Reference Signal Shaping for Time-Optimal Track-Seeking in Hard Disk Drives

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***Abstract*— An algorithm for computing time-optimal reference signals for track seeking in hard disk drives is presented. A discrete-time model of the servo loop in a hard disk drive is identified using a step-based realization algorithm. Based on the identified closed-loop model, time-optimal track seeking profiles are computed by means of convex optimization techniques. Constraints on the output and on the actuator control signal are taken into account. The reference signals are implemented in an experimental hard disk drive set-up.**

Index Terms—**Dynamic Modeling, Realization Algorithm, Input shaping, Convex Optimization**

I. INTRODUCTION

Input shaping is a powerful technique to reduce residual vibrations in linear time-invariant set point control systems as shown in [1]. The targeting trajectory can be optimized (e.g. minimize targeting time or energy consumption) through convex optimization techniques. Recently, those techniques have become more interesting for real-time or nearly real-time applications as shown in [2] since the computational power of control systems has increased substantially. Commonly, finite impulse response (FIR) filters are used to pre-filter input signals as e.g. shown in [3] or [4]. Some closed-loop approaches are given in [5] where input shaping based on FIR filters is also applied to closed-loop systems. For the seeking process in a hard disk drive (HDD), often the shaped time-optimal servomechanism approach (STOS) [6] is employed. Here, mode switching control turns off the feedback during the targeting stage. In [7], the reference signal generation for constrained closed-loop systems based on piecewise affine functions of state and reference vector is shown. In [8] and [9], the reference signal generation is used for a closed-loop system although time-minimal control is not addressed. Limited results are available on performing input shaping on closed-loop systems where reference signals are computed in the presence of constraints on control and output signals. In this study, we show an input shaping technique for an HDD servo system shown in Fig. 1. The developed algorithm computes the time-optimal reference signal r given linear constraints on the output signal y_G, and the VCM control signal y_C.

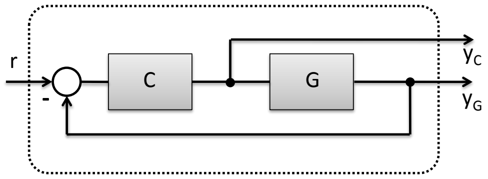

Fig. 1. Schematic of servo loop with VCM model G and controller C

II. MODLING OF CLOSED-LOOP SERVO DYNAMICS

The dynamics of the HDD servo loop were identified using a step input based realization algorithm [10]. In order to impose constraints on the output and the control signal, a single-input dual-output system as indicated in Fig. 1 was identified. All experiments were performed on a drive-level test set-up. The modified 7200 rpm HDD allowed the extraction of gray code information; position error signal and the injection of user-defined seek profiles. A relatively low bandwidth PID controller was chosen as track-following controller. Fig. 2 shows the measured response of the output y_G and the control signal y_C to a 10-track reference step. In addition, the simulated response of a 12th order estimated model is shown (black lines) and good agreement with the measurements is observed.

III. COMPUTING THE TIME-OPTIMAL REFERENCE SIGNAL

First, the constraints on y_C and y_G are defined. The latter constraint is divided into a large amplitude

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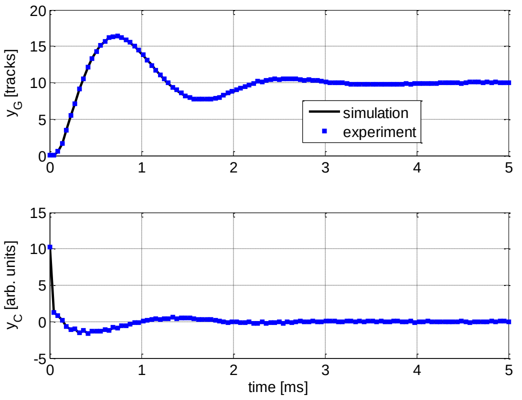

Fig. 2. Simulated and measured response of the head position (top) and control signal (bottom) to a step on the reference signal

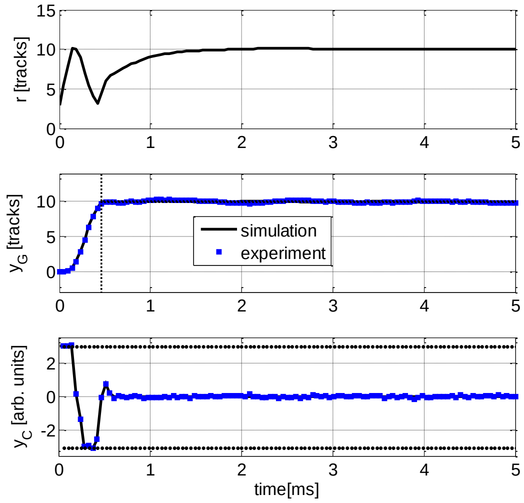

Fig. 3. Track-seek at 10 tracks with a shaped reference signal (top), head position (middle) and control signal (bottom) in simulation and experiment

constraint (virtually no constraint) during the targeting stage and a tight amplitude constraint of value ε during the settling stage. At k* samples the settling stage is reached. A feasibility check is performed by means of a linear program (LP). The LP is solved multiple times until the minimum number of samples k^*_{min} is found that are needed to reach the target y_t. The time-optimal solution of the reference signal computed by the LP is not unique. To overcome this problem and to further optimize the energy properties of the control signal, a quadratic program (QP) is solved. The QP minimizes both the control signal and the distance to the target in a 2-norm sense given the same linear constraints on control signal and output as in the LP:

$$\min_{r, y_C, y_G} \left\|\mathbf{y}_\mathbf{G}-\mathbf{y}_\mathbf{t}\right\|_{\cdot}+\left\|\mathbf{y}_\mathbf{C}\right\|$$

$$s.t. \quad \left|y_C(k)\right| \le y_{C,\max} \quad \forall k$$

$$\left|y_G(k)-y_t(k)\right| \le \varepsilon \quad k \ge k^*$$

$$\begin{pmatrix}\mathbf{y}_\mathbf{G}\\ \mathbf{y}_\mathbf{C}\end{pmatrix} = \mathbf{L}\cdot\mathbf{r}$$

where L contains the estimated dynamics of the servo loop.

IV. EXPERIMENTAL IMPLEMENTAION

The proposed algorithm from section III was applied to the 10-track step identified in section II and applied to the test set-up. Fig. 3 shows the results. Here, an arbitrary constraint of 3 control signal units was chosen to show the effectiveness of the proposed algorithm in the presence of actuator saturation. A DC bias value in the VCM control signal at the measured track was compensated. It can be seen in Fig. 3 that the output settles significantly faster compared to the step response (Fig. 2) and has no overshoot. The computed controller output looks similar to a “bang-bang” control signal which has been shown to be the time-optimal solution for a double integrator.

V. CONCLUSION

The closed-loop response of a HDD servo system was modeled using a realization algorithm. Based on the estimated model, a proposed closed-loop reference signal shaping algorithm was used to compute a time-optimal track seek. It was shown that reference signal shaping significantly reduces targeting time and residual vibrations compared to the output response obtained using standard reference signals such as steps. The seek profiles were experimentally tested in an HDD and showed excellent agreement with simulation results.

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