EFFECTS OF OPERATING PARAMETERS ON LATERAL TAPE MOTION FOR MAGNETIC TAPE IN AN ADVANCED LINEAR TAPE DRIVE

A Thesis

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By

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ABSTRACT

The drive for increased storage capacity in today's magnetic tape cartridges has created a continuing need to improve the understanding of the tribological performance of magnetic tape. One important area of ongoing tribological research is lateral tape motion (LTM). Excessive LTM can cause problems with track misregistration where written data cannot be read back accurately. Tape and drive manufacturers are increasingly challenging the tolerances of LTM in their quest for increased data storage. While the importance of studying LTM is known, many of the sources and reasons for increases in LTM are unknown. This provides the motivation for the work presented.

Several studies are completed to identify sources and contributions to increases in LTM. The first such study is a baseline look at different types of tape under nominal conditions. Six different types of tape are used throughout the studies. These include commercially available metal particulate (MP) tape, an experimental thin MP tape, and four advanced metal evaporated (AME) tapes. A multitude of different operating parameters were identified for analysis in hopes of learning more about their role in LTM generation. Some of these parameters include operating tension and speed, as well as head and bearing setup. Additionally, tape quality metrics such as edge quality and tapes from staggered packs were studied to determine their contributions to LTM.

The results show that all of the tapes with the exception of a negatively cupped

AME tape perform well at nominal operating conditions. Tension was shown to significantly impact LTM at low settings in some tapes due to a lack of surface roughness and tape edge pinning. Operating speed was shown to have a negligible impact on LTM. Changes to the head zenith angle and wrap angle of the tape appear to have a significant impact on LTM generation, while the air pressure used in the tape transport bearings does not. Staggered tape packs and a bearing placement study show a minimal increase in LTM at the head when changes occur "downstream" in the tape path. The results from these studies allow for conclusions to be drawn, as to which tapes and settings optimize performance based on minimizing LTM.

Dedicated to my family and friends

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ABBREVIATIONS

List of most commonly used abbreviations in this thesis.

LTM	Lateral tape motion
LTM_P	Lateral tape motion physical
LTM_M	Lateral tape motion magnetic
PSD	Power spectrum density
MP	Magnetic-particle
AME	Advanced metal evaporated
DLC	Diamond-like carbon
HCA	Head cleaning agent
PABs	Porous air bearings

CHAPTER 1

INTRODUCTION

Magnetic storage is needed for a wide variety of applications including data-processing, audio, and video. The devices used to create this magnetic storage take a wide variety of forms that vary from floppy disks, rigid disk drives, cds, and magnetic tape. In all of these devices magnetic recording and readback occurs through the relative motion between a read-write magnetic head and a magnetic medium. The reading and writing of data utilizes binary coding and the detection of flux direction that represents data in bits of zeros and ones.

The research presented in this thesis focuses on the storage medium of magnetic tape. Magnetic tape has played a critical role in the data storage industry and is particularly valuable for backing up the digital information of companies. Tape provides a high recording density at cost effective prices, while maintaining a reliable performance. However, in order for magnetic tape to remain a viable solution for meeting industry's growing need for data storage capacity, improvements must be made in recording density and data access rates. These improvements will require the use of thinner tapes, narrower data tracks, and faster speeds in tape drives. The implementation of these improvements will present several engineering challenges to tape and tape drive manufacturers.

One of these engineering challenges, which presents the motivation for the work contained in this thesis, is lateral tape motion (LTM). LTM is the up and down motion of the magnetic tape, as it moves linearly through the tape drive. Significant LTM can cause problems with accurately reading back written data tracks, as the excessive motion may move the tape far enough so the written signal cannot be read. This problem is only magnified with the necessary improvements, such as narrower data tracks, needed to increase storage capacity.

Chapter two of this thesis looks at the effects certain operating parameters and types of tape have on LTM generation. Some of the operating parameters examined include operating tension and speed, head zenith angle, wrap angle, the position of guides and tape quality. The study documented in chapter three utilizes a new LTM measuring technique and focuses in on the impact tension and speed have on LTM in different types of tapes. Chapter four provides a summary of the results.

CHAPTER 2

EFFECTS OF DIFFERENT MAGNETIC TAPES AND OPERATING PARAMETERS ON LATERAL TAPE MOTION IN A LINEAR TAPE DRIVE

2.1. Motivation

The most advanced magnetic tapes currently available in the linear tape-open (LTO) format are generation three tapes, which offer data storage capacities of 400 GB and 800 GB compressed (see www.imation.com and www.quantum.com). To achieve multi-terabyte storage capacity without increasing cartridge size, future-generation linear tape systems will require the use of thinner magnetic tapes with smaller track width and pitch (distance between adjacent tracks) and higher tape speed to achieve acceptable data rates (Bhushan, 1996, 2000). Also, new magnetic tapes are being developed for high-density magnetic recording applications (Mee and Daniel., 1996, Luitjens et al., 1996). The future tapes must be smoother to provide lower head-tape spacing required to maintain good signal-to-noise ratio and resolution at higher track densities (Bhushan, 1996). For high recording density close proximity between the head and the tape is required (Luitjens et al., 1996) These requirements present engineering challenges, as thinner, smoother tapes will have reduced dimensional stability and experience increased friction in linear tape drives (Bhushan, 2000). Lower tape tension is desirable to counteract these effects by reducing frictional forces and stresses within the tape.

However, lower tape tension and higher tape speed can lead to increased hydrodynamic effects as the tape passes over bearings and the head (Elrod and Eshel, 1965), potentially creating a less stable tape path and increased lateral (cross-track) tape motion. Excessive lateral tape motion (LTM) can cause the data tracks on the tape to move relative to the read/write modules of the head, leading to so-called track misregistration (TMR) error in writing and reading data tracks. Modern commercial tape drives incorporate servo track following systems that move the head to compensate for LTM, but these systems have limited bandwidth and TMR occurs when LTM events are of sufficient frequency and magnitude. Smaller track width reduces tolerance for LTM by decreasing the magnitude of LTM necessary to cause TMR.

In a previous study Hansen and Bhushan (2004) varied operating tension and speed using commercial metal particulate (MP) tape on a tape transport using stationary guides. The results of their study showed that the coefficient of friction for MP tape was affected by tension at speed due to hydrodynamic effects at lower tensions and higher speeds. The study was unable to draw any strong conclusions on the effects of tension and speed on LTM. In light of this and the introduction of the porous air bearings on the MTS tape deck, a second study on the effects of tension and speed was initiated. Additionally, with a strong focus on future generations of tape and alternate media the tension and speed study has been expanded to include not only MP tape, but also an experimental Thin MP tape and three advanced metal evaporated (AME) tapes.

In addition to the concerns that future tape requirements present in LTM generation, the origins of LTM within the operation of the tape drive system are not well known. Furthermore, the effects of tape quality can potentially be a concern when discussing LTM generation. Goldade and Bhushan (2003) suggested that tape guiding, which helps to govern LTM can be dependent on many factors including quality of the virgin tape edge and type of guiding (stationary/rotary, active/passive) for MP tape. Additionally, using an Advanced Research Corporation model 20 transport Hansen and Bhusan (2004) found that guide type and placement relative to the head had a significant impact on LTM. None of these studies have been completed on an MTS tape drive with porous air bearings. For this reason it is important to study the contributions operating parameters related to head and bearing placement have on LTM in the MTS tape drive. Also, the effects of tape and tape pack quality metrics like edge quality and staggered pack levels on LTM will be studied for the first time on the MTS tape drive.

The current study will first investigate LTM and coefficient of friction in five different types of tape. These tapes represent both current technology and potential tapes for future commercial use. After completing a baseline study in regards to the five tapes, the study will investigate effects caused by varying tension and speed in the five tape samples. Additionally, this study will investigate the quality of slit tape edge in terms of contribution to LTM. Tests will look at staggered tape packs, which contain a series of raised strands to determine if the introduction of raised strands constitutes a serious LTM event. Finally, this study will look at operating parameters on the tape deck in order to further understand any contribution towards a change in LTM creation. The operating parameters under investigation include head zenith angle, air pressure used in the porous air bearings (PABs), bearing placement, and wrap angle.

2.2. Experimental details

2.2.1. Tape transport and test procedure

Drive tests were conducted in a class 10,000 laboratory environment (22 ± 1 °C; relative humidity 45 ± 5 percent) using the Segway Systems / Mountain Engineering II MTS linear tape transport with horizontal tape path, shown schematically in Fig. 2.1 (a). Tape bearings are single-flanged and tapered at an angle of 0.6 degrees to force the lower edge of the tape to ride along the flange. The head mount is designed such that the head zenith angle is the same as the bearing taper angle. Penetration of the head into the tape path was set the same for each test (aside from studies involving wrap angle). Each bearing consists of a housing, porous ceramic bearing material, lower flange, and outriggers. The housing and the bearing member form a plenum connected to an air pump such that airflow through the porous material creates an air cushion that supports the tape. The outriggers at each side of the guide provide cleaning action to the tape (Gavit, 1998).

Tape tension is monitored on both sides of the head by measuring air pressure in the gap between the tape and the bearing member by means of pressure transducers that are mounted in the two guides bracketing the head. The drive controller monitors the

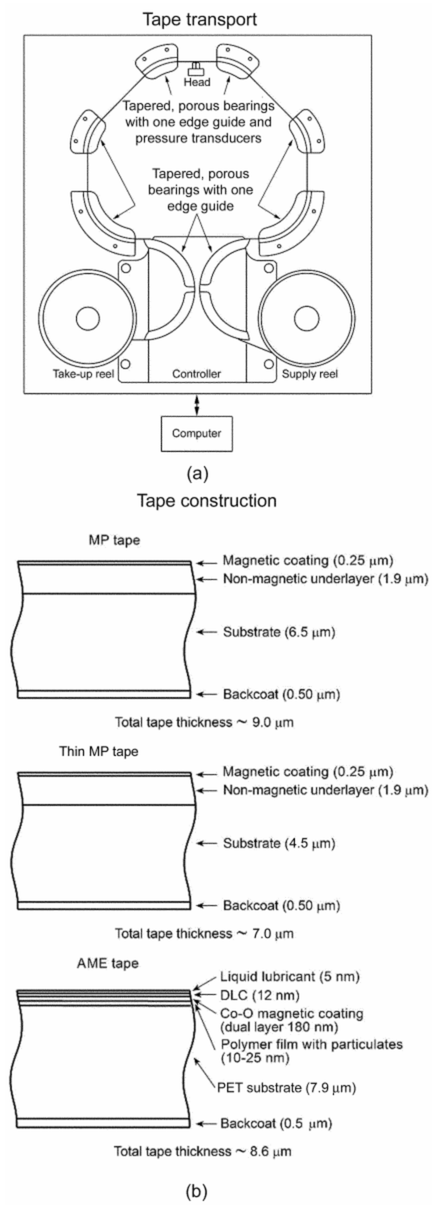


Fig 2.1 (a) Schematic diagram of the Segway Systems/Mountain Engineering MTS linear tape transport with porous air bearings and single-flanged tapered guides (b) Cross-section schematic showing the structure of MP, Thin MP, and generic AME tapes

pressure transducer signals and angular velocities of the tape reels and maintains constant tension and linear tape speed during a pass. The controller is connected to a PC that allows the operator to program certain drive parameters. Up to 600 m of 9 μm-thick tape can be loaded onto the tape reel, and the drive can be programmed to run for a specific number of cycles, with practically any pass length, at tape speeds between 2 and 8 m/s and tensions between 0.5 and 1.2 N. At the beginning of each test a new piece of tape was loaded into the transport and a clean head was mounted. Pass length was set at 30 m with one forward and one reverse pass equal to one 60-m cycle.

2.2.2. Tape and head samples

Figure 2.1 (b) is a schematic of the cross-sections of MP, Thin MP, and a generic AME tape. The MP tape used in this study is commercial, 12.7 mm-wide Ultrium 1 tape. It is a dual-layer metal particle tape with magnetic layer and backcoat thicknesses of 0.25 μm and 0.5 μm, respectively, a substrate thickness of about 6.5 μm, and an overall thickness of 9 μm. The magnetic layer contains needle-shaped, passivated iron magnetic particles and head cleaning agents (HCAs) dispersed in a polymer formulation of binder and fatty acid ester lubricants. The magnetic particles are typically 0.1-0.2 μm or smaller in length and have an aspect ratio of five to ten. The HCAs are generally 0.2-0.3 μm-diameter Al_2O_3 particles and conductive carbon particles, added to improve friction wear properties and electrical conductivity. The Thin MP tape used in this study is an experimental tape with properties similar to the commercial MP tape described above.

The main difference between the two tapes is that the substrate thickness has been decreased to approximately 4.5 µm in the Thin MP tape, reducing the total thickness to 7 µm.

Three AME tapes were used in this study. AME tape is 12.7 mm wide. The overall tape thickness of AME tape is about 8.6 µm. All three of the AME samples are experimental formulations with different cupping (natural curl of the tape edges away or towards the head) orientations. One of the AME samples is negatively cupped (edges curl away from the head) and henceforth, will be referred to as AME-NC tape. The remaining two AME samples are positively cupped (edges curl towards the head), but one sample is much more aggressively cupped. The shallower of the two positively cupped samples will be referred to as AME-PC tape and the more aggressively cupped tape will be known as AME-PC+ tape. The frontcoat of all three AME tapes consists of the dual magnetic layer (180 nm thick) of evaporated Co-O, over which is a 12 nm thick DLC coating, over which is a 5 nm-thick liquid lubricant layer. DLC is a hard coating used to protect the magnetic coating against corrosion and wear. The lubricant enhances the durability of the DLC and magnetic coatings by reducing friction at the head-tape interface. The lubricant commonly used consists of an overcoat of fatty acid esters on a perfluoropolyether (PFPE) coating.

A commercial Seagate LTO (Generation 1) head is used in this study. It is an inductive write/magnetoresistive (MR) read head with Al_2O_3-TiC substrate, 80/20 Ni-Fe

MR stripe, CZT shields and poles, and Al_2O_3 overcoat, undercoat, and gap material. The MR stripe, shields and poles, and overcoat, undercoat, and gap material are sputter deposited on the substrate.

2.2.3. Measurement techniques

During the study, the coefficient of friction is calculated from the drive tension signals using the belt equation and captured by the data acquisition software (NI-6023E, National Instruments, Austin, TX) with a sampling rate of 150 Hz. The data acquisition was controlled by Snap-Master V3.5 data acquisition software (HEM Data Corp., Southfield, MI).

LTM was measured using the MTI 2000 Fotonic sensor, equipped with Edge Probe (MTI Instruments Inc., Latham, NY, probe 2062E with sensitivity of 17.853 μm/V and a noise level of 20 mV_{p-p}). The edge probe is positioned over the tape edge. Light from the light source is reflected by a 90-degree prism to another 90-degree prism and finally reaches a photodiode (light receiver). The Fotonic sensor converts the photodiode signal, which is proportional to the light intensity, into the output units (volts or microns). If the light path is not obstructed by the tape edge the output of the fotonic sensor is 100 percent. The output decreases as the tape moves upward into the gap between the prisms and vanishes to zero when no light reaches the photodiode (Goldade and Bhushan, 2003). The reported LTM values are in the form of average LTM peak-to-peak amplitude (LTM P-P amplitude). This is found by parsing the LTM data into one-second increments and averaging the difference between the highest and lowest tape position in each one-second block over the forward or reverse pass. Additionally, LTM data can be presented in the form of a power spectrum density (PSD). PSD is calculated using Matlab version 6.5 (The Mathworks Inc., Natick, MA) using a program described by Hansen and Bhushan (2004).

Optical measurements of LTM, such as with the edge probe used in this study, may convolve tape motion measurement with the measurement of the tape edge profile. As was discussed by Hansen and Bhushan (2004), two probes used simultaneously to measure LTM on the top and bottom edges are needed to determine the amount of measured LTM that corresponds to actual tape motion. For this reason a majority of the tests completed in this study employed a second MTI Fotonic sensor with Edge Probe (sensitivity 14.723 μm/V and noise level of 20 m V_{p-p}). The coherence of the LTM signals from both the top and bottom edges was calculated to give an idea of how closely the two signals are related. The coherence estimate $C_{xy}(f) = 0$ if the two signals are completely incoherent (unrelated) at the frequency f and $C_{xy}(f) = 1$ if the two signals are fully coherent (closely related) (Beauchamp and Yuen, 1979). The assumption is that the upper and lower tape edge profiles are different, but move together when the tape moves laterally. Therefore, if the two edge probe signals are coherent at certain frequencies, they are measuring actual tape motion at those frequencies and not the tape edge profile.

Even with the dual Fotonic probes used in this study the LTM measurements will involve both true LTM and the physical contour of the tape edge. The contour of the tape edge is not a straight line, but instead it can be rough and jagged. The Fotonic probes may convolve the unevenness of the tape edge as tape motion. The convolution of the tape edge cannot effectively be removed from the measurement of true motion. Thus, the values obtained with the Fotonic probes provide only an estimate of true LTM. The reported values of LTM correspond to the physical location of the tape due to both tape motion and edge contour. In light of this LTM measurements made in this study will henceforth be termed lateral tape motion physical (LTM_P).

In preparation for edge quality measurements, samples were cut into 30 mm strips and mounted on glass microscope slides with double-sided adhesive tape. Optical images were obtained with an optical microscope (OPTIPHOT-2, Nikon Corporation, Tokyo, Japan) in the brightfield mode with a white light source. Gray-scale images (640×480 pixels) were captured with a CCD camera at a resolution of 0.175 μm per pixel and saved on a PC. Relative edge contour length (RECL) is used as the measure of edge quality. Measurements needed to find the RECL of the samples were performed using the methodology developed by Topoleski and Bhushan (2000) and Goldade and Bhushan (2003, 2004).

Tape cupping is the natural tendency of the tape to curl about an axis parallel to the direction of travel along the tape width (Bhushan, 2000, Scott and Bhushan, 2003). Positively cupped tapes curl so the edges are towards the head, while negatively cupped tape edges are curled away from the head. Cupping measurements of the five tape samples in this study were made using an optical microscope following the technique developed by Scott and Bhushan (2003).

2.2.4. Individual test plans

2.2.4.1. Baseline test comparison of tapes

The first portion of this study looks into the performance of five different tapes. As mentioned previously, the five tapes under consideration are a commercially available MP tape, an experimental Thin MP tape, and three different AME tapes. Figure 2.2 (a) displays representative optical micrographs and edge profiles of different tape samples. Specific results will be presented in section 3 of this paper, but one can see visually that AME, both negatively and positively cupped, tapes have significantly more ragged edges compared to MP and Thin MP tapes.

The unworn MP tape used in this study has negative cupping equal to about 1 mm at its greatest. Thin MP and AME-NC tapes displayed a negative cupping slightly greater than 1 mm at its greatest point. The AME-PC sample used in this study has shallow positive cupping equal to about 0.1 mm at its greatest. The other positively cupped AME sample, AME-PC+, has a more aggressive positive cupping equal to about 0.6 mm at its greatest. A tape cupping plot of the five samples is shown in Fig. 2.2 (c).

The goal for this part of the study is to identify the behaviors of the five tapes in regards to coefficient of friction and LTM_P at a tension of 1 N and speed of 6 m/s. .

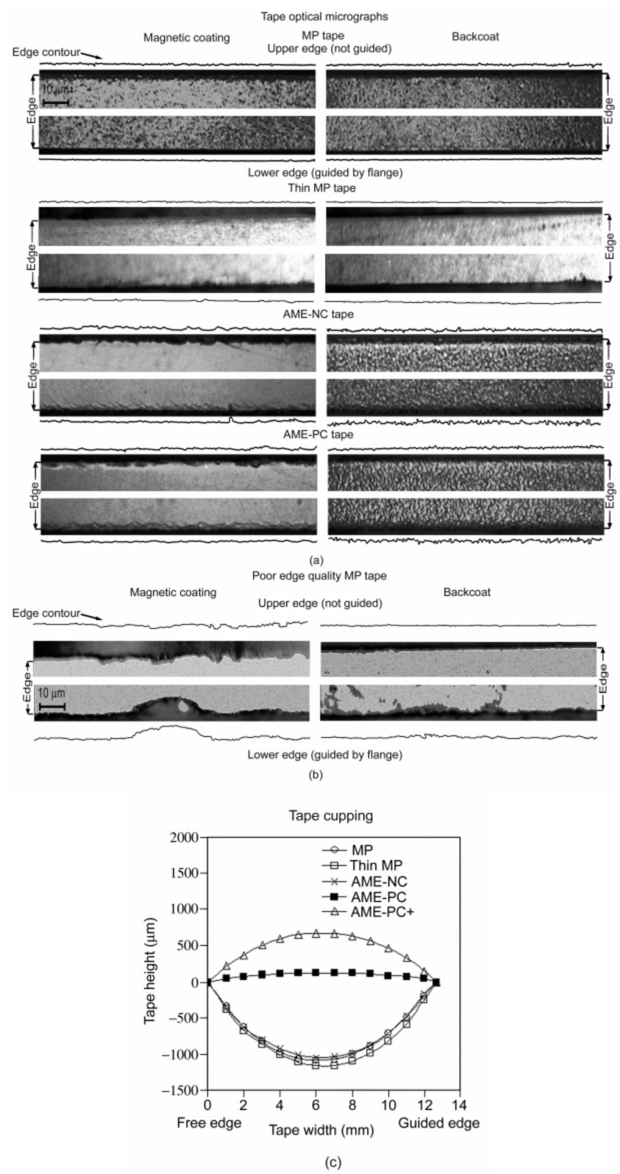


Fig. 2.2 (a) Sample optical micrographs of tape samples (b) Optical micrographs of poor quality MP tape (c) Measured cupping profiles of the five tape samples

Henceforth, the tension and speed combination of 1N and 6 m/s will be referred to as nominal conditions. In order to characterize the behaviors of the tapes 1000-cycle tests were run, while monitoring coefficient of friction and LTM_P

2.2.4.2. Quality of slit edge study

The purpose of this study is to compare LTM_P in two MP tape samples of differing edge quality. One tape sample was selected that had unworn edges comparable to the majority of commercial MP tape samples. This tape will be termed good edge quality sample and a representative example can be seen in the topmost portion of Fig. 2.2 (a). Roughly a dozen MP tape samples were analyzed before a tape sample with a discernable difference in unworn edge quality was located. This sample appeared to have significantly more edge damage compared to typical MP tape and could be characterized by severe cracking and a general raggedness of the tape edge. This sample will be termed poor edge quality sample. A representative image of this tape is shown in Fig. 2.2 (b). This study used 1000-cycle tests.

2.4.3. Staggered pack study

Staggered tape packs deal with packs that have raised strands creating an uneven profile on the top surface of the pack. This is different from a tape pack of normal quality that has a nominally even surface on the top of the pack. Three samples of MP tape with a varying amount of popped strands were used in completion of this study. Figure 2.3 shows images of the three samples used in this trial. Each individual band of

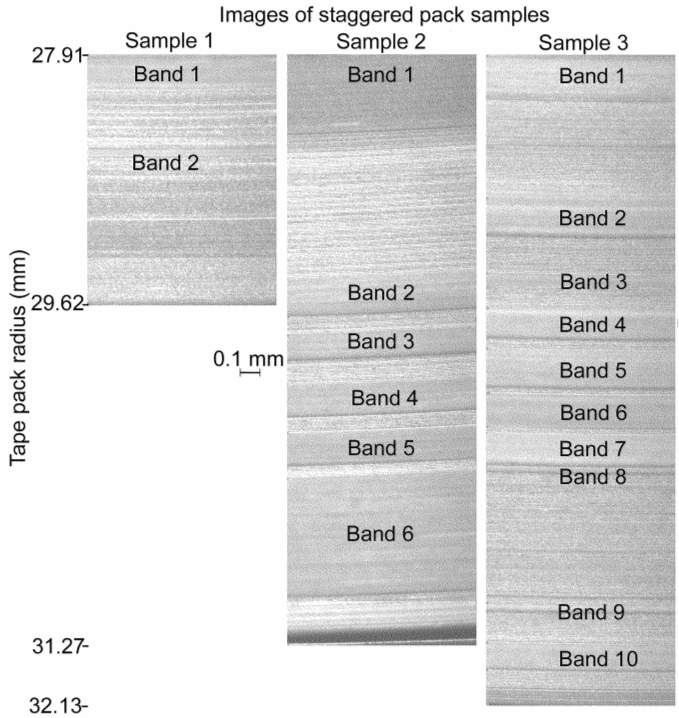


Fig. 2.3 Images of the three staggered pack samples with individual bands of popped strands identified

popped strands is labeled in the images. Also, it should be noted that the pass length for samples 2 and 3 were extended to incorporate a larger amount of popped strands.

In order to complete this portion of the study the staggered tape pack samples needed to be characterized. Optical microscopy provided means for measuring the width of the bands of popped strands for each of the three samples. The width of individual bands of popped strands was measured by taking photographs of the pack samples after they were loaded onto the tape deck and completing an analysis using Adobe Photoshop (Adobe Corp., San Jose, CA). This analysis included relating the measurements taken in Photoshop to macro-scale measurements of tape pack diameter made with calipers. Using this relationship, band widths and approximate locations were identified. An estimated length of each band of raised strands was calculated using equations (1) and (2). The tape thickness for the samples in this study was 9 μm and the hub radius was 27.9 mm.

(1) No. of wraps = (current tape radius-hub radius)/tape thickness

(2) Tape length (m) = 2 x π x ((hub radius x no. of wraps) + (0.5 x tape thickness x no. of wraps x (no. of wraps + 1)))

Another aspect of this portion of the study that needs mentioning is that the typical average LTM_P P-P amplitude measurements generally reported for LTM_P analysis are not useful in this case. This is because the typical method of analysis could average out the potential LTM_P peak-peak data caused by different bands of popped strands. Instead of averaging the one-second blocks of LTM_P data over the forward and reverse pass of each cycle, the average value of each individual one-second block is calculated over the total number of cycles in the test. With the knowledge of the approximate length and location of each band of popped strands and that the tests were completed at 6 m/s an estimate can be completed on when the individual bands of raised strands would pass through the tape drive. This will allow for a comparison of the LTM_P (Note: not LTM_P peak-peak, but rather average position of the tape) in each one-second block based on knowing if popped strands, nominally even tape, or both are passing through the drive in each respective time period. For this study 1000 cycles were used to test each sample at nominal tension and speed.

2.2.4.4. Tension and speed studies

Combinations of the extreme allowable operating tension and speed were used in this study. Tension was varied from 0.5 to 1.2 N and speed was varied from 4 to 8 m/s. Table 1 illustrates the test plan used to study the effects of tension and speed on each tape sample. Two runs of 100 cycles at each of the extreme combinations of tension and speed were completed. Data from the baseline studies at nominal tension and speed was used for comparison. Additionally, the same pieces of tape were used throughout the tension and speed study and the baseline comparison study in an effort to remove any potential effects of tape edge quality on LTM_P.

Tension and speed test matrix

	0.5 N	1.0 N	1.2 N
4 m/s	X		X
6 m/s		X	
8 m/s	X		X

Table 1 Tension and speed test matrix

2.2.4.5. Head zenith angle and air pressure study

In addition to the effects tension and speed have on LTM_P it is important to study sources of LTM_P that arise from the tape transport itself. This study looks into this subject and deals with both the head zenith angle and air pressure used in the porous air bearings (PABs). Head zenith angle refers to the vertical degree of tilt of the head. Under normal operating conditions the head zenith angle is set to approximate the angle of the PABs, 0.6 degrees. In this test the head zenith angle will be changed, so that it is vertically straight up and down in one setting and in another the head will be positioned so that it is tilted past the bearing angle.

The air pressure used in the PABs is normally set to 34 kPa. The lowest operating air pressure the PABs run at is 14 kPa and the maximum allowable air pressure is 41 kPa. This study, thus varies air pressure settings between 14 and 41 kPa.

A 1000 cycle test was completed at the normal settings of the head zenith angle approximating the angle of the PABs and 34 kPa air pressure going to the PABs. This initial 1000 cycle test will be used for comparison to the data collected in subsequent runs. A total of eight 100 cycle runs (two at each combination of settings) were used in this study. The same piece of commercially available MP tape is used for each run.

2.2.4.6. Bearing placement study

Limited by the contours and construction of each of the PABs, the goal of the bearing placement study is to alter the tape path away from the head and determine if LTM_P increases at the head with any changes. Figure 2.4 (a) displays a schematic of the normal setup of the tape transport along with a numbering convention for all of the PABs and gaps between the PABs. An initial 1000 cycle test was completed using the normal setup of the tape transport. Subsequent 100 cycle runs were completed while using settings that altered the tape path away from the head. Two runs were completed at each of the settings that included removing bearings 3 and 4, removing bearings 5 and 6, and moving the take-up and supply reels away from bearings 9 and 10 approximately 80 mm, respectively. The same piece of commercial MP tape was used throughout this study. Also, a companion study measuring LTM_P in the gaps between bearings and at the reels was completed both during normal settings and with the PABS and reels moved in an effort to show the effects of altering the tape path away from the head.

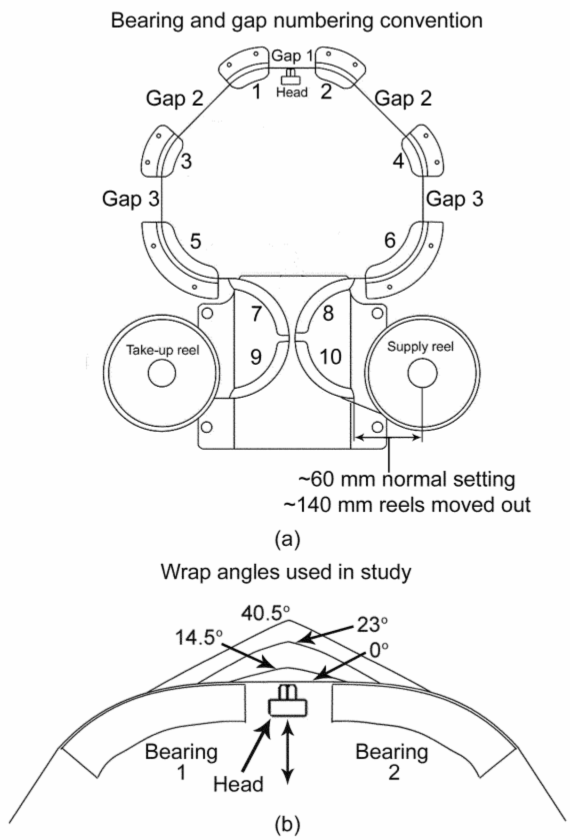


Fig. 2.4 (a) Bearing and gap numbering convention for the MTS tape transport (b) Schematic of the different wrap angles studied

2.2.4.7. Wrap angle study

The final parametric study involves wrap angle. Wrap angle is the angle the tape makes as it wraps around the head. Four different wrap angles were used in this study. The angles used include 0 (no head), 14.5, 23, and 40.5 degrees. Figure 2.4 (b) shows a sketch of the four different wrap angles. Of note in this figure is the fact that as the wrap angle increases, so too does the amount of tape that is lifted off of the front two bearings. Normally set at 23 degrees, the wrap angle can be changed by moving the head further in or out of the tape path. This first portion of this study involves a 1000 cycle test using the standard 23 degree wrap angle. After this test 100-cycle tests at the remaining wrap angles were completed. The same piece of MP tape was used throughout the study. Also, note that the coefficient of friction was not monitored in this study because the varying amount of tape on the front bearings causes errors with the pressure transducers used in its measurement.

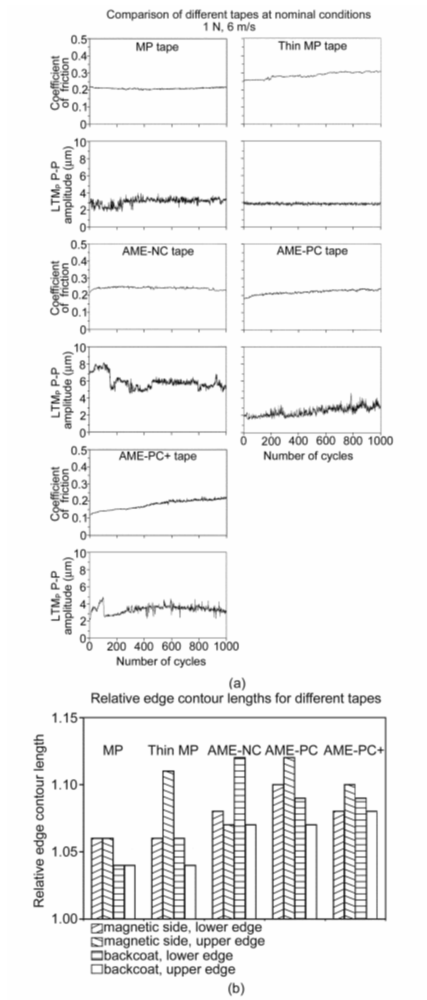
2.3. Results and discussion

Lateral tape motion has long been a concern of the data storage industry, as it causes problems with track misregistration. For this reason several studies were completed to investigate LTM_P in different tapes and how the tapes perform under different operating conditions. Coefficient of friction and LTM_P were monitored for all tests where applicable and edge quality was monitored for the baseline study involving the five different tapes. Before discussing the results note that in the tests involving 100 cycle runs, two trials at each of the pertinent combinations were completed, but since the data was highly repeatable and in the interest of brevity only one data set from each combination is presented. Also, the data presented as the nominal conditions for comparison to the different combinations of settings in each test is the data from the last 100 cycles of a 1000 cycle test.

2.3.1. Baseline test comparison of tapes

The coefficient of friction and LTM_P results for all five tapes studied are presented in Fig. 2.5 (a). All three of the AME tapes exhibit coefficient of friction values lower than MP tape. Alfano and Bhushan (2006a) noted the same trend and determined this was a result of the lubricants used in AME tapes. Thin MP tape exhibited the highest coefficient of friction of the tapes studied. Possible explanations for this include Thin MP having a lower surface roughness compared to the commercially available MP tape sample leading to a higher real area of contact, or that it may be more compliant as it runs through the tape transport because of its reduced thickness.

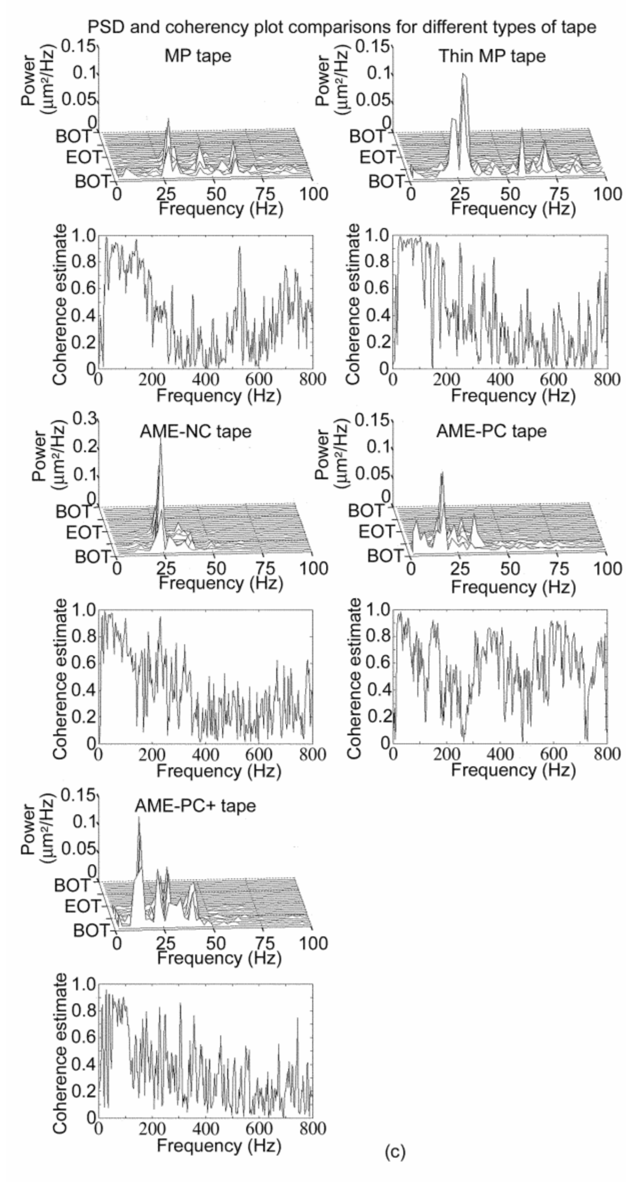
The LTM_P results for the five tapes show that the AME-NC tape produces significantly higher LTM_P than the other four tapes. MP, Thin MP, AME-PC and AME-PC+ all generate similar amounts of LTM_P, but AME-PC and Thin MP have slightly lower values of LTM_P when compared to MP and AME-PC+ tapes. Alfano and Bhushan (2006a) studied the effects of tape cupping on LTM_P and found that the reason AME-NC shows an increase in LTM_P is dual natured in that it suffers from the combination of



Continued

Fig. 2.5 (a) Coefficient of friction and LTM_P results for the five tapes at nominal conditions (b) Relative edge contour length results for the five samples (c) PSD plots and coherency estimates of the five tape samples studied

Figure 2.5 continued



being negatively cupped and it has a smooth surface. When compared to its fellow AME tapes AME-NC shows higher LTM_P because of a lack of tape edge pinning. With negative cupping the edges of the tape are cupped out away from the head, reducing the contact area between the head and tape. This can be contrasted to the positively cupped AME tapes in which the tape edges are cupped toward the head and bearings. In the positively cupped case the edges of the tape are in contact with the head and bearings creating a pinning effect, as the tape moves from bearing to head. The lack of tape edge pinning in AME-NC, thus contributes to the higher LTM_P generation. Now compare AME-NC tape to the other negatively cupped tapes, MP and Thin MP, and again one will see that AME-NC generates significantly higher LTM_P. This is due to the surface roughness of the tapes in question. MP tapes have been to shown to have rougher surfaces compared to AME tapes. The increase in real area of contact (surface asperities) that the increase in surface roughness of MP tapes provides adequately allows for MP tapes to grip the surface of the head and bearings, reducing LTM_P. Combine the lack of surface roughness of AME-NC with the fact that it is negatively cupped and it is easy to see why it generates significantly higher LTM_P.

Edge quality can directly impact LTM_P measurements. For this reason tape optical micrographs of the five tape samples were taken and analyzed. The results of the analysis in the form of relative edge contour length (RECL) are shown in Fig. 2.5 (b).

From the chart one can see that AME tapes exhibit significantly higher values of RECL than MP and Thin MP tape with the lone exception of the upper edge of the magnetic side of Thin MP tape. Goldade and Bhushan (2005) reported that when the initial web of tape is slit a significant amount of stretching of the substrate occurs. This can lead to the generation and propagation of cracks. AME tape is particularly impacted by this stretching because the magnetic layer of AME tape is very brittle, resulting in higher RECL values.

Because edge quality and variation may impact LTM_P measurements the dual edge probe method was employed. This was completed by placing both edge probes in the vicinity of the head. One of the probes measured the top edge, while the other measured the bottom edge of the tape. PSD plots for both the top and bottom edge on all of the tape samples were created. Figure 2.5 (c) presents the PSD plots for only the bottom edge of each tape sample, as the top and bottom edge PSD plots were very similar. Note that the scale for the AME-NC PSD plot is different than the other four tapes. This increase in the scale and likewise power verifies that AME-NC tape has much higher LTM_P than the other tapes.

Also included in Fig. 2.5 (c) are coherence estimates for the top and bottom edge LTM_P measurements. A high coherence estimate indicates that the LTM_P measured on the top and bottom edges are highly relatable. This suggests that the LTM_P reported corresponds to actual tape motion and the contributions of tape edge contour to the measurement of LTM_P are minimized. As the coherence estimate decreases, the relationship between top and bottom edge LTM_P measurements decreases. Looking at the frequencies where the LTM_P signal was measured in the PSD plots, approximately 20-30 Hz, one can see the coherence estimates are fairly high. This is particularly true for MP and Thin MP tape indicating that the LTM_P measurements taken reflect a reasonably true measurement of LTM_P. The coherence estimates for some of the AME tapes are slightly lower than the MP tapes, suggesting that the edge probe measurements may be convolving tape edge profile as tape motion in AME tapes. This may result in an increase in reported LTM_P values for the AME tapes. Please note that the PSD plots and coherence estimates were repeatable between different studies. For this reason their discussion has been excluded in future sections of this report.

2.3.2. Quality of slit edge study

In this study two separate tapes were run for 1000 cycles each. One tape was deemed to have good edge quality while the other was found to have comparatively poor edge quality. Figure 2.6 (a) shows the coefficient of friction and LTM_P results for both tape samples. The RECL results for the two tapes are displayed in Fig. 2.6 (b). Especially on the magnetic side, the poor edge quality sample shows a much worse edge quality compared to the good quality edge sample. This result is verified if one recalls Figs. 2.2 (a) and (b) that visually show the poor edge sample having a much more ragged edge profile.

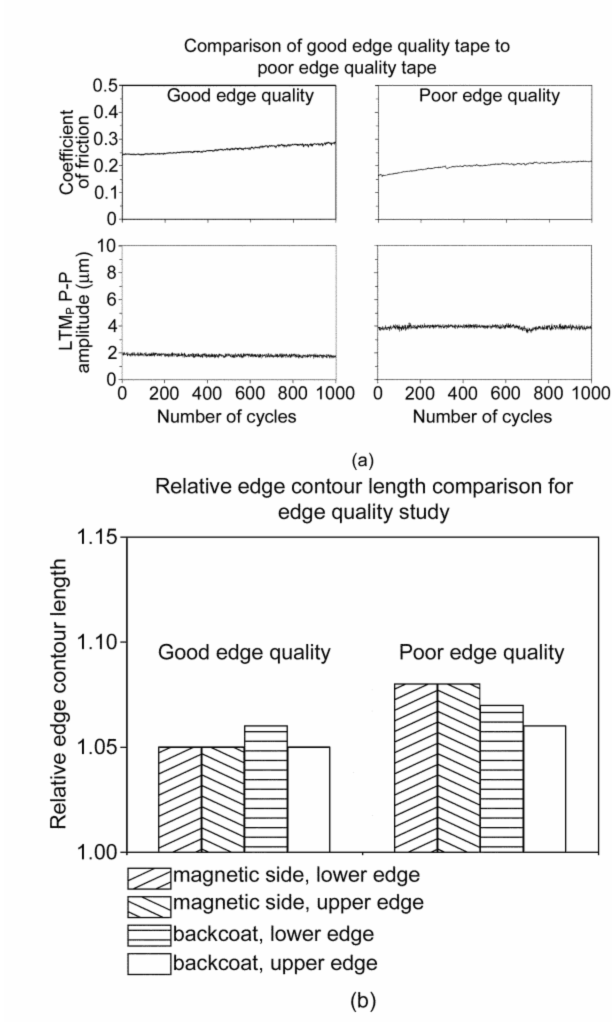


Fig 2.6 (a) Coefficient of friction and LTM_P results for the tape edge quality study (b) Relative edge contour length results contrasting the good quality sample to the poor edge quality sample

The results show that the poor edge quality tape has a lower coefficient of friction and higher value of LTM_P. It is difficult to know whether the differences in the LTM_P results are due to the edge quality level, or just the fact that they are two different tape samples. However, that being said MP tape is negatively cupped, so theoretically the edges would never come in contact with the bearings or head. This suggests that the LTM_P increase in the poor edge quality sample could be due to the edge probe convolving the tape edge profile as lateral motion. Methods being investigated by Alfano and Bhushan (2006b) in which lateral motion of the tape is measured by reading back a written magnetic signal may be able to determine whether or not the increase in LTM_P for the poor quality sample is due to the edge probes convolving the edge profiles of the tape samples.

2.3.3. Staggered pack study

The methodology discussed in section 2.2.4.3 approximated the location, length of each band of popped strands, and the estimated time frame that each band passes through the tape drive. Figure 2.7 shows the LTM_P averaged over each one-second block for all three samples tested. Referencing Fig. 2.3, the individual bands of popped strands that pass through the drive are noted above the LTM_P data for each one-second block. Intervals that are free of popped strands do not have any notations above the LTM_P data. The important things to compare in this study are the one-second blocks where there are

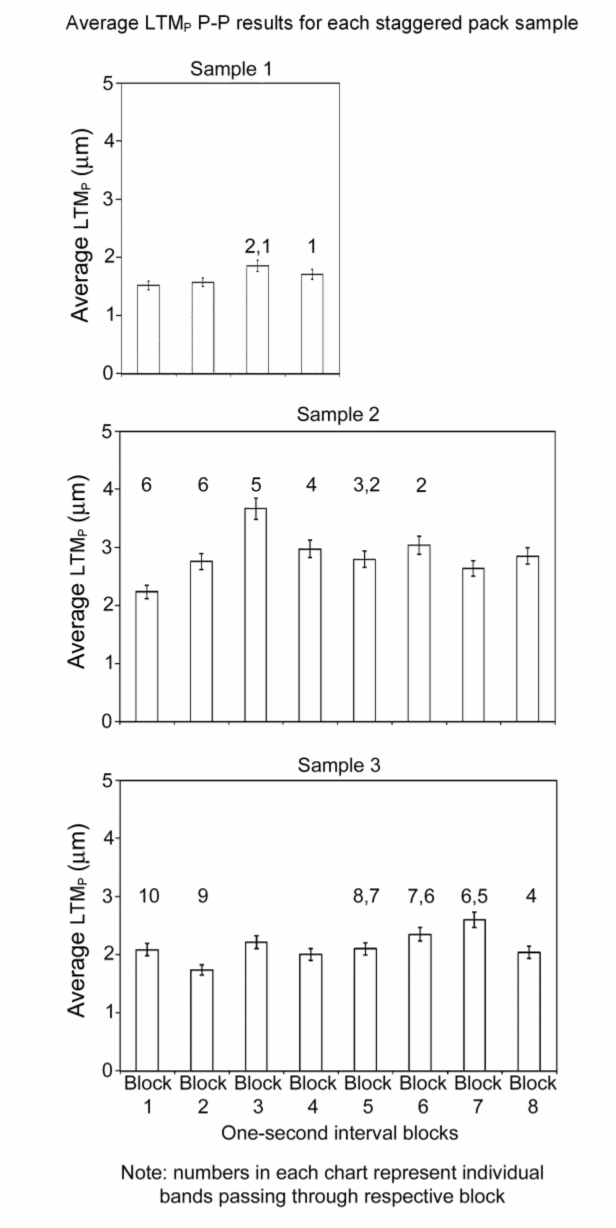


Fig. 2.7 LTM_P results for the three staggered pack samples

no popped strands, or blocks where a raised strand takes up the entire interval to the one-second blocks that have a series of nominally even tape and bands of popped strands traveling through them. Note that in addition to the intervals that are entirely free of popped strands, block 1 in sample 3 was entirely composed of one band and would therefore see one height of tape during that particular one-second interval.

The hypothesis before the study was conducted was that the blocks free of popped strands or composed entirely of a popped strand would show a lower level of LTM_P because the tape passing through that particular time interval would not vary in height. In looking at the results in Fig. 2.7 sample 1 appears to support this hypothesis, as block 1 and 2 have on average lower LTM_P than block 3 or 4. However, samples 2 and 3 cast doubt on the theory. The one-second intervals that were expected to be higher in LTM_P were in general higher compared to the blocks without popped strands, but there are a few intervals where this does not hold true. This suggests that LTM_P measured at the head is only minimally, if at all, affected by the bands of popped strands found in staggered packs. This also suggests that the PABs employed by the MTS tape transport do a sufficient job constraining lateral motion of the tape by guiding tape motion and dampening vibrations, as the tape approaches the head.

2.3.4. Tension and speed studies

The importance of studying different types of tape has been noted previously in this paper. In addition to studying the types of tape it is important to study the operating parameters the tapes will be under while in use. Tension and speed are two such operating parameters. Tape drive manufacturers may be forced to lower tension and increase speed in future drives in order to counteract decreased dimensional stability with thinner tapes and increase data access times, increasing the importance of studying these parameters.

Figure 2.8 summarizes the tension and speed results for all five of the tapes studied. In looking at the coefficient of friction results it is clear that all of the tapes see an effect from varying tension and speed. This is shown with a reduced coefficient of friction at the low tension high speed run in all tapes. It is also interesting to note that both AME-NC and AME-PC tape experience a decrease in coefficient of friction for the low tension low speed run and the other tapes do not. A decrease in the coefficient of friction at the low tension high speed combination indicates that hydrodynamic effects are present for all tapes. Elrod and Eshel (1965) put forth a model of the head-tape interface that explains the hydrodynamic effects. A hydrodynamic air film develops, as the tape moves over the head that lifts the tape off of the head. The head-tape spacing is proportional to $(V/T)^{2/3}$, where V is tape speed and T is tension. Using this model, one can see that decreasing tension and increasing speed would increase head-tape spacing leading to a decrease in the real area of contact between the head and tape surfaces. The decrease in real area of contact between the head and tape results in a reduction in coefficient of friction.

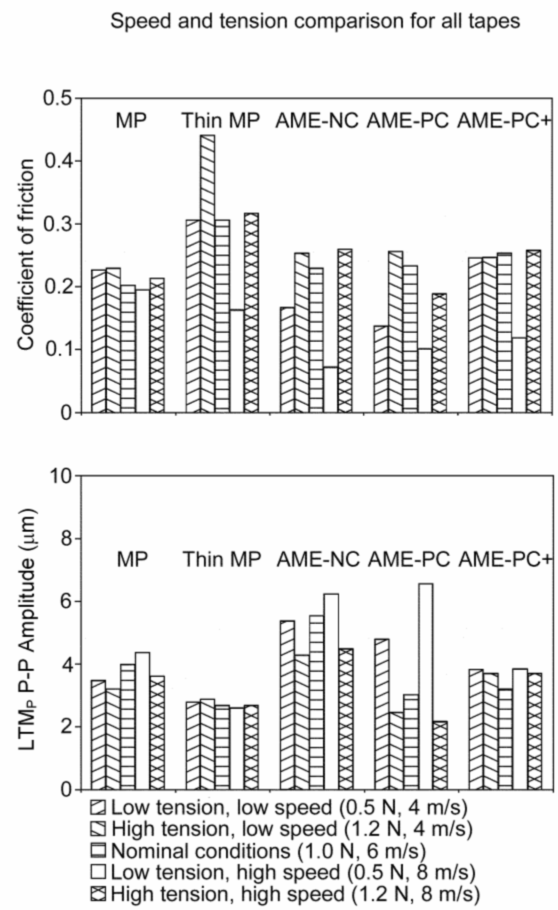


Fig. 2.8 Summary of the coefficient of friction and LTM_P results for the tension and speed studies on all five tape samples

The LTM_P results from the five tapes show that AME-NC and AME-PC are influenced by changing tension and to some degree speed, while MP, Thin MP, and AME-PC+ are not. Reasons for the differences between the tapes that see a significant effect as a result of varying tension and speed and those that do not are a continuation of the discussion from the baseline comparison study. AME-NC tape is both negatively cupped and very smooth. This leads to higher LTM_P compared to the other tapes because of a combination of lack of tape edge pinning and a reduced real area of contact. Previously, Fig. 2.5 (a) and now Fig. 2.8 demonstrates this, as on average the results for each tension and speed combination used for AME-NC tape are higher than all of the other tapes. The runs at low tension compound the problem of reduced real area of contact and lack of edge pinning resulting in even higher values of LTM_P. This occurs because at the runs using low tension, particularly the combination of low tension and high speed, the head-tape spacing increases due to hydrodynamic effects further reducing the real area of contact between the tape and head, increasing freedom of motion. Thus, AME-NC tape at lower tensions has increased LTM_P.

AME-PC tape has been shown in the previously discussed baseline comparison study and again in this study to have adequate edge pinning when higher operating tensions are used. However, when the tension is dropped to 0.5 N the LTM_P values for AME-PC tape are increased significantly. This suggests that at low levels of tension the cupping for AME-PC is not enough to provide adequate edge pinning. Recall that the cupping for AME-PC is very shallow, 0.1 mm at its greatest, and realize that this tape is almost flat. At low tension contact between the AME-PC tape and the head is more between the smooth surface of the tape than the edges. As AME-PC tape is very smooth, it then lacks both the surface roughness and edge pinning at low tension to remain at a low level of LTM_P. Furthermore, the hydrodynamic effects of increasing head-tape spacing at low tension magnify the lack of edge pinning and surface roughness in the AME-PC tape. Comparing the results from AME-NC and AME-PC tape, it is clear that the cupping in AME-PC+ tape is aggressive enough to provide tape edge pinning even at low tensions. Additionally, the results show that the negatively cupped MP and Thin MP tape have sufficient surface roughness to grip the head at low tension.

2.3.5. Head zenith angle and air pressure study

In addition to the effects varying tension and speed may cause it is important to look for other variables present on the tape drive that may affect LTM_P. Two such parameters analyzed in this study are the head zenith angle and the air pressure used in the PABs. The head zenith angle and air pressure were varied between the settings described in section 2.2.4.5.

Results for this test are shown in Fig. 2.9 (a). In regards to head zenith angle the coefficient of friction results do not establish a pattern. Thus, it appears that head zenith angle does not affect coefficient of friction. However, the results show lower coefficient of friction when the lower air pressure of 14 kPa is used signifying that air pressure in the

PABs can have a direct impact on coefficient of friction.

Looking at the LTM_P results in Fig. 2.9 (a) in terms of air pressure the results are grouped closely together suggesting that the PABs air pressure does not affect LTM_P. This is seen when comparing the results at the same head zenith setting, but different air pressure. When looking at the results in terms of head zenith angle however, one does see a significant difference in LTM_P between runs with the head set vertically straight and the runs where the zenith angle is set equal to or exceeds the angle of the PABs. This result can be explained by discussing the schematic of the head zenith angle effect shown in Fig. 2.9 (b). The left most portion of this figure represents the head-tape interface under normal conditions when the head zenith angle approximates that of the PABs. The 0.6 degree angle of the PABs creates a tension gradient across the width of the tape that increases in magnitude moving from the bottom edge to the top of the tape. Under normal settings this tension gradient is applied at the head, so that it is evenly distributed over tape that is in contact with the head. Since the tape is in contact with the head where the tension gradient is applied, the tape is not free to move resulting in LTM_P values that are low. Compare this to the setting when the head is vertical. In this case the negative cupping of the tape and the rotated head enables the top portion of the tape to be free of contact with the head. The greatest portion of the tension gradient from the PABS is applied to the part of the tape that is largely out of contact with the head. This creates a

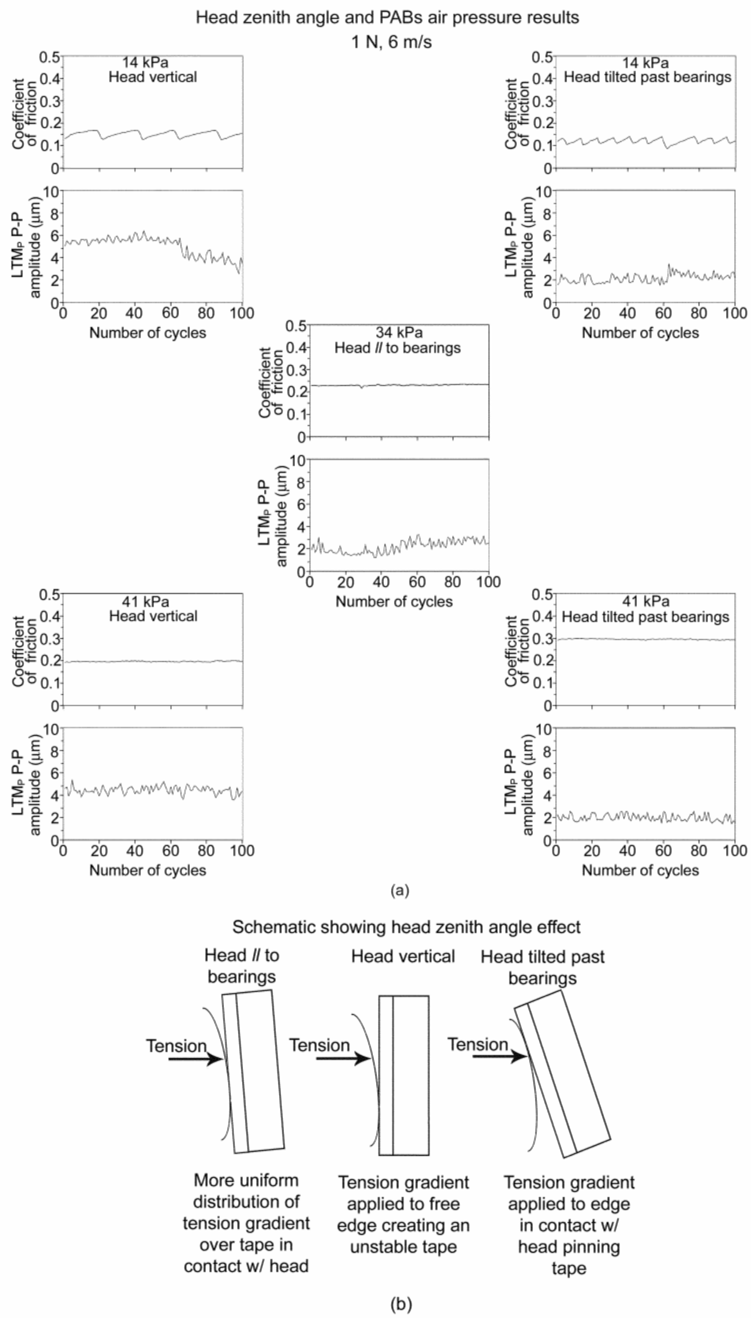


Fig. 2.9 (a) Results for head zenith angle and PABS air pressure study (b) Schematic displaying the head zenith settings and reasons for LTM_P variation

moment about the bottom edge of the tape that is in contact with the head leading to an unstable tape at the head-tape interface. The unstable tape creates freedom for the tape to move significantly increasing LTM_P under the vertical head setting. Finally, looking at the third scenario where the head is tilted past the PABs angle the LTM_P results are low and very comparable to the standard setting. The right most portion of Fig. 2.9 (b) shows what happens in this case. As the head is rotated, the tape-head contact occurs on the top portion of the tape, while the bottom portion of the tape is free from head contact. The greatest portion of the tension gradient is applied where the tape is in contact with the head creating a pinning effect and reducing the ability of the tape to move laterally, effectively keeping LTM_P under control.

2.3.6. Bearing placement study

Another parameter that was studied is the placement of the bearings and reels on the MTS tape deck. Using the settings described in section 2.2.4.6, the goal of this study was to determine if alterations to the tape path "downstream" of the head-tape interface had an impact on LTM_P measured at the head. The results for this study are displayed in Fig. 2.10 (a).

The coefficient of friction data for all four of the runs shows a consistent value typically associated with MP tape. This result makes sense as the same piece of MP tape was used throughout the study and each run was conducted under nominal operating tension and speed. Results for the runs when bearings were removed or the reels were moved show a slight increase in LTM_P compared to the run using the normal setup. It is also interesting to note that the results for the runs where the tape path is altered are virtually identical regardless of which group of bearings was removed or if the reels were moved away from the rest of the transport.

For a more accurate understanding of the LTM_P results at the head it is important to also look at LTM_P measured between bearings and at the reels. Figure 2.10 (b) presents such information. Referencing Fig. 2.4 (a), this figure presents LTM_P data under normal setup and altered conditions in bearing gaps and at the reels. While the magnitude of the LTM_P data presented for normal setup is not of interest because it is expected to be higher in gaps compared to the head, it is very important to note that LTM_P significantly increases in the gaps and at the reel when the tape path is adjusted. For instance removing bearings 3 and 4 nearly doubles the LTM_P measured in gap 2, or the LTM_P measured in between the reels and bearings 9 and 10 raises approximately 15 μm when the reels are moved out. Compare this to the results shown in Fig. 2.10 (a) and results from the bearing placement companion study measured in the gaps and at the reels it is clear to see that the effects of removing bearings or changing the position of the reels have only a minimal effect at the head. This is evidence that bearings 1 and 2, those closest to the head, minimize any effects of increased LTM_P "downstream" of the head. Additionally, this study further supports the conclusions of the staggered pack study. As a section of popped strands is about to enter the tape transport, the guiding created by the

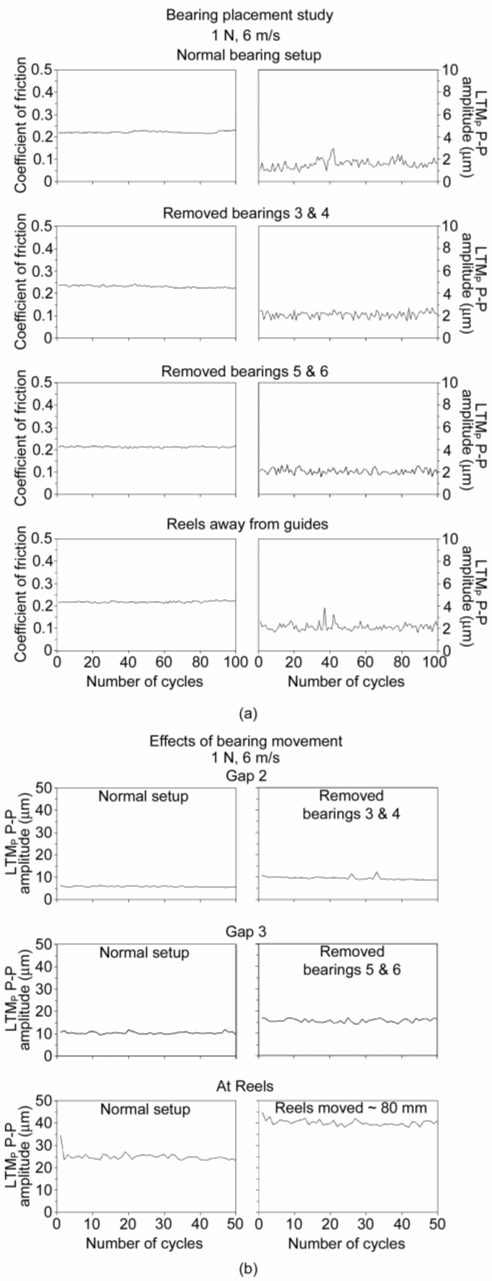


Fig 2.10 (a) Results for the bearing placement study measured at the head (b) LTM_P results from the bearing placement companion study measured in the gaps and at the reels

bearings pull the tape down creating a dramatic LTM_P event, but only minimal evidence of an increase in LTM_P is measured at the head.

2.3.7. Wrap angle study

The final parameter studied was wrap angle. A series of different wrap angles including 0 (no head), 14.5, 23, and 40.5 degrees was used for this study. Results are shown in Fig. 2.11.

The results for this study show that an increase in wrap angle leads to an increase in LTM_P. As the wrap angle is increased, a greater amount of tape is pulled off of the bearing. This effectively increases the distance between the front two bearings and the head. As a result, the tape receives less guiding from the bearings before the head at higher wrap angles, increasing LTM_P. One can definitively say that on the tape transport used in this study wrap angle effects LTM_P. However, the bearings are contoured and positioned such that an increase in wrap angle automatically increases the unguided distance between the bearings and the head. Therefore, it is not certain if the increase in LTM_P is actually due to the wrap angle itself, or simply due to increasing the distance of unsupported tape before the head. Finally, note that the results for the wrap angles of 0 and 14.5 degrees are virtually identical. Intuitively, one might expect to see an increase in LTM_P without a head, but this did not happen. One possible explanation is that without the head the tape runs along the entire width of the front bearings and the tape path is stable as it moves in a straight line from bearing to bearing.

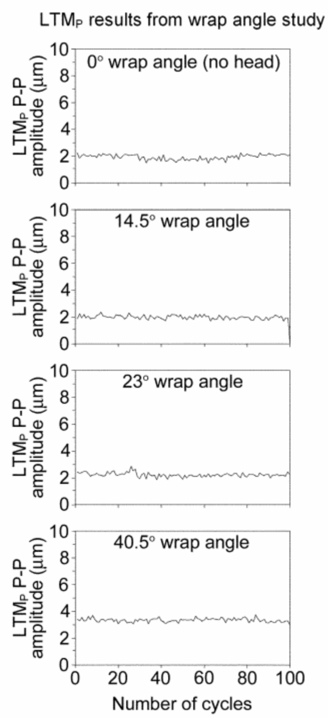


Fig. 2.11 LTM$_P$ results at the different wrap angles studied

2.4. Conclusions

The purpose of this study was to investigate LTM_P in different tapes and the sources of LTM_P due to different operating parameters. This was done in hopes of providing information to tape and tape drive manufacturers on LTM_P, as they work towards increasing data storage capacity. Results show that some tapes perform better than others at nominal operating tension and speed and varying tension and speed can have an impact on some tapes, but not others. Additionally, certain adjustable parameters on the MTS tape deck were identified as having an impact on LTM_P generation. Detailed conclusions follow.

- Thin MP tape was shown to have the highest coefficient of friction, while the AME tapes show slightly lower values of coefficient of friction compared to MP tape.
- AME-NC tape has the highest LTM_P at nominal conditions compared to the other four samples studied. This occurs because AME-NC tape is negatively cupped and is also very smooth.
- Poor edge quality tape was shown to have a higher value of LTM_P compared to a tape sample with good quality edges. The prevailing reason for this result is that the edge probes used in this study may convolve tape edge profile as lateral motion. Methods being developed that measure lateral motion of the tape through the read back of a magnetic signal should be utilized in an effort to truly determine the effects tape edge quality have on LTM_P.

- LTM_P at the head-tape interface may be minimally affected by staggered tape packs. The minimal effect on LTM_P from staggered packs is an indication that the bearings closest to the head control LTM_P due to sources “downstream” of the head.
- Coefficient of friction in all five tapes studied was affected to some degree by varying tension and speed. Hydrodynamic effects that reduce the real area of contact between the tape and head allow for a decrease in coefficient of friction when tension is decreased. This is magnified further with increasing speed.
- Varying tension can have a significant impact on LTM_P in certain types of magnetic tape. LTM_P significantly rose in AME-NC and AME-PC when the tension was lowered to 0.5 N. A combination of a lack of edge pinning and smooth surface roughness causes the increase in LTM_P at low tension in AME-NC and AME-PC tape.
- The effect of speed on LTM_P seems to be predicated on the effect of tension. Speed shows no impact on LTM_P on the tapes where tension does not affect $LTM_{P,}$ or AME-NC and AME-PC tapes at high tensions. However, speed does have an affect for AME-NC and AME-PC tape at low tension, as higher speeds in this case increase LTM_P.
- Head zenith angle can affect LTM_P depending on the setting of the angle. If the head is set vertically, as opposed to the standard 0.6 degree angle matching the bearings, LTM_P significantly increases due to an absence of tape pinning, or an even distribution of the tension gradient across tape in contact with the head. However, a change in LTM_P is not seen if the head zenith angle is set so that it exceeds the standard angle.

- Air pressure used in the PABS does not appear to have an effect on LTM_P.
- The bearing placement study shows that increasing LTM_P "downstream" minimally affects LTM_P at the head. This again shows that the front two bearings by the head minimize increases in LTM_P from sources "downstream."
- Increasing wrap angle on the current MTS tape drive increases LTM_P. This result is due to an increase in unguided distance between the bearings and head, as the wrap angle is increased.

CHAPTER 3

EFFECTS OF VARYING OPERATIONG TENSION AND SPEED ON LATERAL TAPE MOTION IN MP AND AME TAPES USING THE MAGNETIC SIGNAL AND OPTICAL PROBE METHODS

3.1. Motivation

Demand for greater data storage capacity continually forces the data storage industry to improve its products. Currently, the most advanced commercially available magnetic tape cartridges offer storage capacities of 500 GB native and 1.3 TB compressed. In order to improve the data storage capacities to multi-terabyte levels without increasing cartridge size future magnetic tapes will need to be thinner, smoother, have a smaller track width and pitch (distance between adjacent tracks) and increase linear recording density. Additionally, future generation tape drive systems will employ higher tape speed to achieve acceptable data acquisition rates. These improvements will allow for more data storage capacity within the same size cartridge, faster data retrieval rate, and lower head-tape spacing required to maintain a good signal-to noise ratio in high density recording (Bhushan 1996, 2000, Mee and Daniel, 1996, Luitjens et al., 1996).

However, all of these improvements will not come without issues as thinner, smoother tapes will lead to a reduced dimensional stability and an increase in friction (Bhushan, 2000). Lower tape tension can be used in an attempt to counteract the reduced dimensional stability and increase in friction, but the use of lower tension and increased speed for higher data acquisition rates can lead to increased hydrodynamic effects as tape passes over the head in a tape drive (Elrod and Eshel, 1965). The increased hydrodynamic effects may lead to an unstable tape path and an increase in lateral (cross-track) tape motion. Excessive lateral tape motion (LTM) causes the data tracks on the tape to move relative to the read/write modules of the head in a tape drive leading to potential errors in reading and writing data tracks. While modern commercial tape drives employ servo track following systems to combat LTM, they are of limited bandwidth and problems may still occur if the LTM is of sufficient magnitude. The potential problem LTM may cause will be magnified in the future, as narrower data tracks used for increased storage capacity will reduce the allowable tolerance for LTM.

Given the impact tension and speed may have on the future use of magnetic tape it is apparent that further consideration needs to be given to developing a strong understanding of the effects tension and speed have on LTM generation. Hansen and Bhushan (2004) completed a study that varied the tension and speed on commercial metal particulate (MP) tape on a tape transport with stationary guides. The results of their work showed that the coefficient of friction was affected by tension and speed, but they were unable to draw strong conclusions in regard to LTM. A second study on the effects of varying tension and speed was completed by Wright and Bhushan (2006) that used an MTS tape transport with porous air bearings. In addition to commercially available MP tape this study looked at the effects tension and speed had on an experimental Thin MP tape and three advanced metal evaporated (AME) Tapes. The conclusions from this study show that varying tension can have a significant impact on LTM generation in certain types of tape. Due to a lack of edge pinning and a smooth surface two of the AME tapes were shown to have significantly higher LTM at low tensions.

A potential limitation of the previous studies is that all of the LTM measurements were made using an optical probe. While the measurements taken with the optical probes would capture true LTM, they may also convolve the physical edge profile of the tape samples as tape motion, which could alter the LTM measurements. Alfano and Bhushan (2006a) worked on a LTM measuring technique based on reading back a halfway detuned magnetic signal written on the tape. This technique allows one to measure LTM between the edges of the tape, ostensibly leading to a truer measurement of LTM. With the advent of this new LTM measurement technique and the knowledge that probe measurements previously found that tension and speed can have an impact on LTM it is important to further refine our understanding on the impact tension and speed may have on true LTM between the edges of the tape.

As such, the current study will investigate the effects of varying tension and speed have on six different tape samples using the magnetic signal method of LTM measurement. The new technique will allow for conclusions to be drawn on the true impact varying tension and speed has on tapes ranging from current technology to tapes with potential for future commercial use. Additionally, as the magnetic signal technique is not dependent on stationary optical probes, this study will look to not only determine the impact of varying tension and speed on different types of tape, but also seek to determine if the physical location of the written signal in terms of relative position to middle of the tape or close to the top and bottom edges has an effect on LTM. Finally, as the magnetic signal technique for measuring LTM is relatively new, this study will look to compare the results generated with this technique to those taken with the optical probe used in previous studies.

3.2. Experimental details

3.2.1. Tape transport and test procedure

Drive tests were conducted in a class 10,000 laboratory environment (22 ± 1 °C; relative humidity 45 ± 5 percent) using the Segway Systems / Mountain Engineering II MTS linear tape transport with horizontal tape path, shown schematically in Fig. 3.1 (a). Tape bearings are single-flanged and tapered at an angle of 0.6 degrees to force the lower edge of the tape to ride along the flange. The head mount is designed such that the head zenith angle is the same as the bearing taper angle. Penetration of the head into the tape path was set the same for each test. Each bearing consists of a housing, porous ceramic bearing material, lower flange, and outriggers. The housing and the bearing member form a plenum connected to an air pump such that airflow through the porous material creates an air cushion that supports the tape. The outriggers at each side of the guide provide cleaning action for the tape (Gavit, 1998).

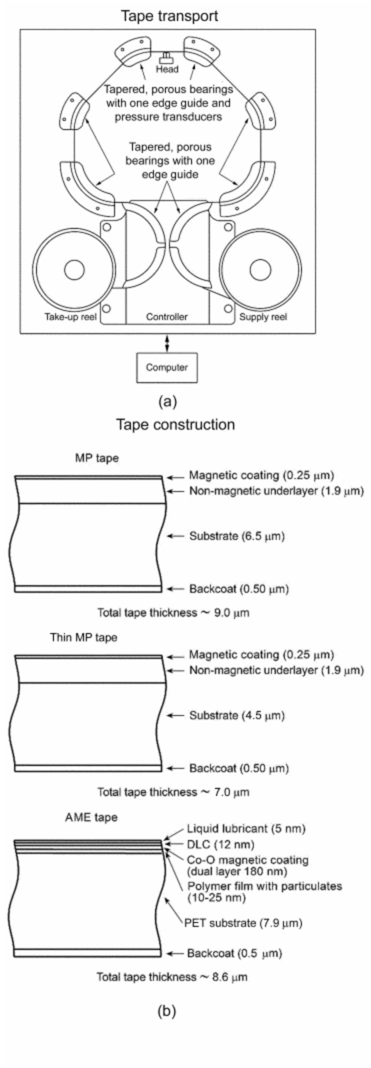


Fig. 3.1 (a) Schematic diagram of the Segway Systems/Mountain Engineering MTS linear tape transport with porous air bearings and single-flanged tapered guides (b) Cross-section schematic showing the structure of MP, Thin MP, and generic AME tapes

Tape tension is monitored on both sides of the head by measuring air pressure in the gap between the tape and the bearing member by means of pressure transducers that are mounted in the two guides bracketing the head. The drive controller monitors the pressure transducer signals and angular velocities of the tape reels and maintains constant tension and linear tape speed during a pass. The controller is connected to a PC that allows the operator to program certain drive parameters. Up to 600 m of 9 μm-thick tape can be loaded onto the tape reel, and the drive can be programmed to run for a specific number of cycles, with practically any pass length, at tape speeds between 2 and 8 m/s and tensions between 0.5 and 1.2 N. Pass length was set at 30 m with one forward and one reverse pass equal to one 60-m cycle.

3.2.2. Tape and head samples

Figure 3.1 (b) is a schematic of the cross-sections of MP, Thin MP, and a generic AME tape. The MP tape used in this study is commercial, 12.7 mm-wide Ultrium 1 tape. It is a dual-layer metal particle tape with magnetic layer and backcoat thicknesses of 0.25 μm and 0.5 μm, respectively, a substrate thickness of about 6.5 μm, and an overall thickness of 9 μm. The magnetic layer contains needle-shaped, passivated iron magnetic particles and head cleaning agents (HCAs) dispersed in a polymer formulation of binder and fatty acid ester lubricants. The magnetic particles are typically 0.1-0.2 μm or smaller in length and have an aspect ratio of five to ten. The HCAs are generally 0.2-0.3 μm-diameter Al_2O_3 particles and conductive carbon particles, added to improve friction, wear, and electrical conductivity. The Thin MP tape used in this study is an experimental tape with properties similar to the commercial MP tape described above. The main difference between the two tapes is that the substrate thickness has been decreased to approximately 4.5 μm in the Thin MP tape, reducing the total thickness to 7 μm.

Four AME tapes were used in this study. AME tape is 12.7 mm wide. The overall tape thickness of AME tape is about 8.6 μm. Three of the AME samples are experimental formulations with different cupping (natural curl of the tape edges away or towards the head) orientations. These samples will henceforth be referred to as Tape A samples. One of these AME samples is negatively cupped (edges curl away from the head) and henceforth, will be referred to as AME-NC Tape A. The remaining of two Tape A samples are positively cupped (edges curl towards the head), but one sample is much more aggressively cupped. The shallower of the two positively cupped samples will be referred to as AME-PC Tape A and the more aggressively cupped tape will be known as AME-PC+ Tape A. The frontcoat of all three AME Tape A samples consists of the dual magnetic layer (180 nm thick) of evaporated Co-O, over which is a 12 nm thick diamond-like carbon (DLC) coating, over which is a 5 nm-thick liquid lubricant layer. DLC is a hard coating used to protect the magnetic coating against corrosion and wear. The lubricant enhances the durability of the DLC and magnetic coatings by reducing friction at the head-tape interface. The lubricant commonly used consists of an overcoat of fatty acid esters on a perfluoropolyether (PFPE) coating. The fourth AME sample is an experimental positively cupped sample, which will be referred to as AME-PC+ Tape B. This sample also has layers of DLC and lubricant of unknown thicknesses.

Figure 3.2 is a schematic of the commercial Seagate LTO (Generation 1) head used in this study. It is an inductive write/magnetoresistive (MR) read head with Al_2O_3-TiC substrate, 80/20 Ni-Fe MR stripe, Co-Zr-Ta (CZT) shields and poles, and Al_2O_3 overcoat, undercoat, and gap material. The MR stripe, shields and poles, and overcoat, undercoat, and gap material are sputter deposited on the substrate. The head is vertically symmetric about the glue line, so only half of the head is shown in Fig. 3.2. The crosshatched areas in the head schematic (not including the blow-up of the thin-film region) are raised surfaces and areas without crosshatching are transverse slots. The outermost raised surfaces are outriggers, designed to remove loose debris from the tape before passing over the poles. The slots are designed to allow air to bleed away from the interface and also serve to capture some loose debris that passes through the interface. The head has eight read/write channels, numbered zero through seven, two servo channels above the read/write channels, and two servo channels below the read/write channels. For each read/write channel there are two thin-film regions (one on either side of the head), giving the head read-while-write capability. The write elements were 27 µm in height and the read elements 12 µm. A Faulhaber 1524E012SR coreless DC stepper motor along with a Faulhaber MVP 2001 motor controller actuated the head.

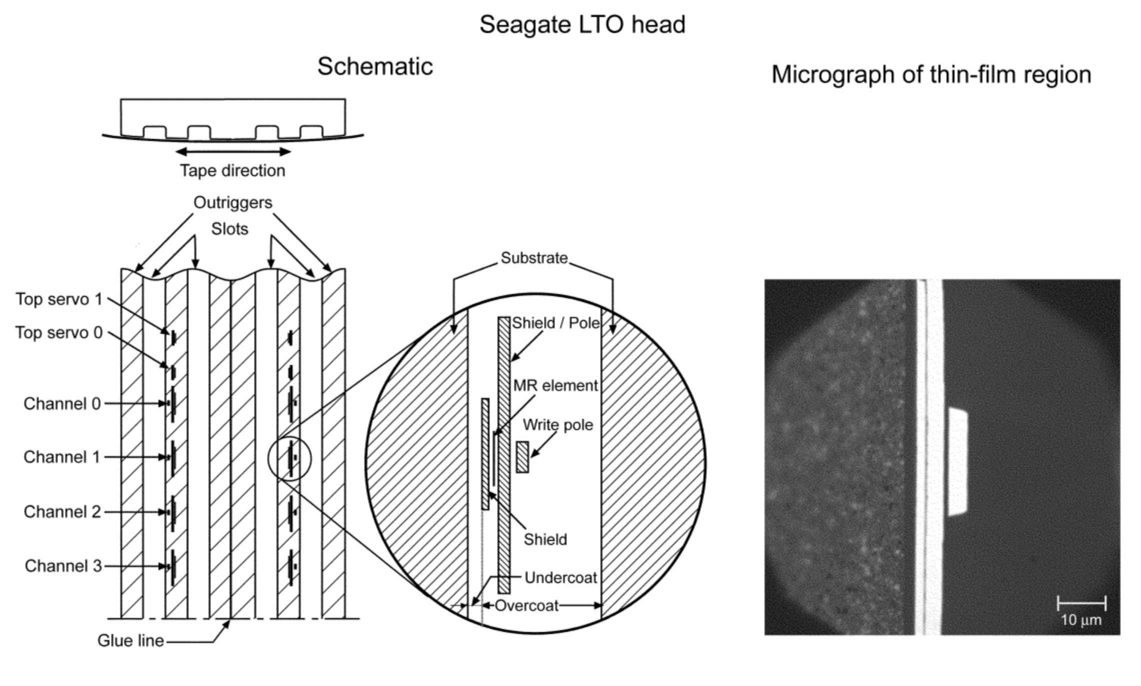


Fig. 3.2 Schematic drawing of one half of the Seagate LTO head (symmetric about glue line) with detailed schematic view and optical micrograph of the thin film region

3.2.3. Measurement techniques

Tape cupping is the natural tendency of the tape to curl about an axis parallel to the direction of travel along the tape width (Bhushan, 2000, Scott and Bhushan, 2003). Positively cupped tapes curl so the edges are towards the head, while negatively cupped tape edges are curled away from the head. Cupping measurements of the six tape samples in this study were made using an optical microscope (OPTIPHOT-2, Nikon Corporation, Tokyo, Japan) following the technique developed by Scott and Bhushan (2003). The MP tape used in this study has negative cupping equal to about 1 mm at its greatest. Thin MP and AME-NC Tape A samples displayed a negative cupping slightly greater than 1 mm at its greatest point. The AME-PC Tape A sample used in this study has shallow positive cupping equal to about 0.1 mm at its greatest. The other positively cupped Tape A sample, AME-PC+ Tape A, has a more aggressive positive cupping equal to about 0.6 mm at its greatest. The AME Tape B sample, AME-PC+ Tape B, was shown to have an aggressive positive cupping of approximately 0.7 mm at its greatest point. A tape cupping plot of the six samples is shown in Fig. 3.3.

During the study, the coefficient of friction is calculated from the drive tension signals using the belt equation and captured by the data acquisition software (NI-6023E, National Instruments, Austin, TX) with a sampling rate of 700 Hz. The data acquisition was controlled by Snap-Master V3.5 data acquisition software (HEM Data Corp., Southfield, MI).

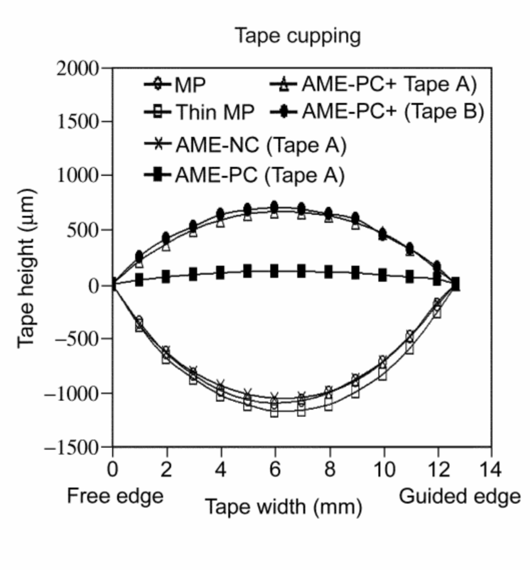


Fig. 3.3 Measured cupping profiles of the six tape samples

LTM was measured using two methods. The first method utilized the MTI 2000 Fotonic sensor, equipped with Edge Probe (MTI Instruments Inc., Latham, NY, probe 2062E with sensitivity of 17.853 μm/V and a noise level of 20 mV_{p-p}). In this method, which has been the predominant LTM measuring technique in the past, the edge probe is positioned over the tape edge. Light from the light source is reflected by a 90-degree prism to another 90-degree prism and finally reaches a photodiode (light receiver). The Fotonic sensor converts the photodiode signal, which is proportional to the light intensity, into the output units (volts or microns). If the light path is not obstructed by the tape edge the output of the Fotonic sensor is 100 percent. The output decreases as the tape moves upward into the gap between the prisms and vanishes to zero when no light reaches the photodiode (Goldade and Bhushan, 2003).

Optical measurements of LTM, such as with the edge probe used in this study, may convolve tape motion measurement with the measurement of the tape edge profile. The contour of the tape edge is not a straight line, but instead it can be rough and jagged. The Fotonic probe may convolve the unevenness of the tape edge as tape motion. The convolution of the tape edge cannot effectively be removed from the measurement of true motion. Thus, the values obtained with the Fotonic probe provide only an estimate of true LTM. Figure 3.4 provides an illustration of the effect tape edge profile may have on the LTM measurements derived from use of the Fotonic probe.

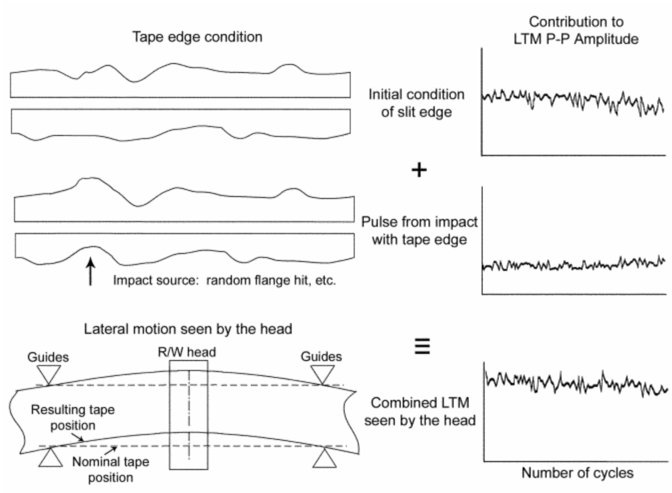


Fig. 3.4 Schematic illustrating the different components of LTM and their contribution to total LTM peak-to-peak amplitude

The second LTM measuring system employed in this study is based on the readback of a magnetic signal described by Alfano and Bhushan (2006a). The use of this technique was designed to eliminate any convolution of tape edge profile as tape motion in LTM measurements. In this method 200 kbpi sine waves were written at 4, 6 and 8 m/s (individually depending on which speed was being used for an individual test) resulting in 5.5, 8.0, and 10.5 MHz signals, respectively, being written to the tape using only read/write channel six. The read signal was then amplified internally with a 47 dB gain factor and filtered using a band pass series RLC circuit tuned to the appropriate frequency to eliminate noise. This AC signal was then converted to a DC RMS voltage using a HP 400EL voltmeter and was recorded by the data acquisition software at 700 samples per second.

During the experiments, once the signal had been written to the tape, the head location was optimized using the stepper motor until the read element produced a maximum value. This optimization is necessary to counteract any head misalignment issues. When amplified, this resulted in a signal output that ranged from approximately 0.17 volts at 8 m/s, 0.30 volts at 6 m/s, and 0.42 volts at 4 m/s. These voltages coincide with the 12 µm read element being completely inside the 27 µm written track. The head was then adjusted so the read channel read approximately 0 V. This coincided with the 12 µm read element being completely outside the 27 µm written track. The head was once again adjusted so the read element gave an output of approximately half of the reported values for signal output with the read element completely inside the written signal. This position lies in the linear region of the MR read element calibration curve and indicates that the read head was placed halfway on the written track and halfway off of the track. This left 6 μm of read element on and off the written track. A schematic of this MR reader placement is shown in Fig 3.5 (a). In order to report the output voltage as displacement in microns, a conversion factor was necessary. This conversion factor can be readily obtained if the plot of output voltage versus displacement is linear.

To determine if the MR read elements would respond linearly to displacement, calibrations were conducted. To be consistent with experimental procedure, the head was placed initially so the read element produced a maximum value. From this position, the head was displaced in 0.1 μm increments and the average voltage output per forward pass from each position was recorded. In order to determine that the output voltage corresponded to the reading of the written track a HP 8568B Spectrum Analyzer was used. Before each data point was recorded, it was determined that the signal was still greater than the current noise floor. Once the signal was below the noise floor, no further data was taken.

Calibrations were completed at all three of the speeds on all six of the tape samples. Plotting the voltage per displacement data for each speed and tape combination produced a calibration curve. An example of one of these curves is shown in Fig. 3.5 (b).

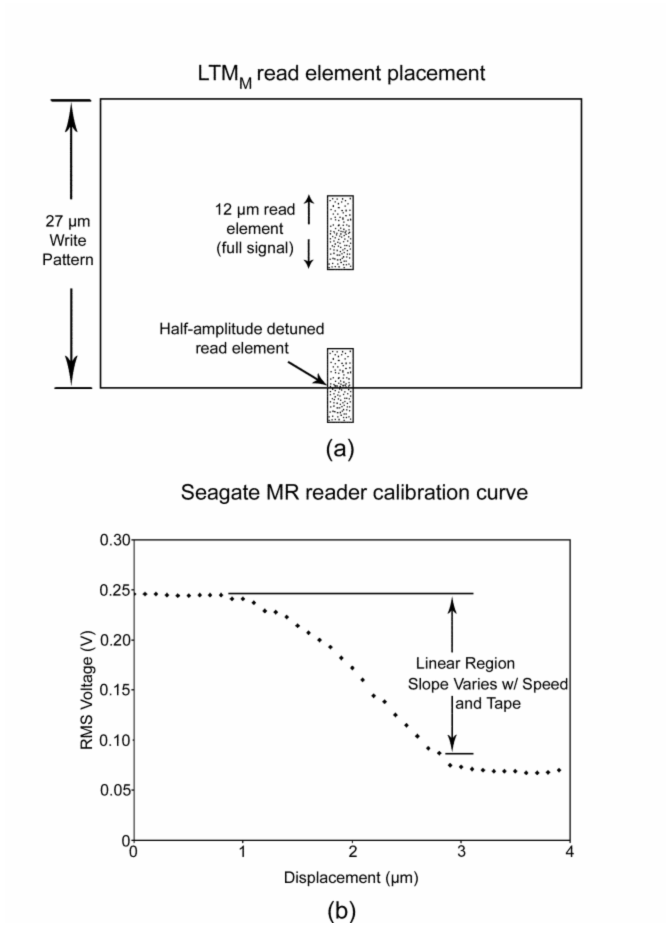


Fig. 3.5 (a) Schematic indicating the LTM$_M$ read element placement (b) Example calibration curve for the Seagate MR reader

Evident from this curve is that a linear region exists between voltages that correspond to the full signal amplitude and the noise floor. Table 2 displays the calibration factors used for each tape and speed combination. Note that Alfano and Bhushan (2006a) found that in completing multiple trials of these calibration curves the results proved to be repeatable. The calibration factor can then be used to convert differences in voltage into LTM measurements.

Since this study will be using two different methods to measure LTM data it will be important to distinguish between the two. The reported LTM values from Fotonic edge probes correspond to the physical location of the tape due to both tape motion and edge contour. In light of this LTM measurements made with the Fotonic edge probe will henceforth be termed lateral tape motion physical (LTM_P). The LTM data taken with the magnetic signal readback method equates to LTM that would be seen by the MR reader during drive operation and would be a measure of LTM that occurs between the edges of the tape. Since this method involves the readback of a magnetic signal all LTM measurements made with this technique will henceforth be referred to as lateral tape motion magnetic (LTM_M). LTM_M data is considered a more accurate reflection of actual LTM, as it is measured in between the tape edges and is the LTM seen by the MR reader.

Calibration factors for magnetic signal technique

Tape/Speed	4 m/s	6 m/s	8 m/s
MP	78.7	76.1	74.5
Thin MP	40.9	39.8	69.3
AME-NC Tape A	40.3	86.2	100.0
AME-PC Tape A	41.4	52.2	94.6
AME-PC+ Tape A	22.4	29.4	29.4
AME-PC+ Tape B	29.6	55.0	79.0

Table 2 Calibration factors used in magnetic method of measuring LTM

One final distinction needs to be made in terms of LTM measurements that are reported in both terms of LTM_P and LTM_M. The first value reported is average LTM peak-to-peak amplitude (LTM P-P amplitude). This is a measure of tape motion within the same cycle and is found by parsing the LTM data into one-second increments and averaging the difference between the highest and lowest tape position in each one-second block over the forward pass. The second type of LTM data reported will be non-repeatable LTM. Non-repeatable LTM measures tape motion from one cycle to another and can be presented in several ways. The most prevalent term used in this study when discussing non-repeatable LTM will be LTM quality factor. LTM quality factor is found by taking the maximum and minimum measurements of tape position at a specific point in time within each pass +/- a 0.05 second window (example second 3 +/- 0.05, 2.95-

3.05). The minimum value of the minimum measurement from all of the cycles in a test is then subtracted from the maximum of all of the maximum points resulting in the measurement termed LTM Quality Factor. An increase in LTM Quality Factor would equate to an increase in variability from cycle to cycle.

3.2.4. Test plan

Combinations of the extreme allowable operating tension and speed were used in this study. Tension was varied from 0.5 to 1.2 N and speed was varied from 4 to 8 m/s. Table 3 illustrates the test plan used to study the effects of tension and speed on each tape sample. Note that the 1 N, 6 m/s combination is considered to be the nominal operating conditions in terms of tension and speed and should serve as a relative midpoint in the variation of tension and speed. Two runs of 100 cycles at each of the tension and speed combinations were completed for each of the six tape samples. These runs were completed with the magnetic signal written in the middle portion of the tape while under the corresponding tension and speed combination.

In addition to measuring LTM_M in the middle of the tape to determine the effects of varying tension and speed this study also includes a look into any effects the position of the magnetic signal may have on LTM_M. Rather the study will attempt to determine if there is a difference in LTM_M depending on the portion of the magnetic tape the signal was written on and if varying the tension or speed impacts any possible difference. In order to complete this portion of the study magnetic signals were written at each tension and speed combination on portions of the tape that are close to both the top and bottom edges. 100 cycle tests were completed at each tension and speed combination on both the top and bottom edges.

Tension and speed test matrix

	0.5 N	1.0 N	1.2 N
4 m/s	X		X
6 m/s		X	
8 m/s	X		X

Table 3 Tension and speed test matrix

3.3. Results and discussion

3.3.1. Tension and speed results

Coefficient of friction, peak-to-peak LTM and non-repeatable LTM were monitored throughout a series of tests that varied the tension and speed in six different tape samples with the magnetic signal located in the middle portion of the tape. The results for these tests will be presented in the following sub-sections. It should be noted that the values presented for the work done with the magnetic signal in the middle of the tape correspond to the average of two runs taken at each tension and speed combination with each tape sample.

3.3.1.1. Coefficient of friction

The top most graph in Figure 3.6 displays the coefficient of friction results for all of the tapes studied at every combination of tension and speed. While it is far more evident in the AME tape samples, one can see evidence that varying tension and speed affect the coefficient of friction values in all tapes. This is shown with a reduced coefficient of friction value in the low tension high speed runs. The reduction in coefficient of friction for the low tension high speed run is fairly dramatic for all of the AME tapes. Also note that the coefficient of friction is substantially reduced in most of the AME tapes for the low tension high speed combination compared to the runs at higher tensions. A reduction in the coefficient of friction at low tension runs indicates that hydrodynamic effects are present when running the tapes through the tape drive.

A model of the head-tape interface developed by Elrod and Eshel (1965) explains the hydrodynamic effect. The tape lifts off of the head, as the tape is moving due to the development of a hydrodynamic air film. Head-tape spacing is directly proportional to $(V/T)^{2/3}$, where V is tape velocity and T is tension. Using this model one can see that decreasing tension would increase head-tape spacing. Increasing speed would further increase the head-tape spacing. An increase in head-tape spacing would reduce the real area of contact between the head and tape surfaces and, conversely this leads to a reduction in coefficient of friction.

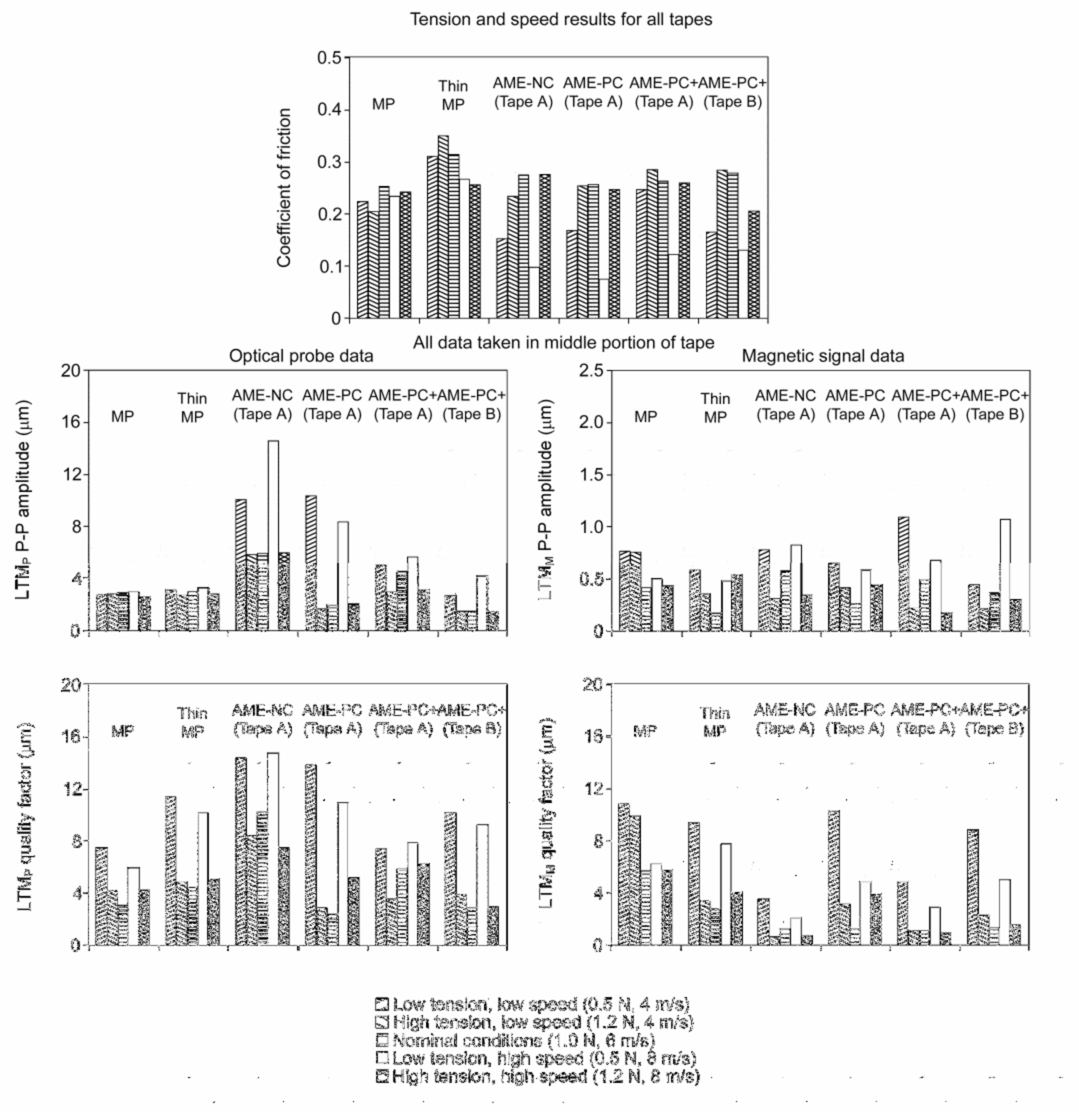


Fig. 3.6 Summary of the coefficient of friction, peak-to-peak LTM_P, peak-to-peak LTM_M, LTM_P quality factor, and LTM_M quality factor for the tension and speed combinations

used on all six tape samples

It should be noted that the MP and Thin MP tapes do not display the same level of hydrodynamic effects as the AME tapes. While the low tension high speed runs for the MP and Thin MP tapes are among the lower coefficient values for these tapes they do not show the dramatic reduction that is present in the AME tapes. One possible reason for this is that the surface roughness of MP tapes is considerably higher compared to AME tapes and because of this the real area of contact would not change significantly with the increased hydrodynamic effects present with low tension in MP tapes.

3.3.1.2. Peak-to-peak LTM

As discussed previously, peak-to-peak LTM is a measure of tape motion within an individual cycle. The middle graphs in Fig. 3.6 display the peak-to-peak LTM results. The left hand side shows the LTM_P results, while the right hand side displays the LTM_M results. Before discussing specific results note that the amplitudes for LTM_P and LTM_M are significantly different. This may be explained by the inclusion of the tape edge profile, out of plane motion, and breathing (changing) of the cupping during cycling in LTM_P measurements.

When looking at the MP and Thin MP data for LTM_P one can see that there is little difference between the different tension and speed combinations. Shifting to the LTM_M results one does not see a lack of variation when looking at the different tension and speed combinations. However, examining the results closely one can see that there is not a discernable trend in this data. For example looking at the Thin MP data the low tension low speed combination is higher than the high tension low speed data, but the low tension high speed data is lower than the high tension high speed LTM_M. This lack of trend in the LTM_M data illustrates what the LTM_P data shows in that there is not an effect on MP or Thin MP tape when varying the operating tension and speed. This was previously found to be the case by Wright and Bhushan (2006) who explained that the surface roughness of the MP tapes is sufficient enough to grip the head at all tension and speed combinations.

One of the first things that can be noticed when looking at the LTM_P data for AME-NC Tape A is that the values are in general higher than the other tapes. Alfano and Bhushan (2006b) hypothesized that the reason AME-NC Tape A shows an increase in LTM_P is two-fold in that it has a smooth surface and it suffers from a lack of edge pinning due to its negatively cupped profile. Note that a general increase in LTM_M magnitude for AME-NC Tape A when compared to all other tapes is not as apparent as the LTM_P results, but for instance the LTM_M data at nominal conditions is higher for AME-NC Tape A than all other tapes. In addition to the general increase in LTM it is clear that both LTM_P and LTM_M increase in AME-NC Tape A at low tension. The prevailing reason for the increase in LTM_P and LTM_M is a continuation of the reasoning for the general increase in these values. The use of low tension compounds the problem of a lack of edge pinning and reduces the real area of contact leading to higher LTM_P and

LTM_M.

When one looks at the LTM_P results for the positively cupped AME tapes one sees first that the values at high tension and nominal conditions are sufficiently lower than the AME-NC Tape A results. This can be seen in some moderation with the LTM_M results, as well. This suggests that at higher tensions the positively cupped AME tapes have sufficient edge pinning. Next one can note that the LTM_P results at low tension for the positively cupped AME tapes all show an increase when compared to the results at higher tension. However, it is easy to see that the increase in LTM_P is greater for AME-PC Tape A compared to AME-PC+ Tapes A or B. The reasoning behind this is that AME-PC Tape A is basically flat and at low tension the tape would be in contact more with its smooth surface instead of its edges. AME-PC+ Tape A and B have more aggressive cupping which help to mitigate any increase in LTM_P when operating under low tension because of an increase in edge pinning. The LTM_M results again confirm that there is an increase for the positively cupped AME tapes. However, the increase in LTM_M at low tension is just as significant if not greater for AME-PC+ Tapes A and B when compared to AME-PC Tape A. This suggests that the tape motion in the middle of tape is increased at low tension regardless of the aggressiveness of the cupping. One explanation for this may be that with the AME-PC+ Tape A and B samples a flexing of the tape may occur around one of the pinned tape edges. This was first discussed by Alfano and Bhushan (2006c). An illustration of this pivoting effect is shown in the left hand side of Figure 3.7. This pivoting effect would allow for greater motion in the center

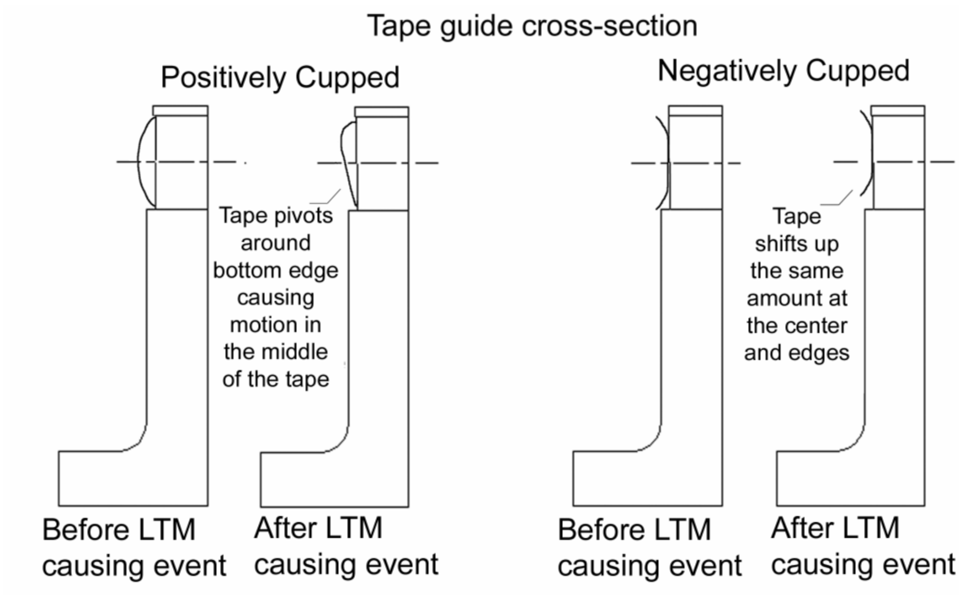


Fig. 3.7 Schematic illustrating the effects of tape cupping and edge pinning

of the tape and would not necessarily be monitored as much in the LTM_P measurements, as the probe would be monitoring the bottom edge that remains in a similar position. As the AME-PC Tape A sample is flat and lacks the edge pinning at low tensions the tape would not pivot around a pinned edge. Instead the tape would move up and down together similar to negatively cupped tapes.

The results of the peak-to-peak study show that any of the tape samples used would be acceptable for future use with the exception of AME-NC Tape A. In terms of LTM it would be highly desirable to use high tension. However, the use of high tension may cause issues with tape wear and optimization of the overall tape performance would be needed. Finally, note that varying speed does not appear to have a significant effect on the LTM_P and LTM_M measurements.

A few comments should be made in regards to comparing peak-to-peak LTM_P and LTM_M measurements. First when looking at the results one can see that the overriding trends in the LTM_P data exist in the LTM_M data. MP and Thin MP tape both show that varying tension does not impact either LTM_P or LTM_M measurements. Also, for all of the AME tapes there is an increase in both the LTM_P and LTM_M measurements when at low tension. However, there does not appear to be a direct correlation between an LTM_P measurement and an LTM_M measurement. This can be illustrated by looking at the data for AME-PC+ Tape A. The LTM_P results show that the low tension low speed measurement is lower than the low tension high speed data, but the opposite is true in the LTM_M data as the low tension high speed data is higher. This can lead to several conclusions. First trends can be measured using either measuring technique. Second there appears to be more variability in the magnetic signal technique. This could lead to difficulty in identifying trends, or it could mean that the variability in LTM is inherent in the tape drive system. Lastly, it is apparent that the probe data may see the overall trends, but it does not capture the overall motion of the tape as clearly as the magnetic signal technique. This may be due to the fact that the tape edge profile is masking some of the actual motion, or that the probes cannot accurately pick things up like the tape pivoting over one of the tape edges.

3.3.1.3. Non-repeatable LTM

Non-repeatable LTM is a measure of tape motion from cycle to cycle. Excessive non-repeatable LTM could cause problems with the playback of previously written data tracks. As an example, if something is written to the tape and then after a series of cycling the tape through the drive so one can read or write other tracks the tape may shift up or down providing limitations on the ability to have a particular data track read back. As discussed previously, non-repeatable LTM will be reported in the form of a measurement termed LTM quality factor. Figure 3.8 presents an example time window plot that shows how the LTM quality factor is determined. At a specific point in time (within a limited range, +/- 0.05 seconds) the maximum and minimum points of each

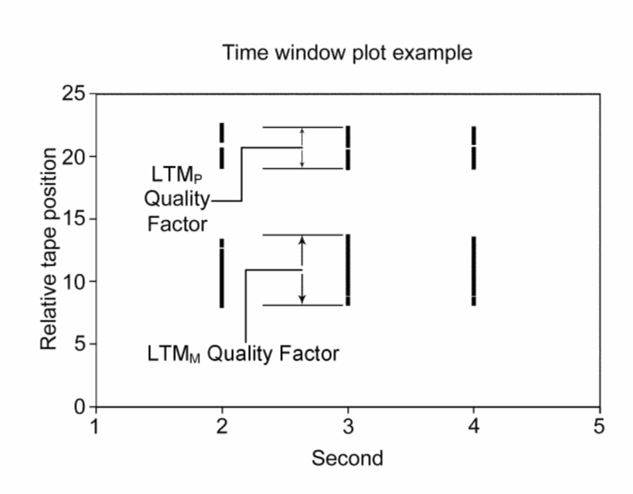


Fig. 3.8 Example of time window plot with illustration of LTM quality factor measurement

cycle are plotted for both the probe and magnetic signal data. The LTM quality factor for both LTM_P and LTM_M is taken as the maximum of all maximum values over the course of the test multiplied by the appropriate calibration factor minus the minimum of all the minimum values multiplied by the same appropriate calibration factor. If space permitted time window plots for all tapes and all tension and speed combinations could be presented. However, in the interest of brevity reverting back to Figure 3.6 the bottom most graphs display the LTM_P and LTM_M quality factor results for all tension and speed combinations on all six tapes.

Both the LTM_P and LTM_M quality factor results show the same overriding trend of increased magnitude when the operating tension is low. This result shows that for all tape samples used the variation from cycle to cycle is in all cases higher when operating at low tension. The prevailing reason for this is that at low tension the tape samples do not have ample edge pinning or surface roughness to secure the same position relative to the head when the tape transport switches from reverse to forward pass, or vice versa. While this reasoning intuitively makes sense, it must be noted that only one tape transport was used in this study. It may be that this particular tape drive has poor tension controlling when operating at low tensions. This could cause the tape transport to lose tension during the switch from reverse to forward pass shifting the tape up or down. However, if the tape transport used in this study has a problem with tension controlling at low operating tensions it would be reasonable to think that tape drives used commercially may have similar problems at low tensions. Finally, note that the quality factor results, particularly the LTM_M results, show a higher value in LTM quality factor when the tension and speed are low compared to when the tension is low and the speed is high.

One final illustration of non-repeatable LTM is displayed in Figure 3.9. The graphs on these plots show non-repeatable LTM for three different scenarios that presented themselves throughout this study. Note that the data presented in the figure is from runs at 4 m/s, but as the results have proven to be independent of speed they could be from any of the speeds used. The non-repeatable LTM presented in this figure is calculated by taking the maximum reading at a specific point in time during the forward pass of a cycle and subtracting out the average maximum value found over the course the test. This difference is then multiplied by the appropriate calibration factor and can be taken as a deviation in terms of tape motion from the average position of the tape in the test. The topmost example in this figure shows non-repeatable LTM_P and LTM_M that varies from the average fairly significantly and has several large peaks. This example typifies what occurred when using a tension of 0.5 N. Two scenarios presented themselves when running the tape drive at 1.0 or 1.2 N. The first is shown in the middle graph of this figure and depicts a variation from the mean that is much less severe than that displayed when using 0.5 N. The second scenario depicts a long term shift in tape position and is displayed in the bottom graph of this figure. This long term shift results when the tape position shifts ever so slightly in the same direction cycle after cycle.

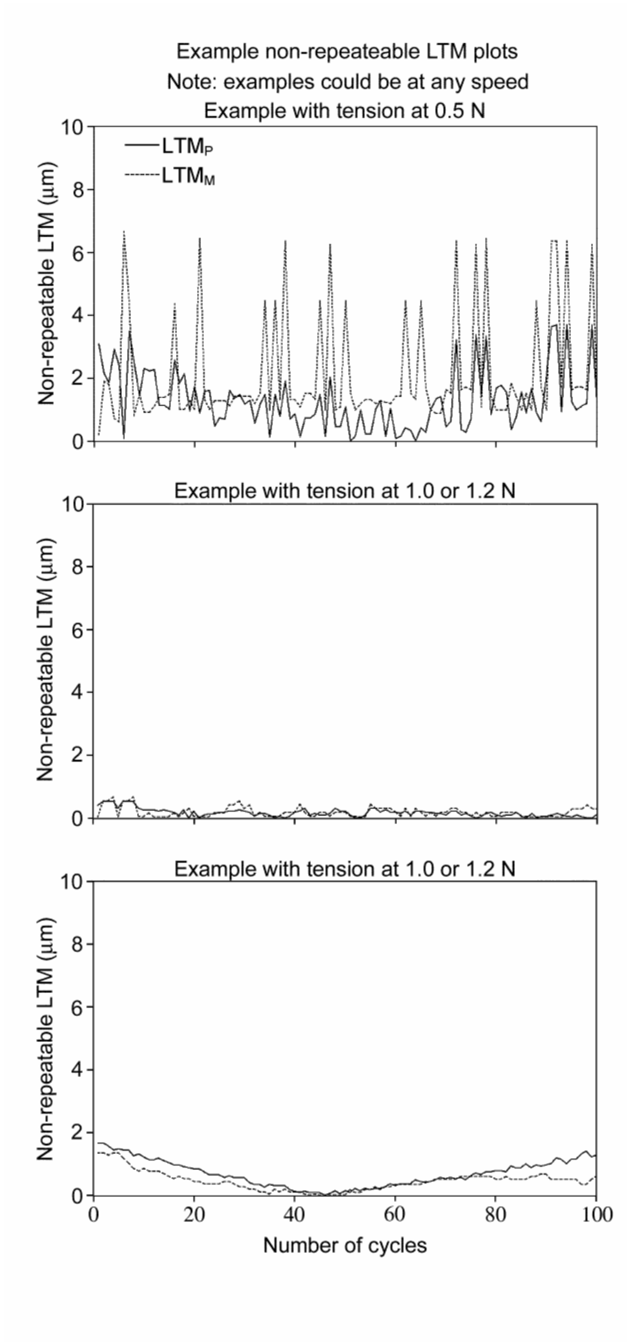
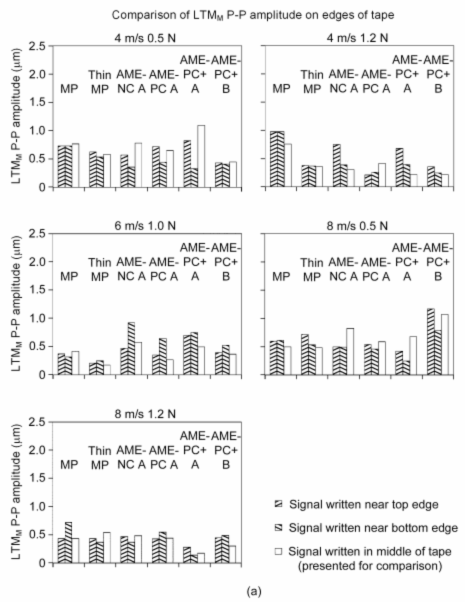


Fig. 3.9 Example non-repeatable LTM plots with three scenarios depicting the variability of tape motion from cycle to cycle

Modern servo followers would not have difficulty adjusting for the small change in tape position every cycle. That is not necessarily the case with the sudden and more severe shifts displayed when the operating tension is low. Also of interest in this figure is that it can be observed, particularly in the 0.5 N example that the non-repeatable LTM_P and LTM_M appear to mirror each other. Finally, note that these non-repeatable LTM graphs could be presented for all tension and speed combinations with all tape samples, but space does not permit their inclusion. As averaging this data may lose some of its effectiveness, Figure 3.9 is presented in an attempt to give examples in what occurs when the operating conditions are varied.

3.3.2. Effect of tape position on LTM

The last portion of the study was completed to see if there was a difference in LTM_M measurements based on where the magnetic signal is written on the tape. In order to complete this work a magnetic signal was written on the top and bottom portion of the tape samples, approaching the edges, at each of the tension and speed combinations. Figure 3.10 (a) displays the results for peak-to-peak LTM_M at each combination of tension and speed on each of the six tape samples. Each of the bar charts represents one of the tension and speed settings and displays the results from the tests that were written on the top and bottom portions of the tape. The results from the middle portion of the



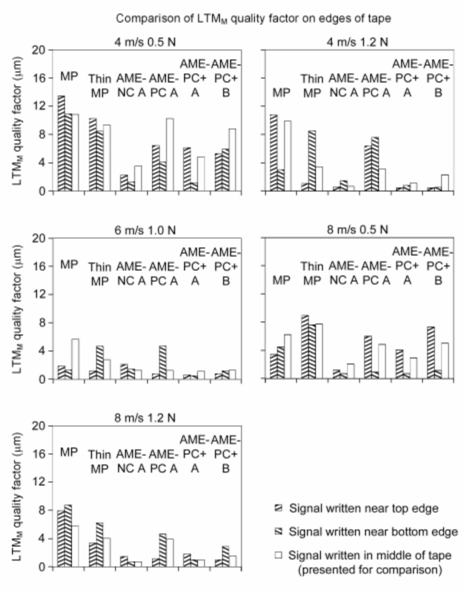


Fig 3.10 (a) Summary of peak-to-peak LTM_M measurements on the top and bottom edges

(b) Summary of the LTM_M quality factor measurements on the top and bottom edges tape are included for comparison and are the results that have previously been discussed in this paper. Looking at the data on the basis of either a tension and speed setting or on the results based on the type of tape there is a failure to find any sort of discernable trend in the data. For instance if one looks at the 8 m/s 0.5 N data it is clear that for some of the tapes the results on the edges are the same as they are on the middle portion of the tape, but some of the results on the edges are higher or lower than those in the middle portion. Again looking at all of the tension and speed combinations and only for instance AME-PC Tape A one sees results that vary on the edges from being higher, lower, or very similar to the results from the middle portion of the tape. This random variation seems to hold true for all tension and speed settings and from tape to tape, which can be an indication of the random nature of tape motion. Also note that there does not seem to be a discernable difference between peak-to-peak LTM_M in terms of being on the top or bottom portion of the tape. This renders the conclusion that peak-to-peak LTM_M is not necessarily affected by physical position on the tape.

In addition to looking at peak-to-peak LTM_M on the edges LTM_M quality factor was also monitored on the edges. Figure 3.10 (b) displays the results for LTM_M quality factor on the top and bottom portions of the tape. Again, the results for the middle portion of the tape are those from previously discussed tests. Examining these results shows a similar lack of discernable trend from tape to tape or between tension and speed combination. Additionally there does not seem to be a difference between the top and bottom edges. The results show no pattern regarding position on tape, thus it should be concluded that physical position on tape does not impact LTM_M quality factor.

3.4. Conclusions

The study was completed in an attempt to further the understanding of the impact of varying the operating tension and speed on the performance of different types of magnetic tape. This was done in hopes of providing information to tape and tape drive manufacturers on LTM, as they work towards increasing data acquisition times and data storage capabilities. Additionally, LTM results found by the new magnetic signal technique were compared with the standard optical probe method. Table 4 is presented as a summary of the peak-to-peak LTM data. From this table one can observe the following:

Summary of peak-to-peak LTM results

Tape/Condition	Nominal Conditions	4 m/s, 0.5 N	4 m/s, 1.2 N	8 m/s 0.5 N	8 m/s 1.2 N
MP	Low	Same	Same	Same	Same
Thin MP	Low	Same	Same	Same	Same
AME-NC (Tape A)	High	Increase	Same	Increase	Same
AME-PC (Tape A)	Low	Increase	Same	Increase	Same
AME-PC+ (Tape A)	Low	Increase	Same	Increase	Same
AME-PC+ (Tape B)	Low	Increase	Same	Increase	Same

Table 4 Summary of peak-to-peak LTM results

- In terms of peak-to-peak LTM AME-NC Tape A performs significantly worse than the five other tape samples under nominal conditions and under high tension. This is due to a lack of edge pining and a smooth surface.

- MP and Thin MP tapes are not affected in terms of peak-to-peak LTM_P or LTM_M by varying the operating tension and speed.
- All of the AME tapes see an increase in peak-to-peak LTM_P and LTM_M when the tension is lowered to 0.5 N. The increase is due to a combination of a lack of surface roughness and tape edge pinning at low tension.
- The increase in LTM_P at low tension is minimized in both of the AME-PC+ samples, as the more aggressive positive cupping provides more edge pinning.
- The same limitation in peak-to-peak data is not seen in LTM_M data. One reason for this may be that the edge pinning allows for the middle of the tape to pivot around one of the edges.
- Varying speed does not seem to have a noticeable impact on peak-to-peak LTM_P or LTM_M on the tapes used in this study.

In addition to these conclusions on peak-to-peak LTM, the following conclusions can be drawn from this study:

- Varying tension and speed directly impacts the coefficient of friction values for the AME tapes. This is caused by an increase in hydrodynamic effects.
- LTM_P and LTM_M quality factors are directly impacted when the operating tension is lowered to 0.5 N for all of the tapes studied. This shows that at low tension the tape moves considerably more from cycle to cycle.

- Results have failed to find any discernable difference in peak-to-peak LTM_M and LTM_M quality factor for all tapes studied based on the portion of the tape that the signal was written on.
- The LTM_P and LTM_M results have shown that the trends can be identified and studied with either method. However, there does not appear to be a direct correlation in comparing a specific LTM_P value to a LTM_M value. This can be attributed to many causes including the LTM_P values convolving tape edge profile as motion and the probe not being able to accurately capture motion in the middle of the tape due pivoting of the tape around one of the edges. For these reasons the magnetic signal readback technique provides the truer measure of LTM.

Solely in terms of performance based on LTM any of the tapes studied with the exception of AME-NC Tape A can be recommended for future use. It is highly preferred that higher tensions be used when using these tapes and it appears that the tapes may be used at high speeds of up to 8 m/s. However, high tension will have an adverse effect on wear and optimization will be needed to ensure the best overall performance of the magnetic tapes.

CHAPTER 4

SUMMARY

The drive for increased storage capacity in today's magnetic tape cartridges has created a continuing need to improve the understanding of the tribological performance of magnetic tape. One important area of ongoing tribological research is lateral tape motion (LTM). The importance of studying LTM will only continue to grow, as the demands for more storage capacity move forward. The research presented in this thesis has been conducted in an effort to improve the knowledge base with regards to LTM generation. Specifically, the goal of the first study was to determine the effects different operating parameters and types of tape had on LTM. The second study utilized a new measuring technique based on the readback of a magnetic signal to further study the effects varying operating tension and speed have on LTM.

Results from the first study showed that there were some differences in LTM based on type of tape or the varied settings of operating parameters. Specifically, negatively cupped AME tape was shown to have the highest LTM_P. Varying tension was shown to have an effect in some of the AME tapes, but not in the MP tapes. Head zenith and wrap angle can affect LTM_P, but the air pressure in the porous air bearings does not appear to have an effect on LTM_P. Finally, the bearing placement study and the staggered pack study showed that increasing LTM_P “downstream” minimally, if at all, affects LTM_P at the head.

Due to potential limitations in the optical probe method of LTM measurements a new method described by Alfano and Bhushan (2006b) was utilized in determining the effects varying tension and speed have on LTM in different types of tape. The findings of this study show that varying tension and speed directly impacts the coefficient of friction for AME tapes. The findings also show that peak-to-peak LTM is not affected in MP tapes, but it is in AME tapes when the tension is lowered to 0.5 N. Non-repeatable LTM increases in all tapes at low tensions. Changing operating speeds did not show a noticeable impact on LTM.

When comparing the optical probe and magnetic signal methods of measuring LTM it is apparent that both methods accurately follow the trends, however there does not seem to be a direct relation between the two. The optical probe method may convolve tape edge contour as motion and it seems that it is not able to accurately capture motion in the middle of the tape due to pivoting of the tape around one of the edges. This shows that the magnetic signal method provides a more accurate measurement of LTM.

Lastly, from the conclusions of this study it is recommended that in terms of minimizing LTM any of the tapes studied with the exception of negatively cupped AME tape can be used. In regards to LTM it is highly recommended that higher tensions be used with these tapes. Also, speed does not noticeably impact LTM, so higher speeds may be used in future tape drives. Note however, that the use of high tension may have a negative effect on wear, thus optimization will be needed to produce the best overall performance of the magnetic tapes.

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