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Feedback control of transport systems in tape drives without tension transducers☆

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ABSTRACT

Accurate control of tape tension and velocity will be required in advanced tape drives, as tape thickness is reduced and track density is increased towards target tape capacities of 100 TB and beyond. In this paper, a novel method is introduced for the feedback control of the tape transport in tape drives without tension transducers. The method relies on estimating tape tension variations from the difference of the measured lateral positions of servo read elements on adjacent servo bands. Furthermore, a technique for the suppression of periodic tape tension disturbances, which are caused by reel eccentricities and other once-around effects, is developed and presented. The technique uses a time-varying narrow-band bi-quad filter with variable center frequency to suppress the slowly time-varying disturbances. To avoid the noise enhancement that would occur when the disturbance frequency moves outside of the loop bandwidth, the filter parameters are determined by H_∞-norm minimization. Using the proposed tape transport system, we experimentally demonstrate a reduction in the standard deviation of the tension of about 40% and a reduction in the standard deviation of the velocity of about 23% with respect to state-of-the-art tape drives.

1. Introduction

Magnetic tape systems are currently the most cost-effective means of storing large volumes of data owing to their very low power consumption and low total cost of ownership. For tape to remain competitive, it is essential to maintain its cost advantage by continuing to scale tape capacity. State-of-the-art commercial linear tape drives provide cartridge capacities of up to 15 TB of uncompressed data. The Information Storage Industry Consortium (INSIC) 2015–2025 tape roadmap [1] projects the continued scaling of the tape-cartridge capacity at historical rates of roughly doubling capacity every two years over the period of 2015 to 2025.

Historically, capacity scaling has been enabled predominantly through areal density scaling. However, increasing the tape length by reducing its thickness has also made an important contribution. In the past, areal density gains in tape systems have been achieved by increasing the linear density and the track density by similar scaling factors. Recently however, areal density gains have been achieved predominantly through track density scaling [2]. In the future, the INSIC Tape Roadmap projects a continuation of the reliance on track density scaling to drive areal density gains [1]. In addition, the roadmap projects that the tape thickness will be reduced by about 4% a year [1]. Current state-of-the-art tape drives operate at a track density of about 18,900 tracks per inch and use a tape that is only 5 microns thick. By 2025, the track density is projected to be scaled to over 72,000 tracks per inch, corresponding to a track pitch of 360 nm, and the tape thickness is projected to be scaled to below 3.5 microns [1].

Improved tape transport control in advanced drives will be a key enabling technology for the continued scaling of the tape cartridge capacity. First, improved tension control during tape transport is key to enabling the use of thinner, more fragile tape. In addition, improved tension control also reduces track mis-registration errors resulting from tension-induced tape width variations and hence also enables the use of higher track densities.

The tape transport problem in tape drives for data storage is related to the transport of webs, as found, for example, in the manufacturing of paper, plastic and sheet metal, and described in [3]. The transport system of a tape drive has the task of determining the motor currents that are applied to control the motion of the tape as it is streamed over the head during write, read and seek operations. To achieve reliable recording performance, it is important to minimize the fluctuations of the tape velocity and of the tape tension around constant predetermined values. However, as the radius and the inertia of each reel vary slowly during transport, and air entrainment affects the value of

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the tape spring constant, the dynamics of tape transport are time-varying and nonlinear.

A state-space formulation of the tape transport system with a controller design based on the Sequential Loop Closing (SLC) technique is presented in [4], whereas a control system design obtained via the Linear Quadratic Regulator (LQR) method is proposed in [5]. The phenomenon of air entrainment, whereby friction draws a thin layer of air into the take-up reel, causing several layers of tape to be wound loosely, has been extensively studied in, e.g., [6,7]. As the tape velocity increases, air entrainment increases the effective length of the tape path, thus lowering the spring constant of the tape and hence the resonance frequency of the transport system. Here, the identification method of [8] is extended to accurately characterize the behavior of the tape spring constant over the entire length of tape.

State-of-the-art tape drives focus mainly on improving velocity control, as in [9], where the control system for each reel consists of a feedback controller based on sensor fusion for tape-velocity control and a feedforward controller for tape-tension control. The trend of decreasing tape thickness, however, has created a need to improve the performance of tape transport systems further, and in particular to improve tension control. Closed-loop controllers for transport systems with time-varying characteristics are presented in [10–13], where the control system is transformed into separate velocity and tension loops using decoupling techniques, and observer-based controllers are adopted in the case where no tension measurements are available. Such techniques, however, rely on high accuracy in the knowledge of the tape transport characteristics, which is difficult to achieve in practice.

The main contribution of this paper is a method to allow feedback of tension without requiring additional transducers in the tape path for tension measurement. Rather, the tension is estimated by expressing the tension deviation from the nominal value as a function of the difference of the head lateral position estimates that are obtained by reading servo patterns written on adjacent servo bands. Clearly, control schemes that do not require tension transducers are desirable for low-cost commercial drives. The achieved performance is illustrated by experimental results in terms of tape tension and velocity standard deviations. Furthermore, the time-varying characteristics of the tape transport system are taken into account to design a velocity and tension feedback control system using p-type controllers that depend on the longitudinal tape position. Analytical expressions are given for the controller gains, for which all transfer functions become essentially independent of the longitudinal position [14]. The proposed methodology is essential for improving the closed-loop performance of the system as it avoids the need for the accurate knowledge of the tape transport characteristics. To the best of our knowledge, a feedback tape transport control system that leads to an improved accuracy of both tape tension and velocity without tension transducers is experimentally demonstrated for the first time.

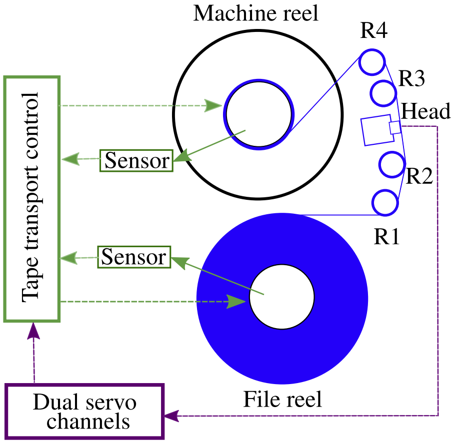

Fig. 1. Block diagram of the tape transport system.

While operating in the steady-state velocity mode, periodic variations of the tape tension around the reference value, also called once-arounds, are induced by the reel eccentricities. In tape transport, this problem is particularly serious when the reel rotation frequencies approach the resonance frequency determined by the tape path. Although the adverse effects of tape tension variations are well acknowledged and understood, no cost-effective method has so far been developed for the suppression of these periodic tension disturbances with slowly time-varying frequency. A feedforward control that addresses the time-varying reel radius to regulate the tension was presented in [15]. Suppression of the time-varying disturbances by feedforward control alone, however, is difficult to achieve in practice without perfect knowledge of the tape system parameters. Adaptive control for disturbance suppression is proposed in [16], assuming the tape spring constant is not time varying in steady state. An H_∞-controller was described in [17] to compensate for a purely sinusoidal tension disturbance in a flexible web-winding system.

A further contribution of this paper is a method for the suppression of periodic tension disturbances in tape drive systems. A time-varying narrow-band biquad filter with variable center frequency is introduced in the feedback loop to suppress the periodic disturbances with slowly time-varying frequency that are originated by the once-arounds [18]. Typically, to suppress periodic disturbances a peak filter is used with a transfer function that is the inverse of a notch filter transfer function. To avoid the noise enhancement that would occur when the disturbance frequency moves outside of the loop bandwidth, here the parameters that determine the zeros of the filter are yielded by H_∞-norm minimization. Performance results from an experimental tape transport demonstrate the efficacy of the proposed methodology.

2. Tape transport system

The block diagram of the tape transport system is shown in Fig. 1. For motion in the forward direction, the tape is transported from the file (or outboard) reel, acting as a supply reel, to the machine (or inboard) reel, acting as a take-up reel, through the tape path consisting of tape guide rollers R1 to R4 and the read/write head. In the reverse direction, the roles of the file reel and machine reel are reversed. Read/write operations are performed with the tape in contact with the read/write head that also hosts dedicated servo reader elements. In tape systems, servo bands are prewritten on the tape during tape manufacturing. For example, in current Linear Tape Open (LTO[1]) drives, five dedicated servo bands are recorded onto the medium straddling four data bands, as shown in Fig. 2. Each servo band contains timing-based servo (TBS) frames, which are designed to provide essential information for the track-following and tape transport servomechanisms. The servo information, including estimates of the tape velocity, tape longitudinal position (LPOS), and head lateral position, is obtained from measurements of the relative timing of the dibit bursts in the read-back TBS signal [19]. In tape systems, two dedicated servo readers are normally present in a head module, as also illustrated in Fig. 2, that provide servo signals, from which servo information is obtained by two servo channels, usually referred to as dual servo channels. A detailed description of the operation of highly accurate dual synchronous servo channels is given in [20]. The estimates of the head position are provided to the track-following servomechanism, whereas the estimates of the tape velocity and LPOS are supplied to the tape transport system. Hall sensors providing a measure of the rotation rate of each reel are used to obtain additional secondary tape velocity information from the individual reels. The secondary tape velocity information may be used for closed-loop tape transport control in the absence of valid parameter estimates from the dual servo channels, for example during initial tape

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[1] Linear Tape-Open and LTO are trademarks of HP, IBM Corp. and Quantum in the U.S. and other countries.