix}$, where u_{min} and u_{max} represent tha minimum and the maximum permitted values for the controller output. The vector l_b can have more complicated shape if more fine grained constraints are required, but the principle is clear from the above example.

3.5 Constraining the plant output

Same method can be used as above. Define a matrix $L_{pes} = S_{pes}$ and the vector $l_{pes} = Ipes_{max}$. This particular shape can be used to limit the maximum value of the *pes*, which is the overshoot.

3.6 Putting it all together

All the constraint matices constructed above and if necessary more, can be stacked together to satisfy all the constraints in the same time $L = \begin{bmatrix} L_u \\ L_{pes} \end{bmatrix}$, $l = \begin{bmatrix} l_u \\ l_{pes} \end{bmatrix}$. In addition to that, the feed-forward term itself can be limited and we will assume that there are no hard constraints of type $A_{eq}R_r = b_{eq}$, so $A_{eq} = []$, $b_{eq} = []$.

Combining all together, the result is

$$R_r = lsqlin(S, \begin{bmatrix} PES \\ Uu_{wght} \end{bmatrix}, L, l, [], [], u_{lb}, u_{ub}); \qquad (7)$$

4. APPLICATION TO SETTLING TUNING

To demonstrate the above, assume, that we want to make a seek of 10 tracks. Also assume that the reference signal for this is a step somehow artificially. Assume that the seek is performed with a seek controller gains, and they switch to settle gains when the head is closer than 4 tracks. It should be clear from the above discussion, that we are interested in the closed loop system states at the moment when the controller transfers from seek mode into settle mode. It is not important how exactly these states were reached, but it is important that they are repeatable. The benefits of the switching controller are quite clear on Fig. 5 – smaller overshoot and faster settling.

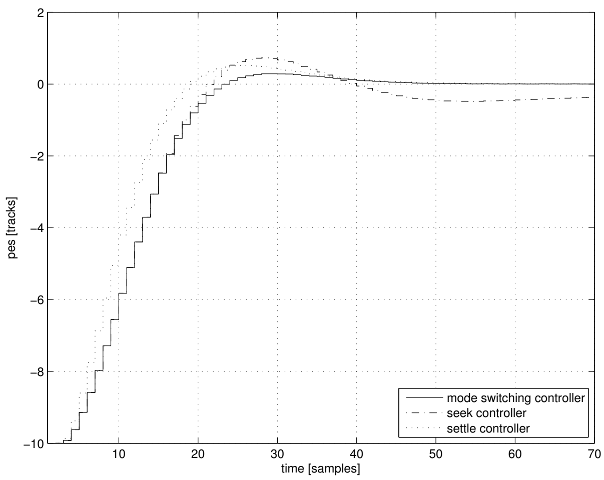

Fig. 5. Example seek with different controllers and no feed-forward

4.1 Design with exact impulse response

Now assume that we want to tune the feed-forward sequence with just 10 elements. We also want to limit the controller output u to 1 and the *pes* overshoot to 0.05 track. We also set the controller output weighting coefficient u_{wght} =0.2. The results are shown on Fig. 6 and Fig. 7. Note the practical importance of the constrained optimization. While the unconstrained least squares produces faster initial response, it is at the cost of higher controller effort.

4.2 Design with inexact impulse response

Higher controller effort may not be desirable not only from point of view of avoiding actuator saturation, but also when the plant dynamics is not completely represented by the impulse responses. To demonstrate this we design again the feed-forward sequence of length $N_{ff} = 10$, but during the design phase we use impulse response from

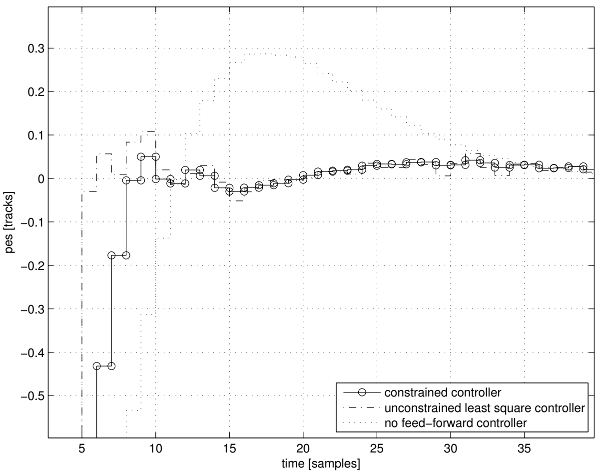

Fig. 6. Plant output with feed-forward during settle

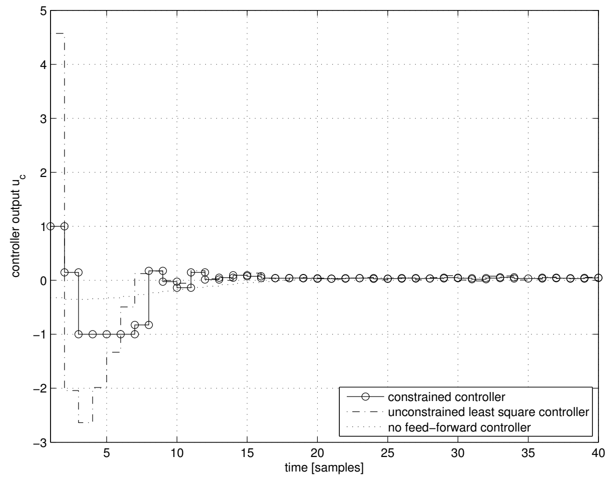

Fig. 7. Controller output $u_c(k)$ with feed-forward during settle

reduced order of the plant of dimension 3. Later the resulting feed-forward sequence is verified by simulating it on the full-scale plant of dimension 79. The resulting sequence is shown on Fig. 8. The constraints on u_c and pes

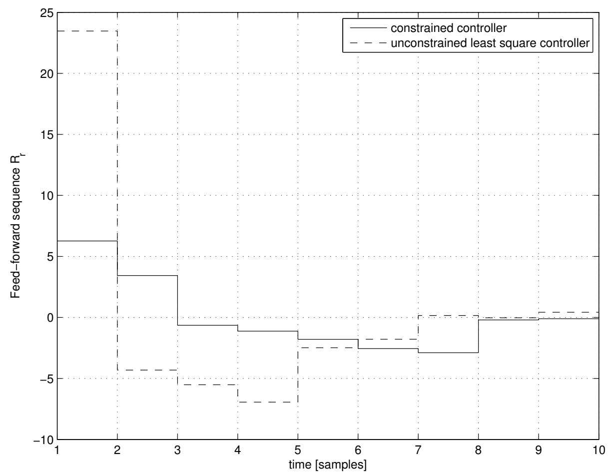

Fig. 8. Feed-forward R_r sequence generated for reduced plant

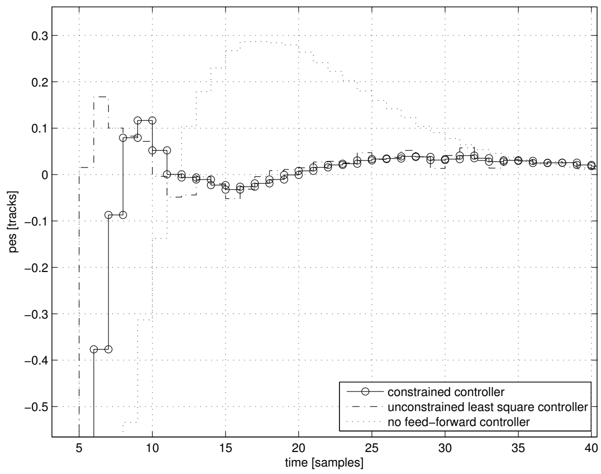

Fig. 9. Plant output with feed-forward R_r sequence generated for reduced plant

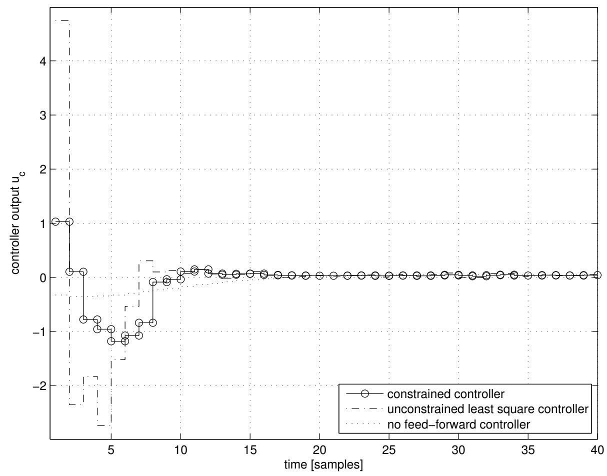

Fig. 10. Controller output with feed-forward R_r sequence generated for reduced plant

on Fig. 9 and Fig. 10 are not exactly observed compared to Fig. 6 and Fig. 7, because the impulse response used for design does not correspond exactly to the full-blown plant model used for verification, but the resulting constraints violation is quite modest.

4.3 Design with uncompensated bias force and inexact impulse response

As mentioned before, the problem of uncompensated bias forces can be solved in the feedback part of the controller using integral control. According to the superposition principle, the uncompensated bias disturbance can be regarded as acting independent of the feed-forward. How this step impacts the pes? Assume at the start of settle mode we have uncompensated bias of 10% of the maximum controller output. Looking at the Fig. 11, which was generated using unit bias step and taking into account, that we will have 10% of this superimposed on Fig. 9, we expect to have an overshoot of approximately 0.4. The plot on Fig. 12 confirms this. It is clear that the existing settling controller, which was not specifically tined to benefit from the feed-forward signal is coping quite

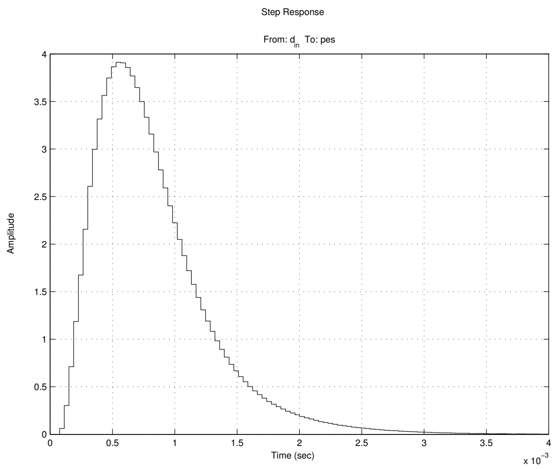

Fig. 11. Bias unit step

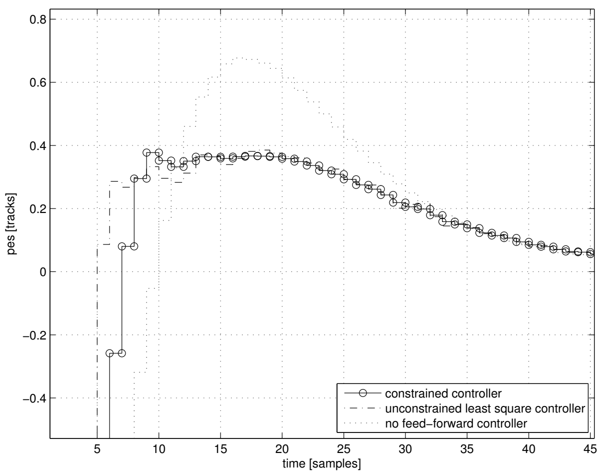

Fig. 12. Plant output with feed-forward R_r sequence generated for reduced plant and uncompensated bias

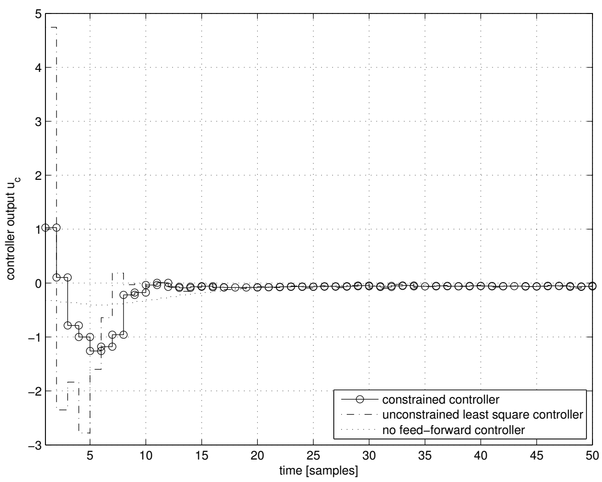

Fig. 13. Controller output with feed-forward R_r sequence generated for reduced plant and uncompensated bias

well with 10% disturbance at the plant input. This is not surprising and probably can be improved additionally by imposing stringent restrictions in the input sensitivity function to ensure faster response to bias disturbance.

5. CONCLUSION

Provided simulation results show the potential practical benefit and flexibility available when using feed-forward control to improve the settling performance. Future work should concentrate on integrating this procedure with some method to tune the settle feedback controller.

REFERENCES

D. Abramovitch, T. Hurst, and D. Henze. An overview of the pes pareto method for decomposing baseline noise sources in hard disk position error signals. *IEEE Transactions on Magnetics*, pages 17–23, 1998.

Karl Johan Astrom and Bjorn Wittenmark. *Computer-Controlled Systems: Theory and Design*. Prentice Hall, 1996.

H. W. Bode. *Network Analysis and Feedback Amplifier Design*. Van Nostrand, NY, 1945.

Ben M. Chen, Kemao Peng, Tong H. Lee, and Venkatakrishnan Venkataramanan. *Hard Disk Drive Servo Systems*. Springer London, 2006.

Kyle Eddy, John Steele, and William Messner. Bias in disk drive rotary actuators: Characterization, prediction and compensation. *IEEE Transactions on Magnetics*, 33(3): 2424 – 2436, 5 1997.

Gene F. Franklin, J. David Powell, and Michael L. Workman. *Digital Control of Dynamic Systems*. Prentice Hall, 1997.

Jian Quin Gong, Lin Guo, Ho Seong Lee, and Bin Yao. Modelling and cancellation of pivot nonlinearity in hard disk drives. *IEEE Transactions on Magnetics*, 38(5):1 – 6, 9 2002.

Yuhong Huang and William C. Messner. A novel robust time-optimal algorithm for servo systems with bias disturbance. *IEEE Transactions on Magnetics*, 34(1): 7 – 12, 1 1998.

Boris J. Lurie and Paul J. Enright. *Classical Feedback Control with MATLAB*. Marcel Dekker, 2000.

Tetsuo Semba, Matthew White, and Hiroshi Uchida. Seek trajectory generation using adaptive filtering. United States Patent 7206162, 2007. Assignee: Hitachi Global Storage Technologies Netherlands B.V.

Kazuhiko Takaishi and Shunji Saito. Seek control and settling control taming actuator resonance of hard disk drives. *IEEE Transactions on Magnetics*, 39(2):838–843, 3 2003.

Kazuhiko Takaishi and Shunji Saito. Head positioning control method for a storage device and head positioning control device. United States Patent 6995944, 2006. Assignee: Fujitsu Limited.

Brian P. Tremaine. Time optimal control of a disc drive actuator with vibro-acoustic constraints. United States Patent 5668680, 1997. Assignee: Seagate Technology, Inc.

Michael L. Workman. *Adaptive Proximate Time-Optimal Servomechanisms*. PhD thesis, Stanford University, 1987.