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Near-optimal tape transport control with feedback of velocity and tension

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Abstract: With the increasing recording areal density and volumetric density targeted by magnetic tapes, high-performance tape transport is of fundamental importance to achieve the required reliability in tape storage systems. In this paper, the time-varying characteristics of tape transport 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 longitudinal position. Experimental results are presented for a tape system where feedback of tension is provided by a tension sensing roller.

Keywords: Tape transport, velocity control, tension control.

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1. INTRODUCTION

Demand for cost effective storage solutions is being driven by the explosive growth in the rate at which data is being created. Tape systems are well suited to address this demand due to their low total cost of ownership compared to other storage technologies. However, the continued success of tape technology critically depends on maintaining its cost advantage over other storage technologies, and hence it is necessary to continue scaling the cartridge capacity and hence the cost per GB of tape systems at least as quickly as competing technologies such as hard disk drive (HDD) storage systems. Historically the capacity scaling of tape systems of roughly 40% compound annual growth rate (CAGR) has been enabled through continuous incremental improvements in track and linear densities, format efficiency and increases in tape length. Although the majority of capacity improvements have been achieved through areal density scaling, tape length increases that are enabled by thinner tape media have also been an important contributor. For example the capacity of the linear tape open (LTO[1]) format was increased from 200 GB in generation 2 to 6 TB in the latest generation 7 format. Approximately 1.58× of this 30× capacity increase was enabled by an increase in tape length from 609 m in generation 2 to 960 m in generation 7. This increase in tape length required a reduction in tape thickness from 8.9 μm in generation 2 to 5.6 μm in generation 7. The International Storage Industry Consortium (INSIC) 2012 Tape Technology Roadmap projects that in the future this trend will continue with tape thickness projected to reach 4.0 μm by the 2022 time frame (INSIC (2012)).

The tape transport problem is related to the transport of webs, as found for example in the manufacture of paper, plastic, and sheet metal, as described in Young and Reid (1993). Because the radii and inertia of the reels vary slowly during transport, and air entrainment affects the value of 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 Mathur and Messner (1998), whereas a control system design obtained via the Linear Quadratic Regulator (LQR) method is proposed in Panda and Engelmann (2002). 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., Keshavan and Wickert (1997); Mathur and Messner (1997); Cherubini et al. (2013). 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. Designs of closed-loop controllers for tape transport systems with time-varying characteristics are presented in Lu and Messner (2001a,b); Baumgart and Pao (2003); Lin (2003).

The tape transport, also known as reel-to-reel, control system of a tape drive has the task of determining the input motor currents that are applied to control the tape motion as the tape is streamed over the head during write and read operations. To achieve reliable recording performance, it is important to keep as small as possible the fluctuations of the tape velocity and of the tape tension around constant predetermined values. Recent work on reel-to-reel control has focused mainly on improving velocity control, as in Pantazi et al. (2014), where the control system for each reel consists of a feedback controller for tape-velocity control and a feedforward controller for tape-tension control. The trend of decreasing tape thickness, however, has created a

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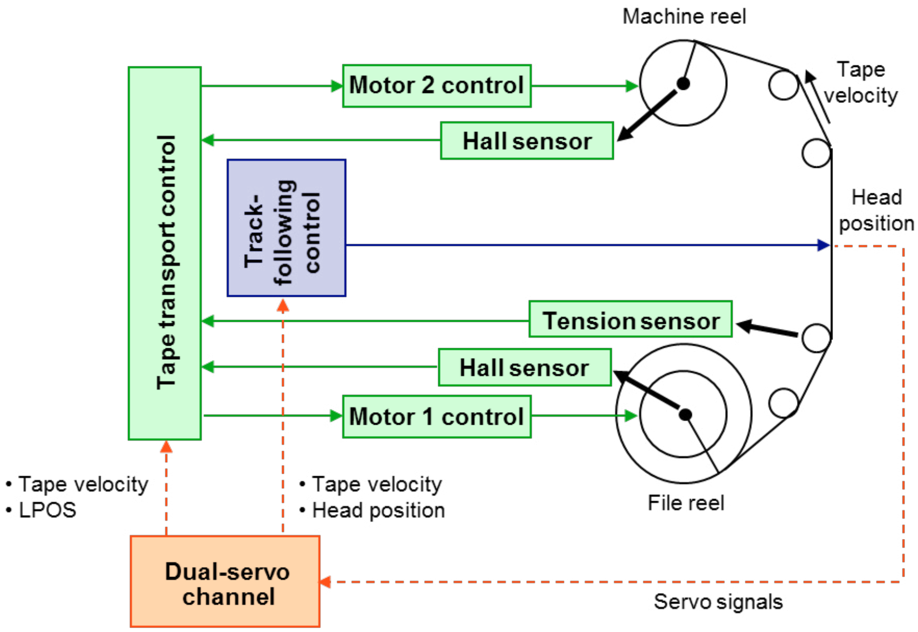

Fig. 1. Block diagram of tape transport and track-following servomechanisms.

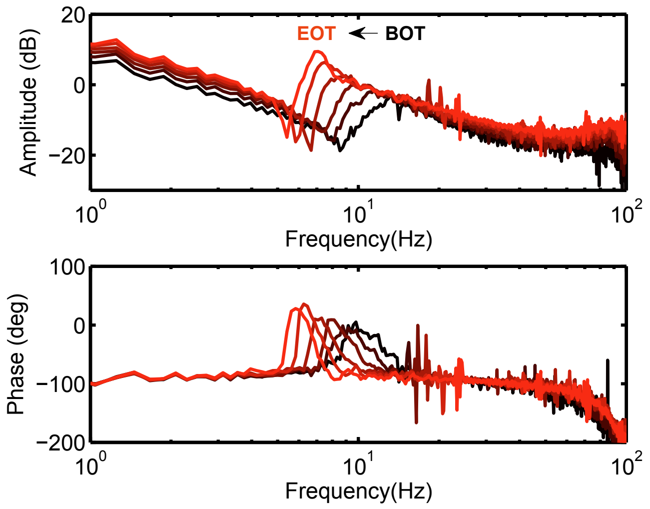

Fig. 2. Frequency responses of file-reel motor current to file-reel velocity for various tape longitudinal positions from beginning-of-tape (BOT) to end-of-tape (EOT).

need to improve the performance of the reel-to-reel control system and in particular, to improve tension control.

In this paper, 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 longitudinal position. Experimental results are presented for a tape system where feedback of tension is provided by a tension sensor incorporated into the tape transport system.

2. TAPE TRANSPORT SYSTEM MODEL

The block diagram of the tape transport and the track-following control systems in a tape drive 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 rollers R1 to R4 and the read/write tape head. In the reverse direction, the roles of the file reel and machine reel are reversed. Read/write operations are performed in contact with the tape by the read/write elements for the servo and data channels that are hosted in the tape head. A dual synchronous servo channel provides estimates of the primary tape velocity, tape longitudinal position (LPOS), and head lateral position, which are derived from servo signals that are generated by two servo readers in the tape head. The estimates of tape velocity and head position are provided to the track-following servomechanism, whereas the estimates of 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 to achieve proper tape transport operation in the absence of valid parameter estimates from the dual servo channel, for example during tape acceleration, or to enhance tape transport performance. Furthermore, estimates of the tape tension are provided by two strain-gauge sensors that are mounted on two of the rollers in the tape path.

As described in detail in Cherubini et al. (2013), the mechanical behavior of the system is governed by second-order differential equations, which are obtained by equating the change in angular momentum to the sum of torques for each reel. In state-space form, the equations at a certain