Active Tape Edge Position Control System

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Abstract—Lateral tape motion (LTM) is a major obstacle to using thinner tapes for greater storage capacity, because impacts between the tape and the flanges of the reel can damage the tape edges. This paper presents an active tape edge position control system employing a tilted rotary guide and photonic sensors. To avoid impacts with the flanges, the tape motion sensor should be placed as close to the reel as possible. Calibration of such a sensors must account for the changing tape path as the reel winds and unwinds. We present the calibration method, the controller design process for a complex proportional integral lead (CPIL) compensator, and the results of experiments, which show promise for reducing damage to tape from LTM at the reel.

I. INTRODUCTION

Magnetic tapes might seem to be an old-fashioned technique in the present day storage market dominated by as hard drives, DVDs, and solid state drives. However, they are still widely used for backup/restore and mass data storage applications because of their low cost per gigabyte, high reliability for a long-term storage, and high volumetric storage capacity.

One of the challenges to continuing improvement in tape storage is to lateral tape motion (LTM). LTM is the motion of a tape perpendicular to the tape transport direction, (the z-axis in Fig. 1). LTM can lead to impacts between the tape and flanges on the reel, which can damage the fragile tape edge. Since thinner tapes are more vulnerable to damage, LTM limits the reductions in tape thickness for higher volumetric capacity. Furthermore, the impact sends a high frequency wave down the tape, which can disrupt the head tracking servo.

Dynamic simulations of LTM dynamically [1], [5] have been employed for improve the design of the tape path. There has also been work to control the lateral motion of moving webs [2]. However, prior efforts on controlling LTM have focused on motion near the read/write head [6].

The focus of this paper is to design an edge position control system employing a tilted rotary guide as actuator and photonic probes as sensor. To avoid a change of the angle between rotary guide and tape as the reel winds and unwinds and therefore of the system dynamics, a fixed post is placed between the actuator and the reel (Fig. 1). In prior work the LTM was measured and controlled close to the actuator at position 1 [6]. However, for more better control at the reel where flange impacts can occur, the sensor should be positioned as close to the reel as possible. Therefore, in this work we placed a second sensor between the fixed post and the reel.

Ordinarily, the photonic sensor measures only the changes in height in the z-direction at a fixed position in the y-direction. However, at this second location the tape path also moves in the y-direction as the reel winds and unwinds. Since the sensor output signal is not constant if the tape edge moves in the y-direction even with constant z-position, a calibration of the sensor in both the z- and y- directions is necessary.

The controller design uses the novel complex proportional integral lead (CPIL) compensator [6], for which this work represents the first reported experimental implementation.

This paper is organized as follows. Section 2 introduces the hardware configuration of the control system. Section 3 shows the controller design process using sensor 1 for feedback, shown in Fig. 2. Section 4 discusses the sensor calibration method and the controller design process using sensor 2 for feedback. Experimental results for the closed loop of the active tape edge control system also appear in section 4. Section 5 contains conclusions and discusses potential future work.

II. TAPE TRANSPORT SYSTEM

Figs. 2 (a)-(c) shows the tape transport system with rotary tilted guide actuator. The actuator of Fig. 2(a) is a rotary voice coil motor of a disk drive to which a tilted guide is attached. Rotation changes the tilting angle which causes the tape to move laterally. The tape edge sensors are MTI-2000 Fotonic Sensors from MTI Instruments Inc. Both sensors are installed on z-axis stages to adjust their height.
A movable post located between the reel and the fixed post is used to adjust the tape in the y-direction for calibration. We used LabVIEW from National Instruments, SigLab from Spectral Dynamics, and MATLAB from MathWorks for data acquisition and controller design.

Fig. 3 (a) shows raw data from the first sensor as the reel winds without activating the rotary guide. There are two large jumps in the LTM. Fig. 3 (b) shows the power spectrum which has two prominent peaks at $15\text{Hz}$ and $50\text{Hz}$. Fig. 3 (c) shows the histogram of this data where LTM changes up to $30\mu m$. Since the clearance between tape and flanges on each side is $25\mu m$ it is very likely that the tape edge is hitting the flanges.

III. CONTROLLER DESIGN FOR SENSOR 1

A. System Identification

1) Initial Model: We extracted the characteristics of the integrated active tape edge control system at the operating point $4\text{m/s}$ and a tension of $1\text{N}$ using a SigLab dynamic signal analyzer. The frequency response data was acquired using a random signal input with frequency range up to $1\text{kHz}$ as input and the first sensor reading as output. Six groups of system identification experiments were conducted (Fig. 4). The following second order transfer function was fitted to these frequency responses.

$$P_{1e}(s) = \frac{18515}{s^2 + 29.9s + 529}.$$  

(1)

The solid black curve in Fig. 4 indicates that this model captures the most significant dynamics of the system.

2) First Controller Design: To design the first controller, we used continuous-time loop shaping and then converted the controller to discrete-time with sampling time of $390.63\text{microseconds}$ and frequency prewarping. Considering the power spectrum of Fig. 3 (b) we chose the open-loop $0\text{dB}$ crossover frequency at twice the first peak frequency (about
Fig. 4. Bode Diagram of the System Characteristics from Online System Identification.

Fig. 5. Open-Loop frequency response of the first controller.

150 rad/sec), for good disturbance rejection. The first controller consists of a proportional-integral (PI) controller and complex lead compensator (complex lead) with maximum desired phase lead of 0.9° at 150 rad/sec with damping ratio of 0.9 [4]. Eqn (2) shows the transfer function. The usage of the additional complex lead increases the phase margin at the 0 dB crossover frequency from 8° to 60° as shown in Fig. 5.

\[ C_{1e}(s) = 1.2 \left( \frac{s + 10}{s} \right) \left( \frac{2.344s^2 + 413.4s + 2.25 \times 10^4}{s^2 + 413.4s + 5.274 \times 10^4} \right) \]  

3) Refined Model For Sensor 1 System: After implementing the first controller on the system, better frequency response data could be obtained using the frequency response of the transfer function, \( T_1 \). The frequency response data was acquired again using a random signal with frequency range up to 1 kHz as input and first sensor reading as output. We then derived a better set of frequency response data for the sensor 1 open loop, \( P_1 \), using the relations in Eqn. (3) and Eqn. (4).

\[ T_1(s) = \frac{Y(s)}{R(s)} = \frac{P_1 C_{1e}}{1 + P_1 C_{1e}}. \]  

\[ P_1 = \frac{T_1}{C_{1e}(1 - T_1)}. \]  

Fig. 6. Block Diagram of Closed-Loop for Sensor 1 with First Controller.

The Bode magnitude plot of \( P_1 \) derived from the new frequency response data agrees well with the one of model, \( P_{1e} \), in the frequency range of interest up to 1000 rad/sec, as shown in Fig. 7. However, the measured phase and the phase of the model are considerably different at low frequencies, probably due to a lack of phase information in the measurement data. The controller can be now redesigned using the more accurate system identification, although phase values in the low frequency range might not be reliable.

B. Improved Controller

Using the more reliable frequency data, it is possible to design a more aggressive controller. Considering the power spectrum Fig. 3 (b) we now place the 0 dB crossover frequency at twice the second peak frequency, (about 600 rad/sec) for good disturbance rejection. The improved controller, \( C_1 \), also uses a PI and a complex lead compensator. The maximum desired phase lead is 65° at 600 rad/sec with damping ratio of 0.7 (Eqn. 5). The phase margin is 40° as shown in Fig. 8.

\[ C_1(s) = 21.5 \left( \frac{s + 10}{s} \right) \left( \frac{2.374s^2 + 1294s + 3.6 \times 10^5}{s^2 + 1294s + 8.548 \times 10^5} \right) \]  

Fig. 7. Bode Diagram of Refined Model for Sensor 1.
C. Limited Performance with Sensor 1

Fig. 9 (a) and (b) show that the closed-loop system employing the refined controller, $C_1$, significantly reduced the LTM to about 10 $\mu$m at sensor 1. However, the data from sensor 2 in Fig. 9 (a) indicates that the LTM is still relatively large at the second location between the fixed post and reel. The LTM at the reel has not been significantly corrected by controlling the LTM at position 1.

The ideal location for a sensor is therefore at the point where the tape winds onto the tape pack. However, the change in radius of the pack limits how close a photonic probe can be to the reel. The gap between two probes of the sensor is about 2.2 mm. Thus, the best location for sensor 2 between the post and the reel is very near the post. The red curve on Fig. 9 (a) shows the output of sensor 2 at this position. It is clear that the sensor output changes as the tape moves in the y-direction as well as in the z-direction. Therefore, additional calibration is necessary to use the probe in this position for feedback.

IV. CONTROLLER DESIGN FOR SENSOR 2

A. Calibration of Sensor 2

The calibration process has two related operations. One is to determine an appropriate height of sensor 2, so that the sensor output will be in the linear range regardless of the tape position in the y-direction. The other is to determine the offset in the linear range as a function of the radius of the pack when the tape moves.

Before verifying the height of the sensor it is necessary to emulate the motion of the tape in the y-direction, because the tape itself has a 10 $\mu$m variance in the edge. The movable post was used to push the tape in the y-direction to emulate the changes in the radius while the tape is not moving in the x or z directions.

The pack radius can change from 32.0 mm to 44.5 mm without touching the probes. The output of sensor 2 was measured at each of nine positions of the movable post corresponding to known pack radii. The height of probes was varied at each of these post locations to determine the linear range. The linear range overlaps by 20 $\mu$m across the nine radial positions. The middle of that range was chosen to be the height of sensor 2.

The offset values at each radius are used to calibrate sensor 2. However, the calibration function must be expressed as a function of time because the tape drive can not provide the radius information in real time. So, we estimated the radius as a function of time using the initial known radius, the speed of the tape, and the thickness of the tape. Eqn. (6) expresses time as function of radius, speed and thickness.

$$t = \frac{\pi}{v d} \left( R(t)^2 - R_0^2 \right),$$

where $v$ is tape speed (4 m/s), $d$ is tape thickness (8.95 $\mu$m), and $R_0$ is the starting radius.

We then calculated the times at which the pack radius would be equal to the radii corresponding to known pack radii. The height of probes was varied at each of these post locations to determine the linear range. The linear range overlaps by 20 $\mu$m across the nine radial positions. The middle of that range was chosen to be the height of sensor 2.

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We then calculated the times at which the pack radius would be equal to the radii corresponding to the measurements. To determine the offset values at other times, we fit a 3rd order polynomial to the offset vs. time points. Eqn. (7) shows one of the calibration functions when $R_0$ is 32056 $\mu$m.

$$Cal(t) = -1.065 \times 10^{-5} t^3 + 1.363 \times 10^{-3} t^2 + 1.641 \times 10^{-2} t - 2.489.$$  

Fig. 10 shows the curve fit relating time to output voltage from the sensor 2 for 0 vertical displacement in the same $R_0$. 

2656
B. System Identification

The transfer function, $P_2$, shown in Fig. 11, is the transfer function from the actuator input to the sensor 2 output. Knowing $P_2$ is essential for compensator design for controlling the LTM at sensor 2. To identify $P_2$, we used the closed-loop topology depicted in Fig. 11. Eqn. (8) shows the relation between $T_2(s) \triangleq \frac{Y_2(s)}{R(s)}$ and other known transfer functions. Fig. 12 shows the Bode diagram to the measured frequency response for $P_2$.

$$P_2 = \frac{T_2}{C_1(1 - T_1)} \quad (8)$$

Fig. 11. Block Diagram with Closed-Loop for Sensor 1 and Sensor 2 for System Identification of the Model for Sensor 2.

Fig. 12. Bode Diagram of Frequency from Actuator to Sensor 2, $P_2$.

C. Controller Design

$P_2$ loses more phase at frequencies over 400 rad/sec than $P_1$. For this reason, we used a complex proportional-integral-lead (CPIL) compensator [3] for the controller instead of a PI plus complex lead compensator. Eqn. (9) shows the structure of the CPIL transfer function, and Fig. 13 shows a comparison between similar CPIL and PI and complex lead.

$$C_{cpil}(s) = \frac{s^2 + 2\zeta\omega_z s + \omega^2_z}{s(s + p)} \quad (9)$$

where

$$\omega_z = \omega_m \left( -\zeta\tan(\phi_m) + \sqrt{\zeta^2\tan^2(\phi_m) + 1} \right), \quad (10)$$

$$p = \omega_m \sqrt{\frac{1 + \sin(\phi_m)}{1 - \sin(\phi_m)}}, \quad (11)$$

The phase contribution at $\omega_m$ is $\frac{3\phi_m}{2} - 45^\circ$. The angle must satisfy $0 < \phi_m < 90^\circ$. The zeros of this compensator are complex when $\zeta < 1$.

The CPIL has several advantages relevant to this design. The CPIL has a wider phase peak, and the slope of the compensator is lower at 400 rad/sec. First, these provide a higher $-180^\circ$ crossover frequency for better gain margin. Second, this means open-loop slope at the 0 dB crossover is steeper, which gives better disturbance rejection below 400 rad/sec. Third, the CPIL is only second order, while the PI plus complex lead is third order.

The final CPIL compensator with damping ratio 0.7 and provides $80^\circ$ at 400 rad/sec, is

$$C_2(s) = 169 \left( \frac{s^2 + 46.43s + 1100}{s(s + 6868)} \right). \quad (12)$$

The corresponding $\phi_m$ is $83.3^\circ$.

Fig. 13. Comparison of CPIL and PI plus complex lead compensators. Solid: CPIL with damping ratio 0.7 applying $80^\circ$ phase lead at 400 rad/sec. Dashed: PI ($\frac{(s + 10)}{s}$) plus complex lead damping ratio 0.7 providing $80^\circ$ phase lead at 600 rad/sec.
loop, shown in Fig. 15, indicates there is about 6 dB attenuation of disturbances at 25 Hz (157 rad/sec).

D. Experimental Results

Since the gap between the flanges on the reel is 12.7 mm and standard tape width is 12.65 mm (Fig. 1) the tape cannot move up or down 25 μm on each side without hitting the flange. The data from Fig. 3 (a) suggests that the LTM at location 2 close to the reel is about 30 μm. After activating controller $C_2$ Fig. 16 shows the LTM at this location decreases to about 10 μm, a reduction of more than 65%.

V. CONCLUSIONS AND FUTURE WORK

This paper presented an active tape edge position control system to compensate for the lateral tape motion (LTM) near the take up reel in a tape transport. It showed the modeling and the design of the controller using frequency response data obtained from a closed-loop system. For sensing the LTM near the reel a novel calibration method was employed to account for change in the horizontal tape position relative to the sensor probes as tape winds and unwinds from the reel.

Another innovation was the use of the recently developed complex Proportional-Integral-Lead (CPIL) compensator for closing the loop using sensor 2. The CPIL provides several advantages with respect to a standard PI plus lead compensation, including wider phase peak and lower slope at the crossover frequency. The implemented control system showed significant reduction of LTM at the sensor near the reel.

For future work we intend to estimate the tape position at the reel by linearly extrapolating measurements from the two positions sensors to reduce LTM at the reel.

VI. ACKNOWLEDGMENTS

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REFERENCES