# NEW DELAY-INTEGRATION METHOD FOR MEASUREMENT OF LATERAL TAPE MOTION AND STUDY OF TAPE PERFORMANCE UNDER HIGH SPEED CONDITIONS

A Thesis

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**ABSTRACT**

Magnetic data tape is one of the most cost-effective means of large scale information storage, and has the capacity to remain so in the future. Many challenges must be met in order to improve the storage density of magnetic tape systems and keep up with customer demands. One of these challenges is to minimize the relative motion between the read/write elements in the tape drive and the data tracks on the tape, also known as lateral tape motion (LTM). Many factors influence LTM, and care must be taken in design of both the tape drive and tape media in order to minimize the negative effects of LTM. This thesis details a study in which a new delay-integration method is applied to LTM measurement. The advantages and disadvantages of the method are discussed, and a comparison is made with previous LTM measurement methods. The delay-integration method is then applied to measure the change in LTM amplitude along an unsupported region of tape for several different tape samples. As many tape systems place the read/write head in the center of an unsupported region, information about the behavior of tape in this situation could be used to minimize LTM, allowing for smaller data tracks and increased storage density.

As the storage capacity of magnetic tape systems continues to increase so does the need for faster read and write access. One possible way to achieve this is to translate the magnetic media past the read/write head at a higher velocity. This increased speed can have unwanted effects on the operation of the tape drive and media. This thesis details a study of the effects that high-speed operation at different tensions can have on the performance of the system. The coefficient of friction between the tape and head was monitored to gauge durability and wear, and lateral tape motion (LTM) was monitored using both magnetic and edge probe methods to measure undesirable tape motion. Results for five different types of tape operating at five different tension/speed combinations are discussed in order to better

determine the effects that tape characteristics and operating parameters have in high speed situation.

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## PUBLICATIONS

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## FIELDS OF STUDY

Major Field: Mechanical Engineering

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# CHAPTER 1

# INTRODUCTION

As society increases its dependence on electronically stored information the demand for larger and more cost effective data storage systems increases as well. This has led to large gains in the capacity and cost effectiveness of common storage methods such as hard disks, optical media, and solid state memory. While these types of storage are sufficient for the needs of the average home computer user, they are often too expensive to use for archiving very large amounts of data, such as government or corporate databases. For these applications, where high capacity, high reliability, and low cost are valued over ease-of-access, magnetic data storage systems are often the best option.

In magnetic tape data storage systems data is stored on thin magnetic tape media. This media consists of a flexible, plastic substrate coated with a magnetic layer. Due to the thinness of the media a single tape cartridge can hold a large amount of tape, leading to a very large magnetic area on which data can be recorded. After the cartridge is loaded into the tape deck the tape is repeatedly wound and unwound between the cartridge reel and an internal drive reel. As the tape is being translated it moves past a read/write head. Elements on the head are able to modify the magnetic orientation of the particles on the tape surface, and this information can then be read back at a later time. Once the information transfer is complete the tape is wound back onto the cartridge and the cartridge can be removed and stored. A typical 3.5 in form factor tape cartridge can hold 500 GB of uncompressed data, achieving a higher volumetric storage density than hard disks or optical media.

In order to remain competitive in the future the magnetic tape industry must continue to increase the capacity of the media. Current industry aims are to achieve a 1 TB native cartridge within the next few years. This goal may be achievable by pursuing thinner tapes and new magnetic coatings. Thinner tapes are desirable, as thinner tapes allow for a longer length of tape to be wrapped onto a cartridge reel of a given diameter, resulting in a larger magnetic area and higher volumetric data density. In order to increase the areal density for the media new magnetic coatings must be pursued, enabling higher signal-to-noise ratios and allowing for smaller bit areas.  Smaller bit sizes correspond to smaller track widths, which can decrease the drive's tolerance for unwanted tape motion. This motion can cause the read and write elements in the head to become misaligned with the data tracks on the tape, resulting in data loss. Chapter two describes a new method for measuring this unwanted motion that overcomes many of the disadvantages of existing methods. Chapter three describes the application of this new method to the measurement of tape motion across an unsupported span, in order to gain a better understanding of how the tape moves in such a situation.

An increase in the rate at which data can be written to and read form the tape cartridges must accompany the increase in storage capacity in order to maintain reasonable read and write times. One way to increase the data throughput rate is to translate the tape past the head at a higher speed, resulting in access to a larger magnetic area over a given period of time. Increasing the speed may have several potential drawbacks, though, such as an increase in wear and unwanted tape motion. Chapter four examines a study conducted to evaluate the performance of several different tapes under a variety of speed and tension combinations. This data could be used to determine desirable characteristics for designing tape to be run at high speeds. Chapter five gives a brief summary of all findings.

# CHAPTER 2

# A NEW DELAY INTEGRATION METHOD FOR RESOLVING INDIVIDUAL COMPONENTS OF A PAIR OF COMPOSITE SIGNALS

## 2.1 Motivation

Measured values are often a composite of several unknown components. A simple example is the distance between two independently moving objects. The individual motion of each object affects the total distance between them. It is not possible, therefore, to determine the individual motion of each object when only the relative distance between the two is known. A measured value and the error in the measured value form a similar composite measurement. Both contribute to the total measurement, but it is not possible to determine the individual contribution of each without additional information. Techniques have been developed to minimize this problem in certain applications. One such technique is to design the original measurement system so that there is an inherent sensitivity towards the quantity that is being measured and less sensitivity to other inputs (Doebelin, 2004). A classical example of modifying a measurement system to make it insensitive to spurious inputs is the use of a Wheatstone bridge in strain gauge measurements. Changes in the resistance of a strain gauge can be due to both deformation of the gauge and a change in the temperature of the gauge. It would not be possible to separate the contribution of each from a single resistance measurement. By placing the strain gauges in a Wheatstone bridge configuration the resistance changes due to temperature are nullified, thus separating the two components of the composite signal. Another method of removing unwanted signal components is signal filtering (Doebelin, 2004; Nise, 2004). Through the use of filtering it is possible to reduce the amplitude of certain frequency components within the original signal. This is useful only if the interfering noise is a different frequency than the desired signal information.

In this study a new "delay-integration method" is described which allows for the reconstruction of the individual components of a pair of composite signals when one of the components is delayed with respect to the other. The delay-integration method was developed to measure lateral tape motion (LTM) in a magnetic data storage tape drive. Information is stored on magnetic data tape by modifying the magnetic orientation of particles on the tape surface as the tape translates past a write head. This pattern can then be read back on a subsequent pass, and the stored data can be retrieved (Bhushan, 1996, 2000). LTM is the mechanical motion of the tape in the plane of the read/write head perpendicular to the translating motion of the tape. This motion can cause read and write errors due to misalignment between the tracks on the tape and the elements in the head. Accurate measurement of this motion has been challenging due to the small scale of LTM (1 to 10 µm) compared to the high velocity of the translating tape (4 to 8 m/s). LTM has been previously measured by utilizing a MTI Fotonic probe (MTI Instruments Inc., Latham, NY) to monitor the height position of the tape edge (Taylor et al., 2000; Goldale and Bhushan, 2003). The height variations recorded by the edge probe when using this technique are a composite of both the tape motion (LTM) and the random profile of the tape edge caused by the tape slitting process (Goldale and Bhushan, 2004; Alfano and Bhushan, 2006). The contribution of each cannot be discerned from a single probe measurement because both LTM and the tape edge profile are suspected to have similar amplitudes and frequency components.

This study applies the delay-integration method to LTM measurement. With this method it is possible to differentiate between the tape edge roughness and the LTM components in the composite edge position measurement. This will allow for a more accurate measurement of LTM, which could assist in the improvement of future tape deck and tape media designs. The method also has promising application for error reduction in other types of systems, including both electrical and mechanical systems.

## 2.2 Experimental details

A delay-integration method for resolving the individual components of a pair of composite signals has been developed. The method can be used to determine the contribution of two different factors in a single measurement or to remove unwanted noise from a measurement. The method is able to distinguish between two component signals of similar frequencies and amplitudes, making it a viable solution in situations where traditional filtering can not be used. The method also has a constant phase offset for all frequencies, minimizing the distortion of the original signal. These qualities make the delay-integration method a valuable tool for resolving a pair of composite signals into their components.

### 2.2.1 Development of delay-integration method

The delay-integration method was originally developed to measure LTM in a magnetic tape data storage drive, and it is in that context that the theory will be developed. The traditional method of LTM measurement utilizes a single Fotonic edge probe measuring the position of the tape edge. If the tape edge were perfectly straight all changes in the edge position measured by the edge probe would be due exclusively to LTM. The tape edge is not straight, how-

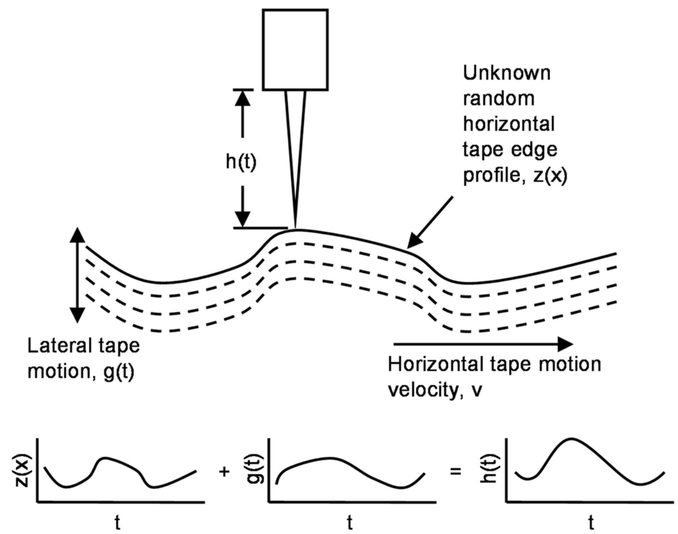



Fig. 2.1 Illustration of how both the tape edge contour variations and the motion of the tape contribute to changes in the tape edge position as measured by the edge probe.

ever, and has roughness on the same scale as the LTM. This roughness also causes changes in the measured position of the tape edge. The edge probe cannot distinguish between a change in the edge height caused by motion of the tape and a change caused by the roughness of the tape edge. The measured tape edge position is therefore a combination of both the LTM and the edge profile of the tape. This is illustrated in Fig. 2.1. For this example the LTM is assumed to be unknown and a function of time, $g(t)$. The profile of the tape edge is assumed to be unknown and a function of the position along the tape length, $z(x)$, with $x$ taken to be the distance from the right leading end of the tape. Knowing the tape velocity, $v$, this can be re-written as a function of time, $z(vt)$. The resulting edge position as measured by a single Fotonic edge probe, $h_A(t)$, is given in Eq. 2.1.

$$h_A(t) = z(vt) + g(t) \tag{2.1}$$

It is not possible to solve for either $z(vt)$ or $g(t)$ individually knowing only their sum. It is therefore necessary to add an additional Fotonic edge probe in series with the first. A schematic of the resulting system is shown in Fig. 2.2. The second edge probe measures the LTM component of the tape edge position simultaneous to the first edge probe, and measures the tape edge profile at a slight delay. The resulting measured edge position for the second Fotonic edge probe, $h_B(t)$, is given in Eq. 2.2.

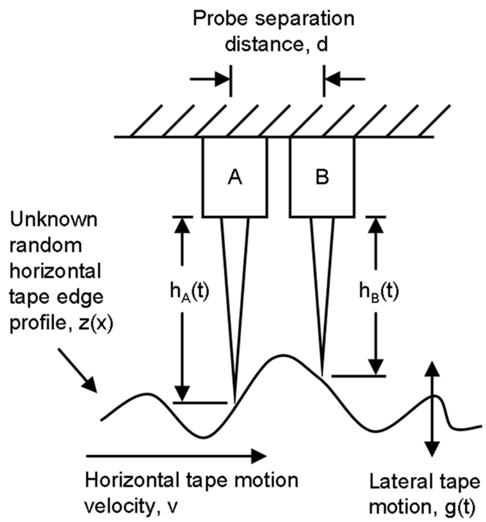



Fig .2.2 Setup diagram for LTM measurement using two Fotonic edge probes. The signals recorded by both probes contain LTM and edge roughness information, but the edge roughness information is delayed for the second probe.

$$h_B(t) = z(vt - d) + g(t) \tag{2.2}$$

It is also known that the edge profile measured by the first probe will again be measured at the second probe after a time delay equal to the probe separation distance divided by the surface horizontal velocity. Therefore,

$$h_B(t + d/v) = z(vt) + g(t + d/v) \tag{2.3}$$

Solving Eq. 2.3 for *z(vt)*,

$$z(vt) = h_B(t + d/v) - g(t + d/v) \tag{2.4}$$

Substituting Eq. 2.4 into Eq. 2.1,

$$h_A(t) = h_B(t + d/v) - g(t + d/v) + g(t) \tag{2.5}$$

Rearranging terms gives

$$g(t + d/v) - g(t) = h_B(t + d/v) - h_A(t) \tag{2.6}$$

The left side of Eq. 2.6 is the change in *g(t)* over time span *d/v*. The right side of Eq. 2.6 is known. Integration of these changes over time yields an approximation of the LTM. The unknown vertical surface motion, *g(t)*, can now be computed using Eq. 2.7.

$$g(t) \approx \int( v/d\ (h_B(t + d/v) - h_A(t)\ )\ ) \tag{2.7}$$

where *g(t)* is the lateral tape motion [m]; $h_B(t)$, $h_A(t)$ are the height profiles recorded by Fotonic probes [m]; *v* is the tape velocity [m/s]; *p* is the probe sampling period [s]; and *d* is the probe separation distance [m].

The result of the delay-integration method is an approximation of the original noise. This approximation becomes more accurate as the delay time is decreased. A delay time of zero is not practical, however, as the two input signals would then be identical.

### 2.2.2 General validation of delay-integration method through simulation

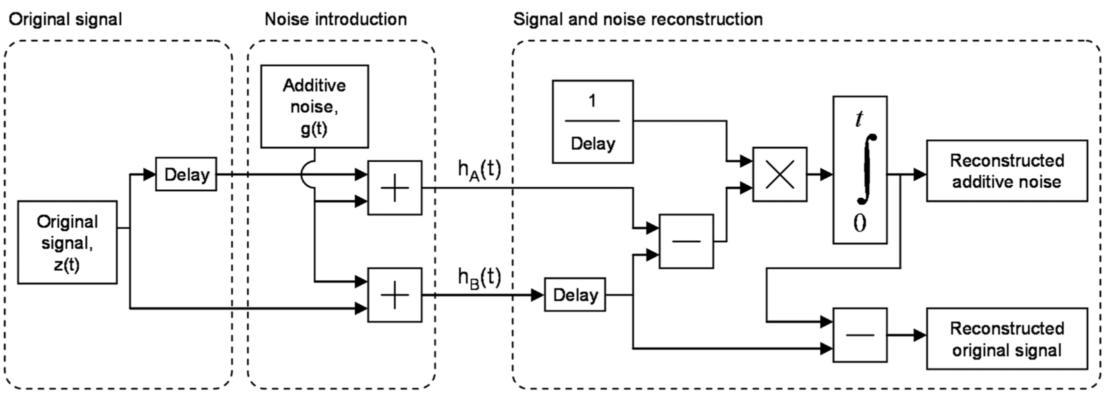



Fig. 2.3 Graphical representation of signal generation and reconstruction using the delay-integration method. In the LTM application the "Original signal" and "Noise introduction" sections represent the way in which the LTM ("Additive noise") and edge roughness ("Original signal") are combined in the probe measurements. The resulting signals $h_A(t)$ and $h_B(t)$ represent the signals recorded by the probes. The "Signal and noise reconstruction" section is the application of the delay-integration method, resulting in the reconstruction of the LTM and edge profile signals.

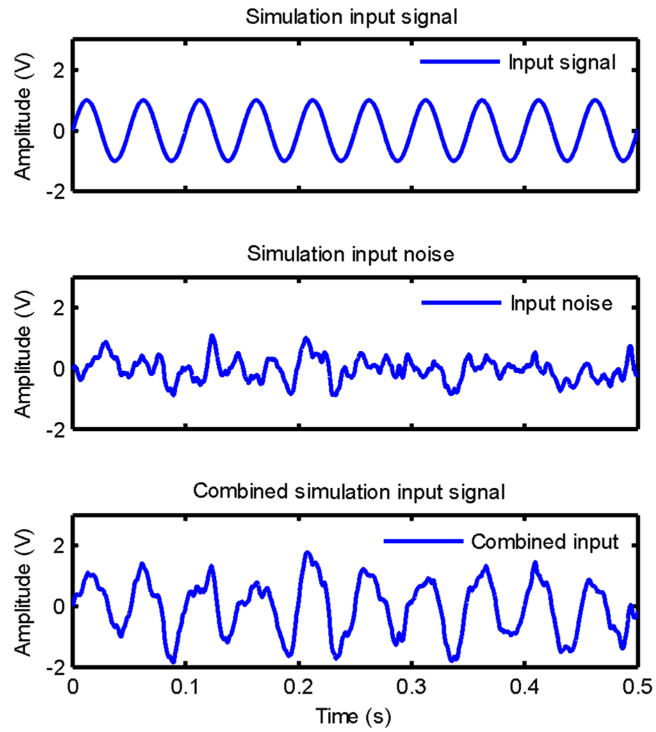



Fig. 2.4 The original signal and additive noise generated for use in the ideal simulation of the delay-integration method are shown in the upper and middle plots. These components were added together to create the two composite input signals. One of the two composite input signals is shown in the lower plot. Using the delay-integration method these composite signals can be decomposed back into the two original components.

A simulation was created to test the validity of the delay-integration method using MATLAB (Mathworks Inc., Natic MA). This simulation was based on the block diagram shown in Fig. 2.3. A sine wave was used as the original signal input, *z(t)*. Low-pass filtered band-limited white noise was used as the additive noise input, *g(t)*. The original signal and additive noise had approximately the same amplitude. These inputs and one of the resulting composite signals are shown in Fig. 2.4. A delay of 0.001 seconds was used. This simulation represents the operation of the delay-integration method under ideal conditions, where all parameters were precisely known and there was no error caused by differences in physical sensors or extraneous electronic noise.

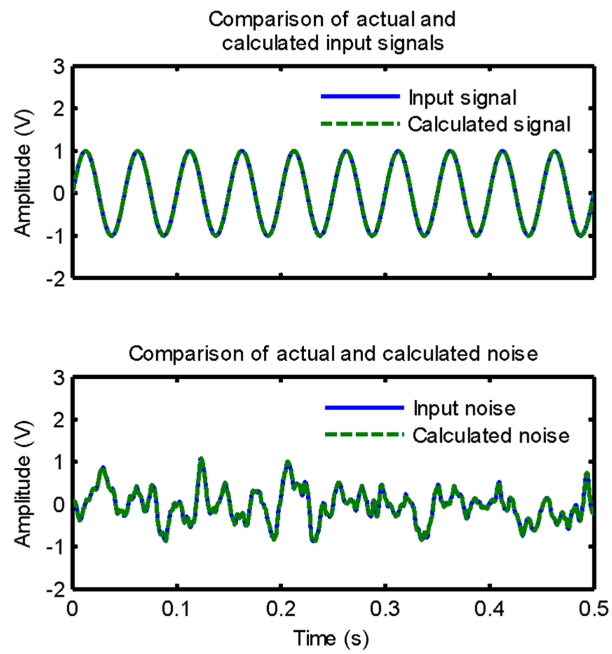



Fig. 2.5 Reconstructed original signal and additive noise from ideal delay-integration method simulation. Both signals were accurately reconstructed, as is shown by comparison to the original simulation inputs.

In the ideal simulation the original signal and noise were accurately reconstructed through the use of the delay-integration method. The results of the ideal simulation are shown in Fig. 2.5. These results indicate that the method is valid under ideal conditions, causing minimal distortion of the calculated signal and noise. The method can be used to reconstruct the original signal and the noise signal to a very high degree of accuracy. The accuracy of the method is decreased as the delay time is increased, though. The method is also very sensitive to disturbances that are individual to each of the two composite signals. These disturbances should be minimized to achieve an accurate reconstruction of the component signals.

### 2.2.3 Frequency response characterization through simulation

A second simulation was created to determine the effect that the delay length had on the frequency response characteristics of the delay-integration method. The simulation was run in an iterative fashion, with the input signal maintained at zero and a sine wave used as the noise input. The frequency of the noise input sine wave was changed for each iteration, with test frequencies logarithmically distributed between 1 and 10000 Hz. At each frequency the amplitude

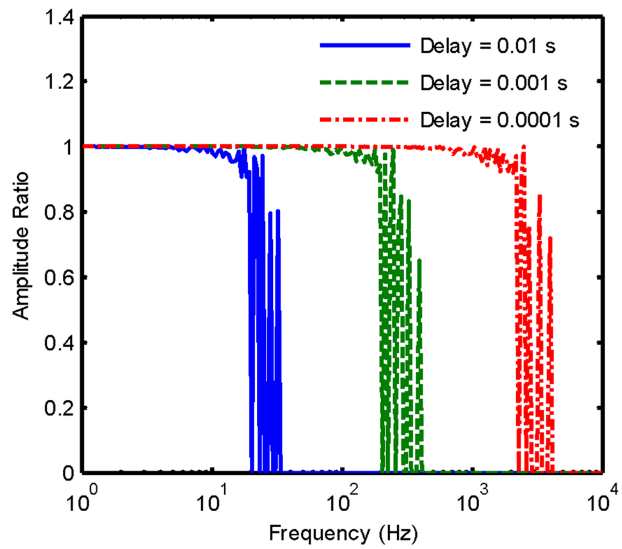



Fig. 2.6 Frequency response of delay-integration method using different delay times. The applicable frequency range for accurate reconstruction using the method is dependent on the delay time, with shorter delay times allowing for reconstruction of higher frequency components.

of the calculated noise signal was compared to the amplitude of the original noise signal. The same process was repeated for delay times of 0.01, 0.001, and 0.0001 seconds.

A direct correlation between the delay length and the range of noise frequencies that could be accurately reconstructed was found. The frequency response diagrams for several different delay times are shown in Fig. 2.6. The accurate reconstruction of noise of a given frequency is dependent on the length of the time delay with shorter delay times allowing for reconstruction of higher frequency noise. High frequency noise that could not be accurately reconstructed was not subtracted from the original signal and remained in the calculated signal. Based on the results of this simulation an approximate cutoff frequency for noise reconstruction, $\omega_c$, in Hz, is given in Equation 2.8, where Δ is the delay time in seconds.

$$w_c \approx \frac{0.1}{\Delta} \tag{2.8}$$

The results of this simulation can be used to determine the optimal setup parameters for the application of the delay-integration method, which will minimize error in the final reconstructed signals.

## 2.3 Application of delay-integration method

The delay-integration method has many possible applications to a variety of different systems. The method can be applied to any system that has measurement outputs in the same forms as Eqs. 2.1 through 2.3. Several different applications are described below to illustrate the versatility of the method. The first application is the measurement of LTM in a magnetic data tape storage drive. A simulation was developed to specifically model LTM measurement using the method. Information gained from this simulation was then used to optimize the measurement of LTM on an actual tape deck. Two alternative applications of the delay-integration method are also described. Noise form an improperly grounded electrical system was removed and the original transmitted signal successfully reconstructed using the delay-integration method. Also, the method was applied to a mechanical system and used to remove noise caused by a moving height sensor mount. In all cases the delay-integration method was applied through the use of a custom computer script. This required that all measurements be digitized through a

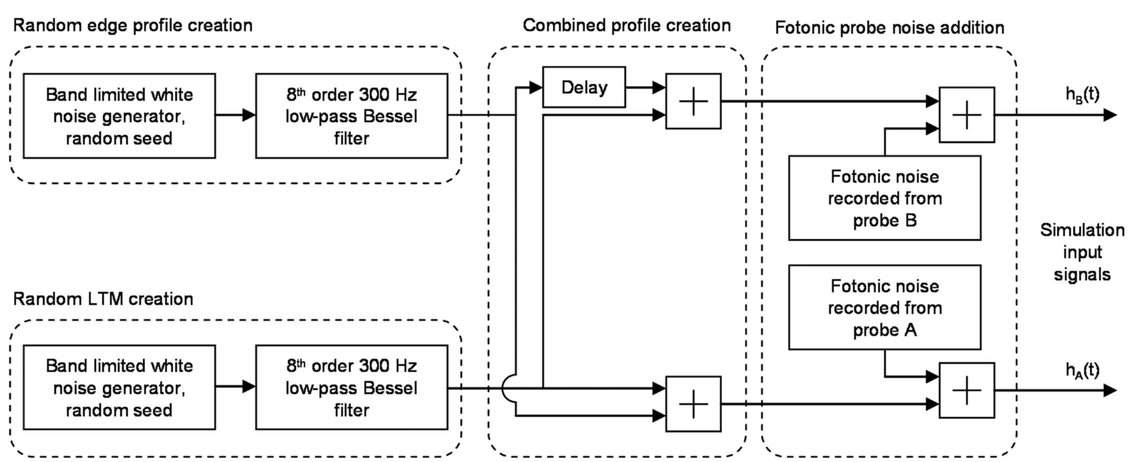



Fig. 2.7 Graphical representation of method used to create the input signals for the LTM measurement simulation. The tape edge roughness and LTM signals were randomly generated. Actual Fotonic noise recorded onto disk were incorporated into the composite signal.

data acquisition (DAQ) board and saved to disk. Once the signals were recorded to disk the data was processed and the components of the composite signals could be reconstructed.

### 2.3.1 Simulation of LTM measurement using delay-integration method

The delay-integration method was first applied to measurement of LTM in a magnetic tape data storage drive. One technique previously used to measure LTM in these drives utilizes a Fotonic probe to monitor the position of the tape edge as the tape is moving through the drive. In order to use the delay-integration method and separate the LTM and tape edge profile contributions it is necessary to add a second Fotonic probe. The resulting setup is shown in Fig. 2.2. This setup has many variable parameters which can greatly affect the accuracy of the measured LTM. These parameters include the distance between the two Fotonic probes, the rate at which the DAQ board samples the Fotonic probe signals, the speed at which the tape is run through the drive, and the filtering used to remove unwanted noise.

In order to determine the optimal setup parameters for this application of the delay-integration method a third simulation was developed. Previous experience with Fotonic edge probes indicated that the noise level for the desired range of measurement for this application (less than 20 μm) would be between 5 and 10 percent of full scale. This was acceptable in past studies, but the integration of such error over a long period of time leads to large errors in the calculated LTM when using the delay-integration method. In order to determine appropriate compensating actions the simulation was designed to closely model the LTM measurement process. This included the effects of the Fotonic probe noise, scale differences between the two Fotonic probes, and Fotonic probe measurement drift. Actual Fotonic probe noise was included in the simulation by using data recorded from a Fotonic probe measuring a constant height. Individual noise for each of the two Fotonic probes was recorded in this manner. This noise was then added to the simulated composite signals containing edge profile and LTM information. A block diagram of this signal generation method is shown in Fig. 2.7. The resulting input signal components and one of the resulting composite signals are shown in Fig. 2.8.

Different filtering configurations were tested in the simulation to minimize the impact of the Fotonic probe noise and drift on the accuracy of the calculated LTM. The final configuration consisted of a 5 to 400 Hz band-pass 8$^{th}$ order Bessel filter applied to the input signals to remove the higher frequency Fotonic noise and low frequency sensor drift and relative offsets. A 5 Hz 8$^{th}$ order Bessel high-pass filter was applied to the final calculated LTM signal to remove slowly accumulated error due to integration of remaining noise and scale differences between the two probes.

The simulated LTM and tape edge signals were reconstructed using the delay-integration method. The LTM measurement simulation results are shown in Fig. 2.9. The Fotonic noise and

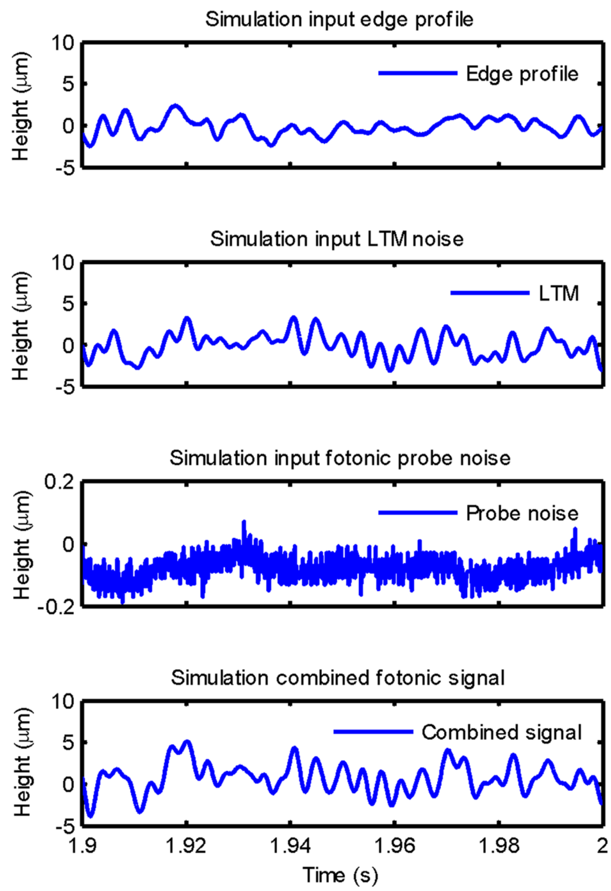



Fig. 2.8 Signal components and resulting composite input signal for simulation of LTM measurement using delay-integration method. The simulation includes Fotonic probe noise and drift specific to LTM measurement that was not included in previous ideal simulation of method.

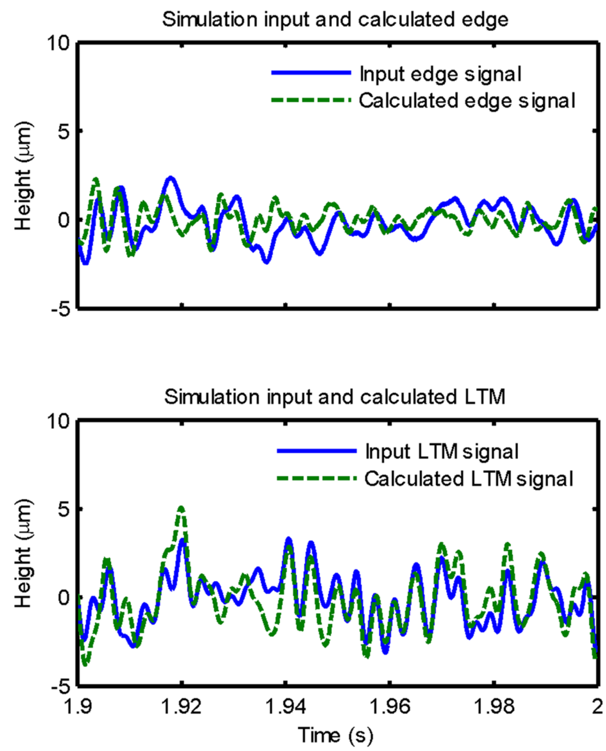



Fig. 2.9 Comparison of simulation results inputs. The Fotonic probe noise caused some error in both the calculated LTM and tape edge roughness.

drift caused some error in the calculated LTM because both probes experienced different noise, which was then misinterpreted as LTM. Integration of these small differences over time led to large errors in the reconstructed LTM signal. In order to minimize this error, filtering was applied to both Fotonic probe signals. This filtering distorted the calculated LTM signal, but generated a more accurate approximation of the original input than was calculated without filtering.

It was found that the selection of the delay time used had a large impact on the error in the calculated LTM signal due to the Fotonic probe noise. Decreasing the delay time increases the error caused by the Fotonic probe noise. This is because the difference between the two Fotonic probe measurements is divided by the delay (Eq 7), and so a smaller delay time amplifies the Fotonic noise error. Increasing the delay time, however, reduces the range of LTM frequencies that can be accurately reconstructed (Eq 8). The delay time should therefore be selected so that the cutoff frequency for LTM reconstruction is as close to the maximum expected LTM frequency as possible. This causes the LTM to be accurately reconstructed while minimizing the error due to amplification of Fotonic probe noise.

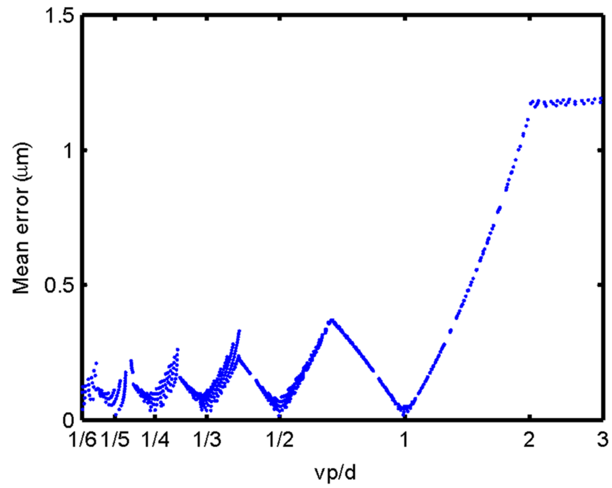



Fig. 2.10 Relationship between setup parameters and LTM signal error. The error can be minimized by coordinating the sample rate, probe separation distance, and tape speed to ensure that the same spot on the tape edge is being measured by both probes.

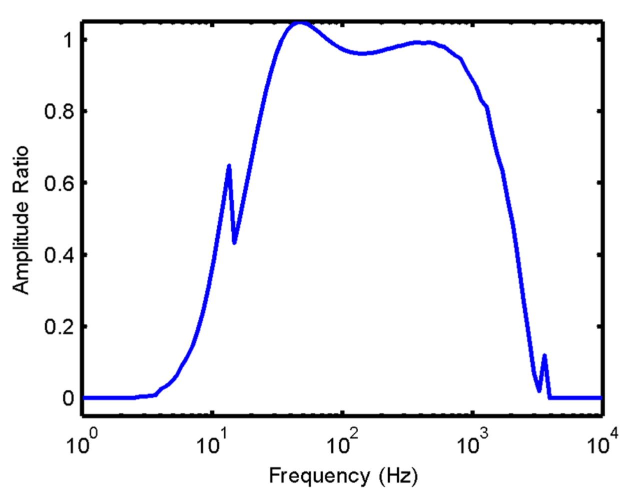



Fig. 2.11 Frequency response for delay-integration method applied to LTM measurement. The method is able to accurately reconstruct signal components between 12 and 1000 Hz with the given setup and filtering parameters.

The tape simulation was also used to determine the optimal mechanical setup parameters for applying the delay-integration method to the measurement of LTM. A range of values for tape velocity, DAQ sampling period, and probe separation distances were used to reconstruct a known simulated LTM signal, and the error between the known and calculated LTM signals was determined.

It was found that coordination between the tape velocity, probe separation distance, and sample period is necessary to minimize the error in the calculated LTM. The resulting error for different parameter combinations is shown in Fig. 2.10. These results indicate that the error is minimized when both probes sample the same points on the tape edge profile. This condition can be expressed as

$$\frac{vp}{d} = \frac{1}{n} \tag{2.9}$$

where *v* is the tape velocity in m/s, *p* is the DAQ sampling period in seconds, *d* is the probe separation distance in meters, and *n* is any integer greater than 0.

Using these settings and the previously mentioned filter configuration the frequency response plot for the complete LTM measurement setup was generated using the same iterative technique described in the ideal simulation section. The resulting frequency response diagram is given in Fig. 2.11. In this configuration the delay-integration method can be used to accurately reconstruct LTM signals with frequencies between 12 and 1000 Hz. This frequency range could be expanded by using probes with less noise and drift, allowing for less stringent filtering of the recorded signals.

### 2.3.2 Application of delay-integration method to actual LTM measurement

The delay-integration method was used to measure lateral tape motion (LTM) in an actual magnetic data storage tape setup. The test was conducted using a Segway Systems/Mountain Engineering MTS linear tape transport with a horizontal tape path and porous air bearing guides. Approximately 100 m of Advanced Metal Evaporated (AME) tape was run at a transport velocity of 8 m/s and a tape tension of 1 N. The position of the tape edge was measured using two MTI Fotonic sensors equipped with edge probes. These probes project light between two prisms and measure the percentage of light that is blocked by the tape edge. The probes were placed as close together as physically possible, resulting in an effective separation distance of 1.9 mm. A diagram of this setup is given in Fig. 2.2. A thin piece of opaque material was placed between the two probes to prevent light from one probe being detected by the other probe. The probes were placed to measure the tape edge height in the center of a 6 cm long unsupported span of tape. The Fotonic signals were routed to a NI-6023E DAQ board (National Instruments, Austin, TX, USA) board and recorded to disk. A sample rate of 50526 Hz was chosen to ensure

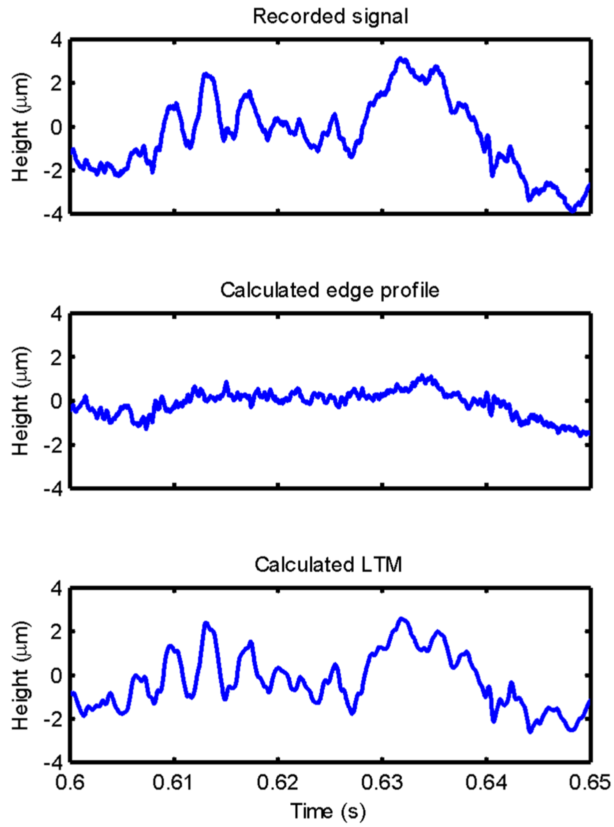



Fig. 2.12 Actual LTM measurements taken using delay-integration method. The top plot shows the combined signal containing both LTM and edge roughness information, as recorded by a single Fotonic edge probe. The center and lower plots contain the edge profile and LTM components, respectively. Error in the LTM measurement caused by the tape edge roughness has been removed using the new method.

that the same point on the tape edge would be sampled by both probes, satisfying Eq. 9. Filtering was done in MATLAB using the same program created for the LTM measurement simulation. The data was then processed using the delay-integration method, resulting in the reconstruction of the LTM signal. Finally, the calculated LTM signal was subtracted from the original composite signal containing both LTM and edge profile information, resulting in a calculated edge profile signal.

Using the settings and filters validated by the simulation the delay-integration method was successfully applied to measurement of LTM on a tape transport. The results are given in Fig. 2.12. The top plot in Fig. 2.12 shows the LTM as measured with the old technique, where a single Fotonic probe is used and the resulting LTM measurement contains error caused by the tape edge roughness. The center and lower plots in Fig. 2.12 show the results of the delay-integration method where the edge profile and LTM information are separated. Because the LTM and edge profile information can be separated from each other the delay-integration method allows for more accurate measurements than the traditional edge probe technique. The delay-integration method also has advantages over magnetic monitoring of a pre-written track, a technique often used in industry research (Alfano and Bhushan, 2006). The magnetic method assumes that the track written on the tape is straight and level, which is not always the case. Variations in this reference track are misinterpreted as LTM. The delay-integration method does not require a reference line on the tape, and so is not subject to this problem. The LTM measured using the delay-integration method is in the same order of magnitude as those found in other studies measuring the LTM using traditional techniques (Hansen and Bhushan, 2004; Boyle and Bhushan, 2005; Taylor and Talke, 2005; Wang and Talke, 2005; Alfano and Bhushan, 2006; Wright and Bhushan, 2006). This agreement helps to show that the new delay-integration method can successfully be applied to LTM measurement, even though a direct comparison to a known correct LTM value for this specific case is not possible. The calculated edge profile is also similar to that seen in other studies on this type of tape (Hansen and Bhushan, 2004; Alfano and Bhushan, 2007). The ability of the delay-integration method to remove edge roughness error from the measured LTM allows for a more accurate measurement of LTM, especially in cases where the tape being used has an excessively rough edge profile.

In a possible future study the delay-integration method could be applied to improve the magnetic signal tracking technique for measuring LTM. It may be possible to distinguish track motion caused by LTM from variation in the track position resulting from the writing of the track. This application would require two consecutive read heads, making the measurement situation different form the normal one-head operating conditions. The spacing between the two heads would also need to be minimized in order achieve acceptable frequency resolution for the reconstructed LTM signal.

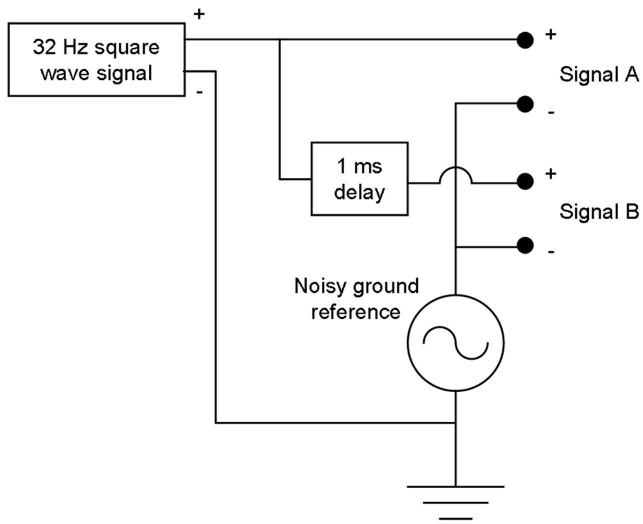



Fig.2.13 Setup diagram for the electrical application of the delay-integration method. The original signal is split and one component delayed, making it possible to reconstruct the original signal even after ground noise has been added

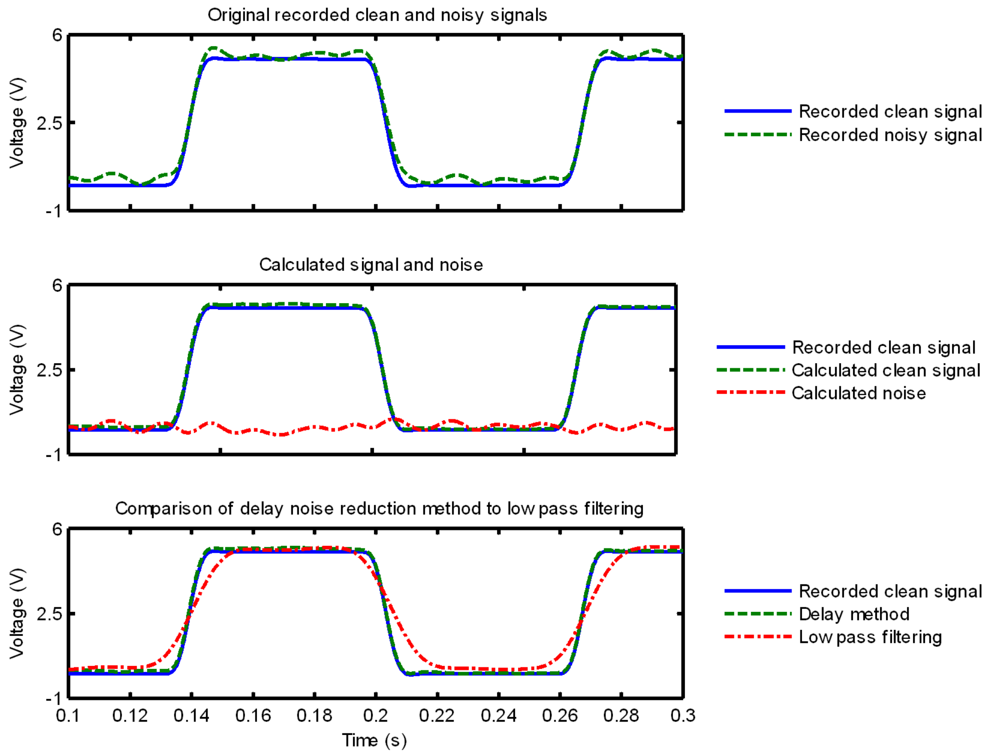



Fig.2.14 Results of the electrical application of the delay-integration method. The additive noise was successfully removed and the original signal accurately reconstructed. For comparison, a low-pass filter was applied for similar noise removal. The delay-integration method results in less signal distortion than the filtering.

### 2.3.3 Application of delay-integration method to an electrical system

To demonstrate the versatility of the delay-integration method it was applied to an electrical system simulating the transmission of an analog voltage signal and comparison of the signal to a randomly changing ground reference voltage. This application required the original signal to be split into two and one of the signals be delayed before the addition of any noise. With the signals in this configuration any noise added simultaneously to both signals can be removed using the delay-integration method. Fig. 2.13 shows an electrical diagram of the test setup. The original signal was generated in LabVIEW (National Instruments, Austin, TX, USA). One portion of the signal was delayed by 1ms, and then both signals were output through the digital input/output (DIO) channels of the aforementioned DAQ board. These signals were then read using

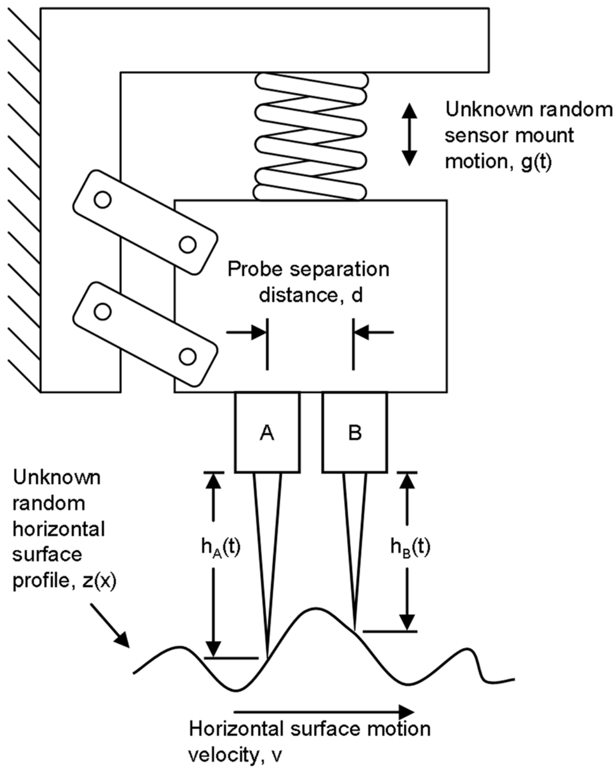



Fig.2.15 Setup diagram for the mechanical application of the delay integration method. The moving sensor mount causes error in the height measurement when only one sensor is used. By adding a second sensor and using the delay-integration method the error can be minimized.

analog inputs on the same DAQ board. A long wire was attached to the ground reference pins of both signals to collect electrical noise from the room. The two resulting signals were saved to disk. Both signals were first filtered using an 8$^{th}$ order low-pass Bessel filter with a 100 Hz cutoff frequency. This removed frequency components outside of the accurate noise reconstruction range for this delay length. The signals were then processed using the same MATLAB program used to run the simulations.

The integration-delay method was able to remove a large amount of the noise and reconstruct a close approximation of the original signal. The results of the electrical application test are shown in Fig. 2.14. For comparison, the reconstructed and original waveforms were

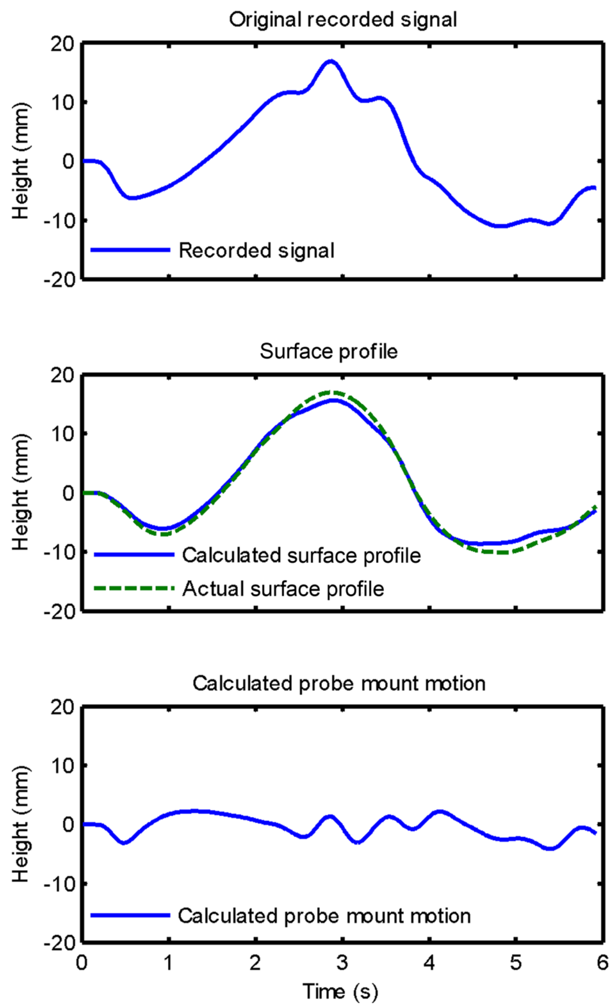



Fig.2.16  Results for the mechanical application of the delay integration method. The top plot shows the original recorded signal containing noise caused by the sensor mount motion.  The center plot compares the surface profile calculated using the method with the known profile.  The method was able to remove most of the additive noise.  The lower plot shows the calculated sensor mount motion.

compared to a waveform from which the noise was removed using traditional low-pass filtering. The delay-integration method was able to remove the noise as effectively as the filtering but without the signal distortion caused by traditional filtering.

### 2.3.4 Application of delay-integration method to a mechanical system

The delay-integration method was applied to a mechanical system to illustrate that it can remove error caused by motion in the sensor reference position when measuring a moving object. This situation would occur where height sensors (or other similar sensors) are mounted to moving or vibrating machinery and are measuring the profile of a surface moving along a conveyor belt. A test setup and measurable surface were created to simulate this situation. A diagram of the setup is given in Fig. 2.15. In this instance linear slide potentiometers were used as the height sensors, with an effective separation distance of 3 mm between the two sensor tips. The test surface was advanced at a velocity of 60 mm/s by a slider on a lead screw driven by an electric motor. This created an effective delay time of 0.05 seconds, with a resulting noise reconstruction cutoff frequency of 2 Hz. During the test the sensor mount was manually moved in smooth, random motions to introduce noise to the system. The signals from the two potentiometers were routed to the NI-6023E DAQ board and saved to disk. An $8^{th}$ order low-pass Bessel filter with a cutoff frequency of 2Hz was applied to the signals to remove noise outside of the accurate noise reconstruction range, and processing was done using MATLAB .

Noise due to the motion of the sensor mount was reduced through the use of the delay-integration method, and the measured surface profile was reconstructed. The results of the mechanical test are given in Fig. 2.16. Error in the reconstructed surface profile is attributed to mechanical differences in the way the two height sensors followed the test surface, resulting in misinterpretation of the differences as sensor mount motion. It is believed that this error could be reduced through the use of different, more precise height sensors and by reducing the effective delay time between sensors.

The delay integration method was successfully applied to three different systems. In each case the method was able to determine the individual components that made up a composite measurement. This allowed for the accurate measurement of LTM in a magnetic data tape storage drive and the reduction of noise in both an electrical and mechanical system.

## 2.4 Conclusion

The new delay-integration method described in this study is a process for decomposing a pair of composite signals into their individual components, allowing for the possible removal of one of the components if desired. The method is able to distinguish between two signals with similar frequency components and amplitudes, making it a viable solution in situations where simple low or high pass filtering would remove needed signal information. Other advantages over traditional filtering are the constant delay time, minimal signal distortion due to phase shift changes across a frequency range, and the high degree of accuracy with a properly selected delay time.  The method was successfully applied to measurement of LTM in a magnetic data storage tape drive, removal of noise caused by a floating ground reference in an electrical signal transmission, and removal of noise caused by a moving sensor mount in a mechanical profile measurement system, and has many other possible future applications.

# CHAPTER 3

# STUDY OF MAGNITUDE AND FREQUNCY VARIATION OF LATERAL TAPE MOTION ACROSS AN UNSUPPORTED TAPE REGION

## 3.1 Motivation

Information is stored on magnetic data tape by modifying the magnetic orientation of particles on the tape surface as the tape translates past a write head. This pattern can then be read back on a subsequent pass, and the stored data can be retrieved (Bhushan, 1996, 2000). Many advances have been made in the past decades to improve magnetic recording technology and more challenges must be overcome in order to proceed with the development of higher data density magnetic data tape storage devices (Kawana et al., 1995; Bhushan and Patton, 1998; Luitjens and Rijckaert, 1999). One of these challenges involves the relative motion between the read/write head and the data tracks on the tape, known as lateral tape motion (LTM). As data densities increase and track widths decrease the amount of tolerable LTM decreases as well. It is therefore more important than ever to understand how LTM can be minimized.

LTM events can be separated into two distinct categories, repeatable and non-repeatable. Repeatable LTM events are those that occur at the same point in the tape cycle each time the cycle is run. This LTM is often caused by tape features, such as edge roughness and variations in stiffness and thickness along the length of the tape. Repeatable LTM events can have a small impact on the performance of the tape because the same events occur at the same point in both the write and subsequent read cycles. Therefore, even though the tape may be misaligned for part of the data write cycle it is also misaligned in the same way during the data read cycle, and the track can still be effectively read. This is illustrated in Fig. 3.1(a). However, if a tape that was written in one drive is read in a different drive, subtle variation in the drives will cause the LTM events to not be repeated in the same way, leading to possible errors. Long-term physical changes to the tape, such as edge wear or substrate aging, can change the way the tape interacts with the guides in the drive, and thus lead to different LTM patterns.

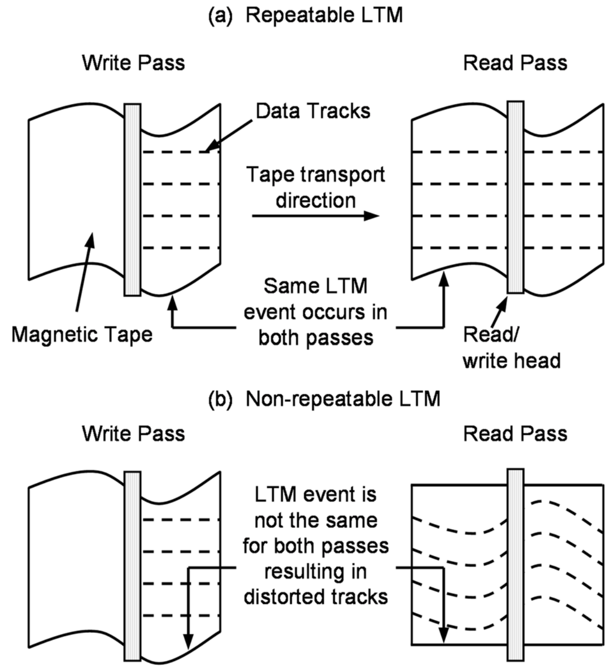



Fig 3.1 (a) Repeatable LTM events occur in the same way on each cycle, so that the data tracks and read elements remain aligned even though the tape is moving. For this reason repeatable LTM can be difficult to detect using track-based LTM measurement methods. (b) Non-repeatable LTM does not reoccur in the same way in each cycle. Events occurring during the write cycle can create distorted reference tracks, which can be misinterpreted as LTM in subsequent passes when using track-based LTM measurement methods.

Non-repeatable LTM events are those that do not occur in a regular pattern as the tape cycles. This type of LTM is often caused by randomly occurring events, such as a sudden localized failure in the tape substrate or a mechanical jolt to the tape drive. Because of the random nature, non-repeatable LTM has a larger impact on the performance of the drive. Fig. 3.1(b) illustrates an occurrence of non-repeatable LTM for comparison to repeatable LTM.

This study describes the application of a new delay-integration technique to the measurement of LTM. The method is compared to traditional LTM measurement techniques and the differences between the methods are highlighted. A study using the delay-integration method to measure LTM along an unsupported region of tape is then described, and the correlations between tape properties and LTM magnitudes are suggested.

### 3.2 Comparison of LTM measurement techniques

One traditional method of measuring LTM is to monitor the position of a servo or data track written onto the tape. This is the method most commonly used in research and development of magnetic tapes (Alfano and Bhushan, 2006, 2007). This method, known as the "halfway-detuned method", places the read element in the head so that it is straddling the edge of the track (Alfano and Bhushan, 2006). Because only part of the read element is over the magnetically altered material in the track, the element does not read at full strength. Instead, it registers a signal strength that is roughly proportional to the percentage of the read head that is over the track. If the tape moves and a greater proportion of the read element is over the track, the signal strength will increase. The reverse is true if the tape moves so that less

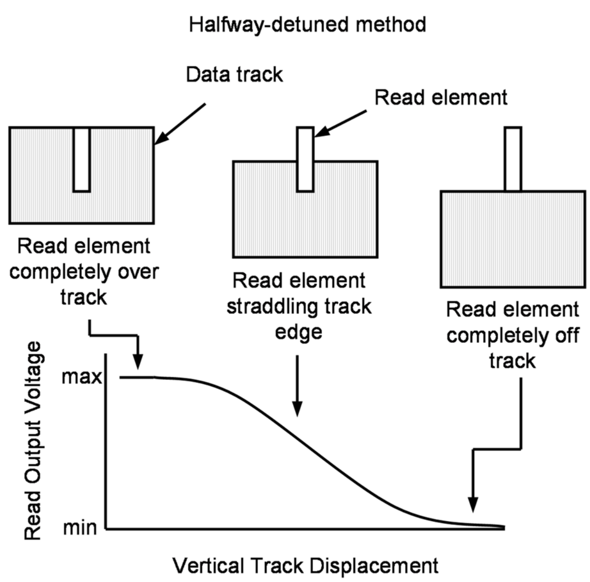



Fig 3.2 Illustration of the halfway-detuned LTM measurement method. The position of the track edge relative to the read element can be determined based upon the magnitude of the read element output signal. This method of LTM measurement depends on a straight reference track, and can be unable to detect repeatable LTM in some situations. It is also unable to distinguish between amplitude changes caused by LTM and those due to changes in the head-tape spacing distance.

of the read element is over the head. The setup can be calibrated so that the relative position between the read element and the track edge can be correlated with a read output voltage. Thus, by measuring the detuned voltage it is possible to monitor the motion of the tape. This is illustrated in Fig. 3.2. This method has several disadvantages. First, the method cannot distinguish between a change in signal strength due to LTM and a change due to variation in the spacing between the tape surface and the head. Second, the method assumes that the track being monitored is straight and that all measured motion is motion only in the tape. An LTM event occurring in the writing cycle would cause the written track to not be straight, and this deviation in the track would be interpreted as LTM in all subsequent read passes even if there is no actual LTM on those passes. If the track being monitored was originally written on the same drive it is possible that repeatable LTM events are occurring but are not being seen due to the fact that identical LTM events are occurring in each cycle. Because of this inability to detect repeatable LTM, measurements made with this method usually indicate lower amplitudes and amounts of LTM than other methods.

An alternative method to measuring LTM through track-following is to monitor the position of the tape edge using a Fotonic edge probe (MTI Instruments Inc., Latham, NY) (Taylor et al., 2000; Goldale and Bhushan, 2003). A Fotonic edge probe is a device that passes a beam of light between two prisms and back to a light detector. An object placed between the prisms will block the light, causing the detector to see less light. For a given range the amount of light received by the detector is proportional to the area between the prisms that is blocked by the object. This can be used to measure small motions of the object, and has often been applied in the past to measuring the LTM of a magnetic tape. The technique does not suffer from many of the shortcomings that the servo-track monitoring techniques do, such as the need for a pre-written reference track or errors caused by head-tape spacing changes. However, the Fotonic edge probe is unable to differentiate between changes caused by tape motion (LTM) and changes caused by tape edge roughness (Goldale and Bhushan, 2004; Alfano and Bhushan, 2007). All tape edges exhibit some ammount of roughness as a result of the tape slitting process. Different tapes have different amounts of roughness. Fig. 3.3 shows optical micrographs of the edges of five different tape samples, highlighting the differences in the edge contours. Both the edge roughness and the tape motion alter the amount of light that is able to pass between the prisms, creating a composite measurement with each component contributing an unknown quantity to the total measurement. This is shown in Fig. 3.4. The tape edge roughness is thus misinterpreted as LTM, even if the tape is experiencing no lateral motion. This puts a severe limit on the accuracy of the Fotonic edge probe method, in that both the LTM and edge roughness are thought to have similar amplitudes and component frequencies.

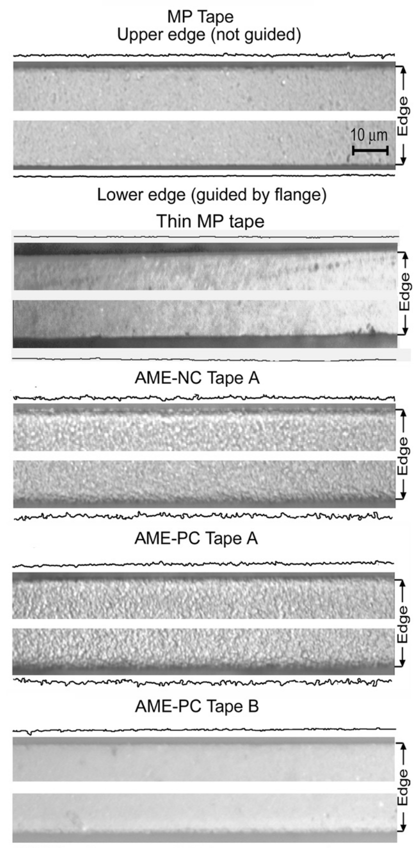



Fig 3.3  Optical micrographs of tape edges showing edge roughness for magnetic particle (MP) tape, Thin MP tape, advanced metal evaporated (AME) type A negatively cupped (NC) tape, and AME types A and B positively cupped (PC) tape.  Cupping is said to be positve if it is concave with respect to the head, and negative if it is convex. (Alfano and Bhushan, 2006; Wright and Bhushan, 2006)

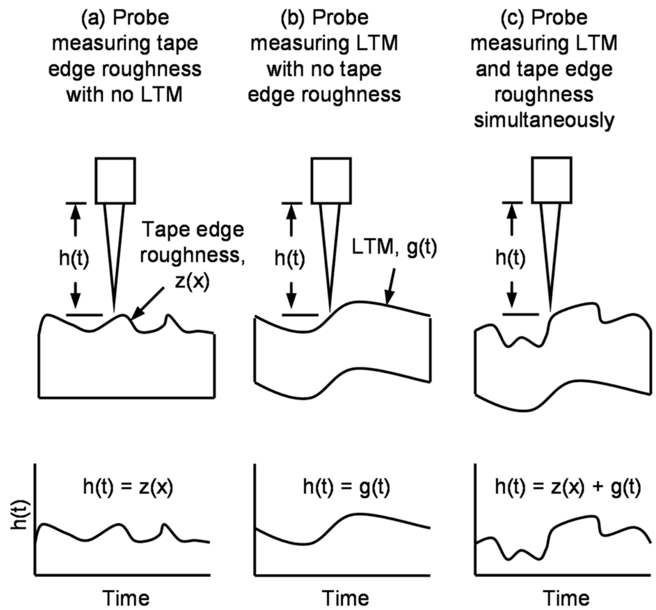



Fig 3.4 Both the LTM and the tape edge roughness contribute to the measurement taken using the Fotonic edge probe LTM measurement technique. The edge roughness is interpreted as LTM and adds error to the measurement.

LTM measurements taken using this method often indicate higher amounts of LTM than other measurement methods due to the inclusion of the edge roughness.

Another version of the Fotonic edge probe measurement technique involves the addition of a second edge probe to the opposite edge of the tape, so that one probe is monitoring the top edge and the other the bottom edge (Hayes and Bhushan, 2005). The coherence of the two signals is then calculated and signal change in which both signals are fully coherent is assumed to be due to tape motion. The addition of the second probe offers few advantages, though, as it is no more possible to take two random, independent signals and separate out an unknown common signal than it is to do so with a single random signal. Since both the top and bottom tape edge have independently random profiles it is impossible to determine if any correlation is actually due to tape motion or a coincidental similarity in the two profiles. Also, tape motion occurring when the two profiles are very different from each other will not be detected, as the differences in the profiles will prevent coherency between the signals.

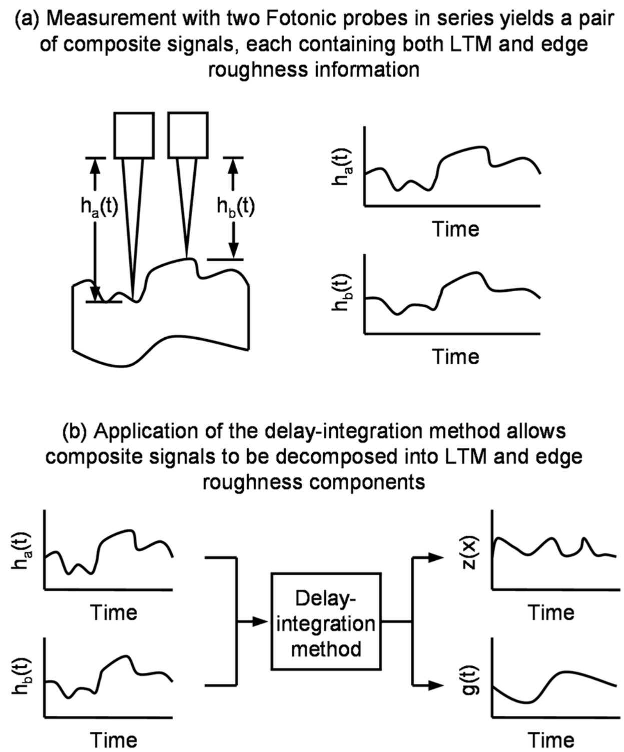



Fig 3.5 The delay-integration method can be used to separate the LTM and edge roughness information from a pair of composite Fotonic edge probe signals. This method overcomes the limitation of the single edge probe method in that the edge roughness is no longer contributing error to the LTM measurement. The method is able to measure repeatable LTM, is not reliant on a reference track, and is not affected by head-tape spacing.

A technique developed by Petrek and Bhushan (2007), known as the "delay-integration method", overcomes the major limitations of the Fotonic edge monitoring technique, the dual probe technique, and the data track monitoring technique. The delay integration method relies on a second edge probe placed in series with the first to provide additional information needed to differentiate between the LTM and edge roughness components. This is illustrated in Fig. 3.5. Monitoring the LTM using the delay-integration method has many advantages over traditional methods. First, it does not require a pre-written reference track to monitor. This eliminates the possibility for error caused by a distorted reference track. It also is able to measure both repeatable and non-repeatable LTM reliably, as the events in one cycle do not have any effect on measurement in future cycles. Second, unlike the halfway-detuned method, the delay-integration method is unaffected by head-tape spacing. Finally, the delay-integration

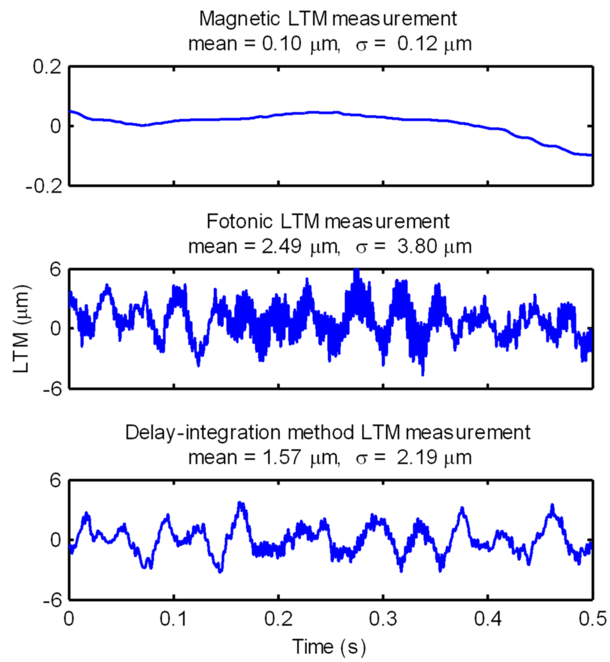



Fig 3.6 Comparison of LTM measurements made on a sample of AME type B PC tape with halfway-detuned magnetic technique (top), edge monitoring with a Fotonic edge probe (middle), and delay integration technique (bottom). The halfway-detuned magnetic method does not measure repeatable LTM, while the Fotonic edge probe interprets edge roughness at LTM. The delay-integration method overcomes both of these sources of error. Both the mean value of the LTM and the standard deviation (σ) for the LTM are given for each technique.

method is able to distinguish LTM from the tape edge roughness, making it a more accurate way to measure LTM than a single Fotonic edge probe. LTM measurements taken using the delay-integration method often have amplitude values between those measured using traditional track following and edge probe techniques. This is due to the fact that the delay-integration method includes repeatable LTM that may not be measured by the track following method, and is able to remove the error caused by edge roughness that is included in single edge probe measurements. An example of an LTM measurement made using the delay-integration method is compared to measurements made using the halfway-detuned magnetic method and the Fotonic edge probe method in Fig. 3.6. Due to space and equipment limitations it was not possible to take all three measurements at the same location, but the basic characteristics of each remain valid and allow for general comparison.

The delay-integration method does have some drawbacks, though. It is very sensitive to noise, scale, and offset differences between the two Fotonic probes. These differences, integrated over a long period of time, can lead to substantial error. This can be overcome through the use of low pass filtering, at the expense of not being able to accurately measure low frequency (below 10 Hz) LTM. The method also is unable to reconstruct LTM in frequencies above a certain high-frequency cutoff point, which is dependent upon physical setup and sampling parameters and is generally around 400 Hz.

Another benefit of the delay-integration method is that it can be used to measure LTM at locations other than at the tape head. This can be taken advantage of in order to study the way LTM changes along a region of unsupported tape. This information could provide valuable insight into which tape parameters are most influential in determining a tape's behavior in unsupported situations, and guide the development of future tapes.

## 3.3 Experimental

### 3.3.1 Tape transport and tape samples

Tests were conducted on a Segway Systems/ Mountain Engineering multi-terabyte tape storage (MTS) linear tape transport (Goldale and Bhushan, 2003; Alfano and Bhushan, 2007). The transport was equipped with porous air bearings. These bearings allow compressed air to be forced trough a ceramic element, so that the air provides a cushion between the tape and the bearing surface. Two of these bearings were equipped to monitor tape tension by measuring the pressure of the air between the tape and bearing surface. This information, in conjunction with the angular velocity of the tape reels, is then used by the controller to maintain constant tape tension and transport velocity throughout the pass. All tests were done at a tension of 1 N and a speed of 8m/s.

Five different tape samples were used for testing, including magnetic particulate (MP) tape, Thin MP tape, and three types of advanced metal evaporated (AME) tape. Fig. 3.7 shows generalized cross sections of the different types of tape (Wright and Bhushan, 2006; Alfano and Bhushan, 2007). The MP tape used was a commercially available 12.7 mm wide Ultrium sample with an overall thickness of 8.9 µm. The Thin MP tape is an experimental sample with a thickness of 6.9 µm. Two of the AME samples tested were experimental tapes and differed in the amount and direction of cupping, with one being positively cupped (PC) so that the tape is con-

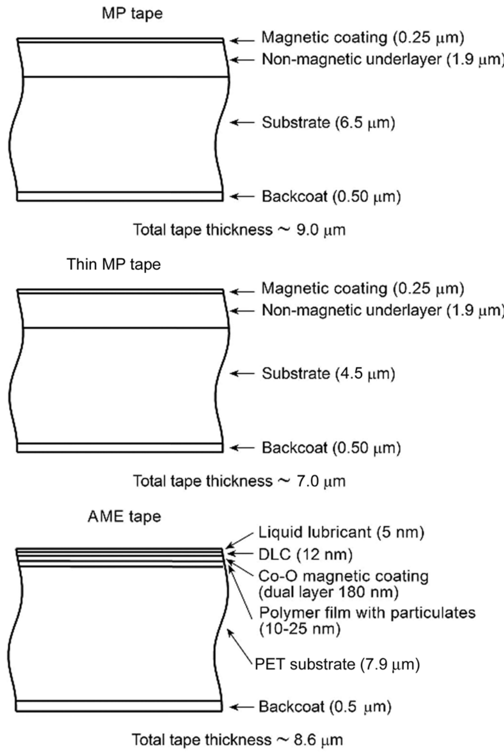



Fig 3.7 Cross section views of MP, Thin MP, and AME tapes. (Wright and Bhushan, 2006; Alfano and Bhushan, 2007;)

cave with respect to the head, and the other being negatively cupped, so that the tape is convex with respect to the head. The third AME sample was a positively cupped commercially available tape. All AME samples had a thickness of approximately 8.6 µm.

### 3.3.2 Tape property measurements

Several mechanical properties of each tape were determined in order to make effective comparisons. Tape cupping was measured using an optical microscope by determining the focal length adjustment needed to bring different points on the tape surface into focus (Hunter and Bhushan, 2001, Scott and Bhushan, 2003). The relative edge contour length of each tape was determined by photographing the edge using an optical microscope and comparing the profile length of the actual edge to that of an ideal, straight edge (Goldale and Bhushan, 2003, 2004).

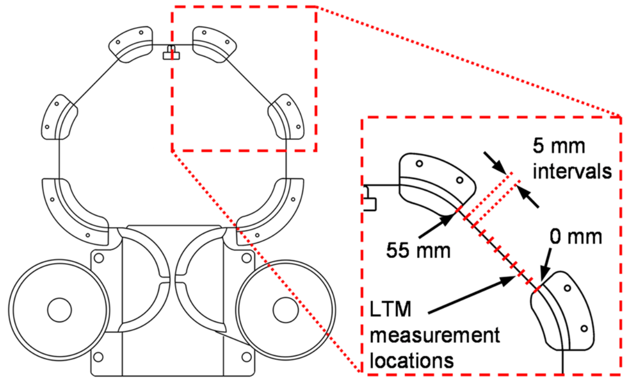



Fig 3.8  Tape deck layout and location of LTM measurements along unsupported tape region (Wright and Bhushan, 2006)

The bending stiffness of each tape sample was measured using a method developed by Scott and Bhushan (Scott and Bhushan, 1997). The process first involves forming a loop with a small section of tape and mounting the tape loop to a micrometer with a precision of 0.1 µm (Mitutoyo America, Aurora, IL). The loop is then pressed into the tray of a microbalance with a precision of 0.1 mg (Denver Instrument Company, Denver, CO), with the amount of deflection carefully controlled through the use of the micrometer. This is shown in Fig. 3.8. The microbalance operates by applying force to maintain zero net overall displacement of the tray, so the microbalance does not effect the overall deflection of the tape loop. Force measurements are taken for different amounts of tape loop deflection, and a load-deflection curve is created. By approximating the tape loop as a thin-walled cylinder and using the theory of virtual work, Scott and Bhushan developed an analytical expression that determines the bending stiffness based on the slope of the load-deflection curve. This can then be used to calculate the overall elastic modulus of the tape sample.

The bending-stiffness measurement process was first tested on a piece of aluminum foil. The calculated elastic modulus agreed with the accepted elastic modulus value for aluminum. Each tape sample was then tested between three and six times, or until the standard error percentage for the group of measurements came within acceptable levels. Standard error was calculated as the standard deviation of all measurements divided by the square root of the number of samples. Standard error percentage was calculated as the standard error divided by the mean value.  Each tape sample was tested in both the machine direction, which is parallel to the direction the tape transports through the deck, and the transverse direction, which is parallel to the read/write head.  The measurement of the stiffness in the individual directions was necessary due to the fact that the materials used to construct the tape and the way in which they were combined can lead to non-isotropic behavior.

In order to calculate the overall elastic modulus for each tape the thickness was determined.   This was done by layering 20 pieces of tape and measuring the total thickness of the stack with a micrometer, readable to 0.1 μm.  The total thickness was then divided by the number of tape layers in the stack to determine the individual thickness.

### 3.3.3 LTM measurement technique

The delay-integration method of LTM measurement was used in this study.  By using two Fotonic edge probes in close proximity it is possible to capture two slightly different composite signals.  The differences between these signals indicate minute changes in the lateral position of the tape edge that occurred within the time it took the tape to transport the distance from one

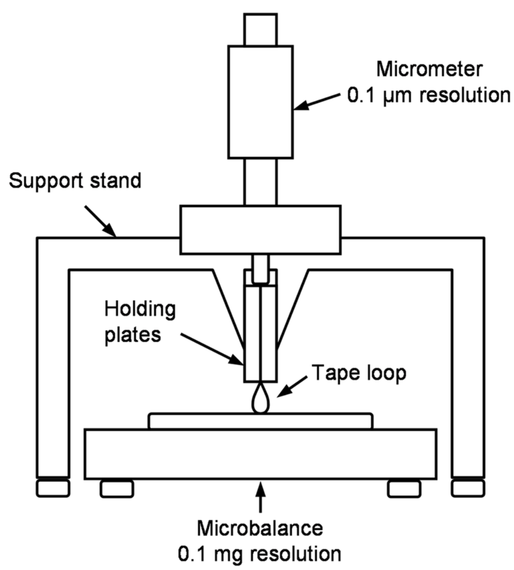



Fig 3.9  Experiment setup for measuring bending stiffness of tape samples.

Fotonic probe to the other. By integrating these small differences over time the actual LTM can be reconstructed. The delay-integration method can be used to measure LTM at any location accessible to the Fotonic probe. This allows more versatility than methods requiring the use of the read/write head, which is in a fixed or limited location. This versatility was utilized in this study to measure the LTM at various locations along an unsupported region of tape. A 5 cm long region free of guides was chosen at the location along the tape path shown in Fig. 3.9. LTM measurements were taken at 5 mm intervals along this region. At each location one seconds worth of LTM data was recorded in each of five forward passes. The measurements were coordinated using a small notch cut into the top edge of the tape. This notch triggered the data collection, ensuring that the same span of tape was being monitored in each cycle. This would limit the variability in LTM caused by differences in the tape edge along the length of the tape and allow for a more consistent comparison. The data from both edge probes was collected using a National Instruments data acquisition (DAQ) board (NI-6023E, National Instruments, Austin TX). Data was collected at a sample rate of 50526 Hz. In order to prevent aliasing an analog low-pass filter was used to remove signal information above 20 kHz from each Fotonic probe signal before introduction to the DAQ board. The data was recorded to disk using LabVIEW software (National Instruments, Austin TX) and processed using MATLAB (Mathworks Inc., Natic MA).

Several LTM measurements were also made using the halfway-detuned magnetic method for comparison to the measurements made using the delay-integration method. This required that the read/write head maintain alignment with the edge of the data track. The reversal of the tape direction between passes often resulted in track misalignment, though. To overcome this problem a head position servo control feedback loop was developed. A custom designed LabVIEW application monitored the strength of the detuned signal. This application then changed the position of the head by communicating with the head position servo motor through the serial port in order to re-align the head and track at the beginning of each run. Once the track and head were properly aligned the servo control was turned off and the LTM measurements were made.

Different amounts of LTM can have different effects on a system's performance depending on the characteristics of that system. For example, a recording scheme with data tracks 30 µm wide may be able to operate successfully under larger LTM magnitudes than would a system with data tracks 15 µm wide. Therefore, it was decided not to measure LTM in terms of "dropouts" as had been done in past studies. A dropout is an unacceptable loss of signal. The qualifications for what is acceptable or not can vary greatly from system to system, though, making this measure of LTM useful only in systems very similar to that on which the experimental data was obtained. Two different measures of LTM are used to interpret the data gathered in this

| Tape Sample | | MP | Thin MP | AME type A-PC | AME type A-NC | AME type B-PC |
|---|---|---|---|---|---|---|
| Cupping Magnitude (µm) | | -1075 [a] | -1075 [b] | -600 [a] | 100 [a] | 700 [a] |
| Edge Roughness Factor | | 1.071 [a] | 1.068 [b] | 1.126 [a] | 1.100 [a] | 1.093 [a] |
| Tape Thickness (µm) | | 8.9 | 6.9 | 8.6 | 8.6 | 8.6 |
| Bending Stiffness ($\mu Pa\ m^3$) | Machine | 0.2962 | 0.1489 | 0.3071 | 0.2555 | 0.2868 |
| | Transverse | 0.2630 | 0.1382 | 0.3581 | 0.2943 | 0.5007 |
| Elastic Modulus (GPa) | Machine | 4.6 | 4.9 | 5.3 | 4.4 | 4.9 |
| | Transverse | 4.1 | 4.6 | 6.1 | 5.1 | 8.6 |

[a] Alfano and Bhushan, 2007; [b] Wright and Bhushan, 2006

Table 3.1  Summary of properties for tapes tested.

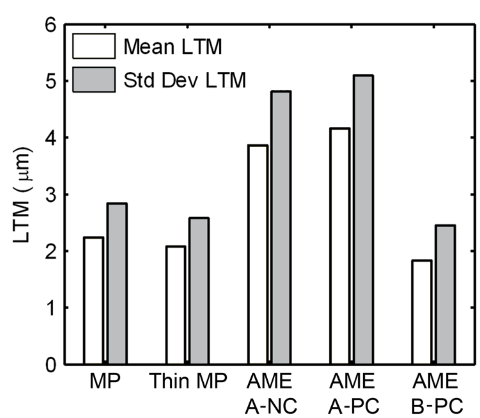



Fig 3.10  Comparison of LTM averages across the entire unsupported region for the five types of tape tested.

study. The first measure is the mean displacement between the center of the tape and the assumed center of the tape path, known as "mean LTM". In this measure all points are weighed equally into the calculation. The second measure is the "standard deviation LTM". This is the standard deviation of the tape center's position with respect to the center of the tape path. In this measure those points furthest from the mean position are given heavier weighting. The standard deviation can be used to determine a more complete picture of the LTM characteristics, especially when a Gaussian distribution can be assumed. Once an acceptable limit for LTM for a certain drive is established, the standard deviation can be used to calculate the probability (or regularity) of an unacceptable LTM event occurring for that specific drive.

### 3.4 Results and Discussion

The delay-integration method of LTM measurement was used to determine how the amplitude and frequency characteristics of the LTM changes over an unsupported region of tape. Results for each tape sample used were then compared with the properties of those tape samples in an attempt to correlate certain properties with certain tape behavior.

The results of the bending stiffness measurements are given in Table 3.1. It can be seen that the elastic modulus for all the tapes is in the same general range. The bending stiffnesses, however, vary greatly, and are closely related to tape thickness. In order for a tape to be both thin and stiff it would need to have a very large elastic modulus. The thinnest sample tested here, Thin MP tape with a thickness of 7 μm, did not have a higher elastic modulus than the other tapes and had a much lower bending stiffness in both the transverse and machine directions as a result.

The mean LTM amplitudes for the entire region varied greatly between the different types of tape. This is shown in Fig. 3.10. The AME type A tapes had the largest mean LTM across the entire region, while the AME type B PC tape had the smallest mean LTM. These trends reflect findings that were done in the past using similar tape samples (Alfano and Bhushan, 2007; Wright and Bhushan, 2006), and are in the same order of magnitude as measurements taken on other types of tape (Boyle and Bhushan, 2005; Hansen and Bhushan, 2005; Taylor and Talke, 2005; Wang and Talke, 2005). The overall values of the LTM for these tapes are somewhat higher than those measured in other situations due to the fact that the tape is in an unsupported position in this case.

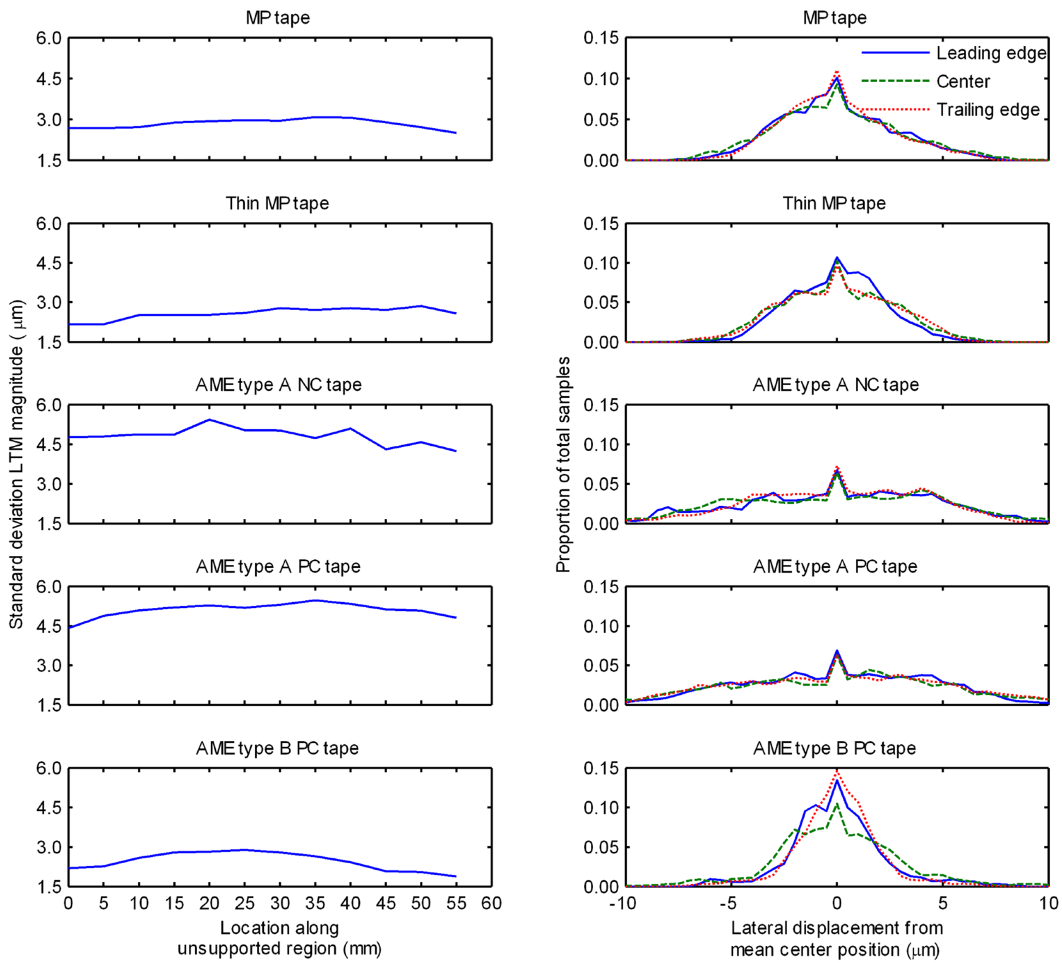



Fig 3.11 The plots in the right column show how the standard deviation LTM varies across the unsupported region. The plots in the right column characterize the distance and frequency of occurrence of lateral motion at the leading edge (0 mm), center (25 mm) and trailing edge (55 mm).

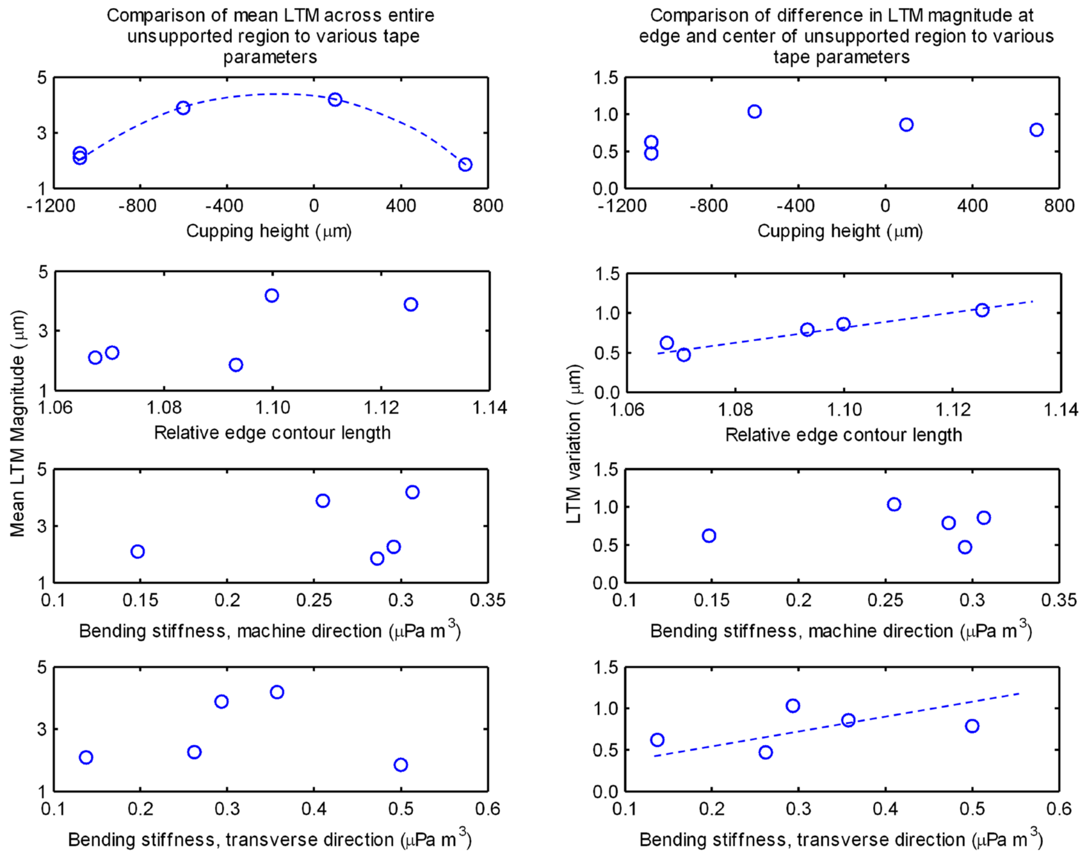



Fig 3.12 Comparison of LTM and LTM variation do properties of tapes. The left column compares the average across the entire region to cupping magnitude, edge roughness, and bending stiffness, while the right column compares these values to the difference between the LTM magnitude at the supported ends of the region to the LTM magnitude at the center of the region

Examination of the change in standard deviation LTM amplitude across the length of the region revealed that LTM was often highest in the center of the region and lower on the ends where the tape was supported by the guides. These results are shown in the left hand column of Fig. 3.10. Each data point represents the average LTM for a set of 5 trials. The standard error between the different trials was under 0.2 μm or the majority of points, and under 0.3 μm for all points. The minimum value of LTM for each tape occurred at one of the supported end points. The maximum value of LTM occurred in the center of the region, except for the Thin MP tape which experienced maximum LTM 5 mm away from the trailing edge guide. The AME type A NC tape shows sudden changes in the LTM amplitude along the region, which is inconsistent with the results seen for the other types of tape. As these results appeared questionable the tape was tested several more times, with all tests yielding similar results. The Thin MP tape also showed a similar behavior, but to a lesser degree. These two tapes had the lowest machine bending stiffnesses of the tapes tested, indicating that a high machine bending stiffness may contribute to the stability of the tape. Histograms of the lateral displacement for each tape are shown in the right hand column of Fig. 3.11. The distribution of displacements at the leading edge (0 mm), center (25 mm) and trailing edge (55 mm) are shown. The same general trends in the distribution can be seen for all five tapes. The center histograms show the lowest proportion of samples occurring at zero displacement, and the highest proportion of samples occurring at larger displacements. The ends exhibit the largest proportion of samples with zero displacement, with the trailing edge having more zero displacement samples than the leading edge for three out of the five tapes.

The variation in amplitude of LTM along the unsupported region was compared to measured mechanical properties of the tapes, and the results are shown in Fig. 3.12. To achieve statistical significance a much larger number of tapes with a wide variety of proprieties would need to be tested, which is beyond the scope of this study. These results, therefore, are simply observations meant to provide a starting port for possible future studies. Three possible trends should be noted from the plots in Fig. 3.12. The first is shown in the top plot in the left column, which compares the mean LTM for the entire region to the magnitude of tape cupping. The tapes with the largest cupping magnitudes, either positive or negative, have lower mean LTM than the tapes with less cupping. This may indicate that larger cupping magnitude increases the effective stiffness of the tape, resulting in less motion from disturbances caused by interactions between the guides and the rough edges. The second trend is illustrated in Fig. 3.12 in the second plot from the top in the right column, which compare the increase in LTM amplitude between the ends and center of the region and the edge roughness factor of the tape. As the edge roughness factor increases the amplitude difference increases as well. This indicates that LTM events caused by large changes in the roughness of the tape edge are amplified at the center of the unsupported region. A smooth edge would be desired to keep LTM at the center of the

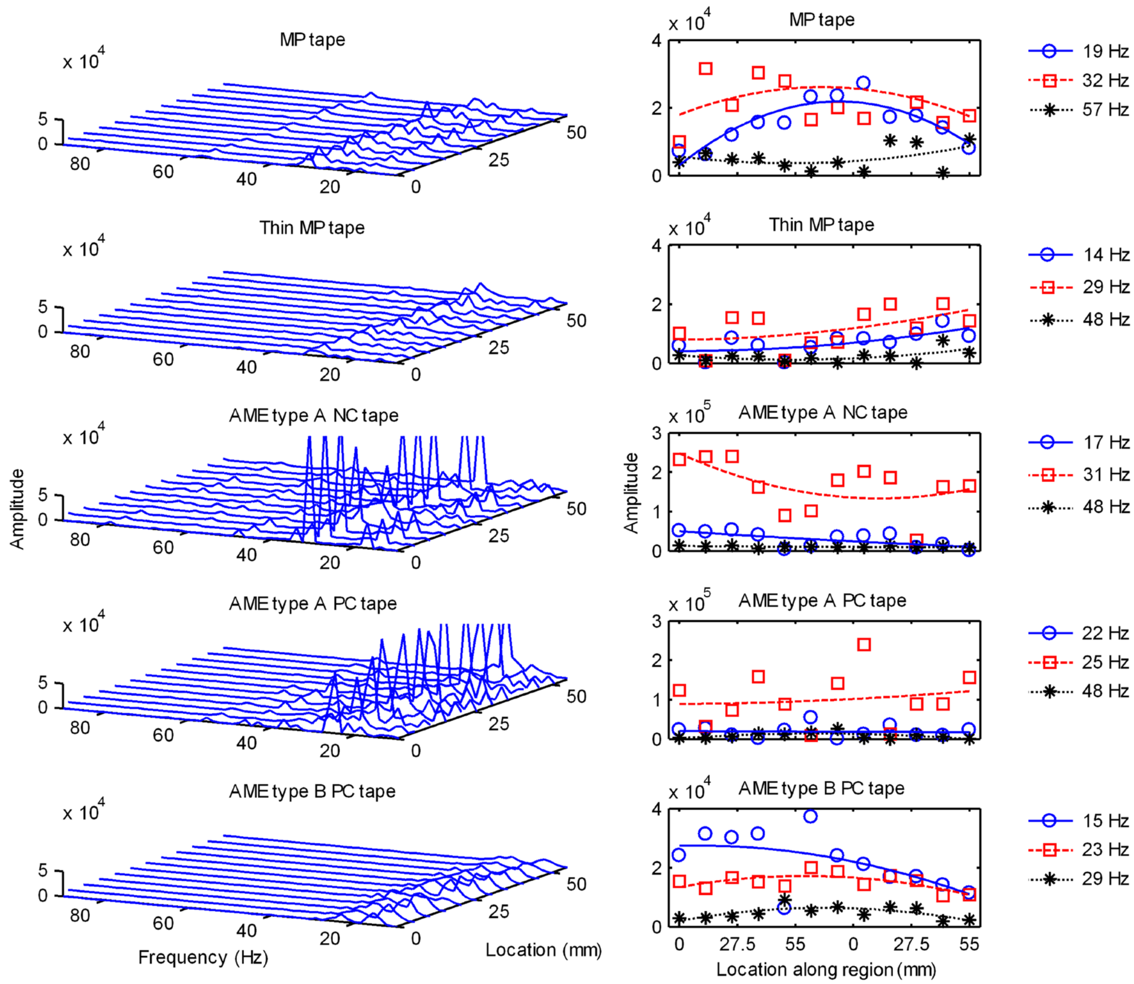



Fig 3.13 Frequency components in LTM for the different kinds of tapes. The left column shows the frequency makeup of the LTM at every measurement location across the unsupported region for frequencies below 100 Hz, as little activity was detected between 100 Hz and the high-frequency cutoff point for the delay-integration method of 400 Hz. The right column plots highlight the changes in magnitude for the three most active frequencies across the region.

region to a minimum.  Finally, the bottom-right plot in Fig. 3.12, which plots the increase in LTM amplitude between the ends and center of the region and the transverse bending stiffness of the tape, indicates that a higher transverse bending stiffness allows for greater amplification at the center of the unsupported region.

The component frequencies making up the LTM for each tape were examined, and the results are shown in Fig. 3.13.  The left column of Fig. 13 shows the LTM activity for each location along the region between 5 and 100 Hz.  None of the tapes exhibited large LTM activity above 100 Hz.  It is clear that each of the tapes had distinct sets of active LTM frequencies, and that these frequencies differed from tape to tape.  Each frequency also varied in amplitude for different locations along the region.  This is shown in the right column of Fig. 3.13, where the amplitudes of the three most active frequencies for each tape are plotted at each location. Several correlations between the change in active frequency amplitudes along the region and tape mechanical properties can be seen.  First, the tapes with the lowest bending stiffness in the machine direction ( AME type A NC and Thin MP) tend to have larger amplitudes in the active frequencies at the supported ends, while the stiffest tapes in the machine direction (AME type A PC and MP) have active frequencies whose amplitudes are largest in the center and smallest at the supported ends.  It is suspected that much of the LTM in an unsupported region is caused by interactions between the rough tape edge and the guides at both ends of the span.  The active frequency amplitudes are therefore highest at their point of generation for tapes with low machine bending stiffnesses, and decrease with distance from the LTM source.  This indicates that a low bending stiffness in the machine direction allows for some dampening of these LTM frequencies to occur, while high machine bending stiffnesses do not allow for such dampening and actually encourage the amplification of the LTM generated at the supported ends.  A different trend is apparent for how the transverse bending stiffness affects the frequencies which are most active for each tape.  The two tapes with the highest transverse bending stiffness, AME type B PC and MP, had the majority of their activity in the lower frequencies compared to the other tapes, indicating that a high transverse bending stiffness is desirable to minimize high frequency LTM which is often more difficult to compensate for than low frequency LTM.

### 3.5 Conclusions

The delay-integration method of LTM measurement was successfully used to obtain LTM measurements with greater accuracy than traditional methods.  The delay-integration method was able to measure both repeatable and non-repeatable LTM, did not rely upon a pre-generated reference line, and was able to differentiate between LTM and tape edge roughness information. Because the method did not require the use of the read/write head it also had the advantage of versatility, and could be applied anywhere accessible to the photonic probe.

The delay-integration method was applied to measuring the change in LTM along an unsupported region of tape. These results were then compared to the mechanical properties of the tape, such as bending stiffness in the transverse and machine directions. Measurements of the bending stiffnesses showed that the stiffness of a tape is closely related to the thickness, and that large increases in the elastic modulus of the substrate and coatings would be necessary to achieve a thin tape with a high bending stiffness. Based on the mechanical property measurements and the LTM measurements several correlations have been suggested. The first is that a large cupping magnitude, in either the positive or negative sense, can reduce LTM amplitudes compared to lower cupping magnitudes. The second is that greater edge roughness can contribute to greater amplification of LTM at the center of an unsupported region. Finally, high transverse bending stiffness can also contribute to increase LTM at the center of an unsupported region.

The mechanical properties of a tape can also contribute to the component frequencies that make up the LTM. A low bending stiffness in the machine direction is thought to allow greater dampening and can actually cause some active frequencies to have lower amplitudes at the center of an unsupported region than at the ends, where the LTM is being generated. High bending stiffness in the machine direction has the opposite effect, with active frequency amplitudes being larger in the center of the region. High bending stiffness in the transverse direction has been associated with LTM composed of lower frequencies. Such lower frequencies are often easier to compensate for in the design of the tape drive.

# CHAPTER 4

# STUDY OF DURABILITY AND LATERAL TAPE MOTION OF MAGNETIC DATA STORAGE MEDIA UNDER HIGH SPEED OPERATING CONDITIONS USING MAGNETIC AND EDGE PROBE TECHNIQUES

## 4.1 Motivation

Magnetic data storage systems have several advantages over other types of storage media. The most important of these advantages are the low cost-per-byte, the high volumetric data storage capacity, and the relative portability of the tape cartridges. For these reasons, tape systems are commonly used for backup, archiving, and other situations where large quantities of data must be safely stored but may not be needed for immediate, random access. The focus of future tape development has therefore been directed to the areas of storage density, durability, and media stability that will ensure that this storage method continues to remain competitive in the future.

Many advances in increasing the storage density of magnetic tape have been made in the past decade (Kawana et al. 1995; Bhushan and Patton, 1998; Luitjens and Rijckaert, 1999). Many of these advances have had the goal of increasing the volumetric data density of a tape cartridge. This has been achieved by utilizing thinner substrates, resulting in the ability increase the length of tape that can fit in a given cartridge size. The areal data density has also been increased by utilizing new advanced magnetic coatings, which have higher magnetic coercivity than previous coatings. The industry now has a near-term goal of achieving a cartridge with terabyte native capacity within the next few years. An increase in storage capacity must also be accompanied by an increase in data throughput rates, the rate at which information can be written to and read from the tape, in order to maintain reasonable read and write times. There are several ways to increase the data throughput, such as increasing the number of read and write elements on the head to enable a larger number of tracks to be accessed simultaneously, and to increase the tape transport speed, so that a larger tape surface area passes the head in a given amount of time. While both of these methods are being pursued by industry, this study concentrated solely on the high-speed aspect.

Increasing the transport speed in a tape drive can have several undesirable consequences. The first possible problem is that of increased wear of the tape surface and edges. Many tapes feature protective surface coatings and lubricants to prevent wear, and it must be ensured that these treatments continue to perform in high speed situations. Another drawback of increasing the tape transport speed is a possible increase in the amount of lateral tape motion (LTM). LTM is the motion of the tape in the plane of the read/write head, perpendicular to the normal transport direction. This motion can cause the read and write elements in the head to become misaligned with respect to the data tracks on the tape surface. Severe misalignment can cause a track misregistration error, where data is lost or written onto an incorrect track. For this reason care must be taken to measure and minimize LTM, regardless of the transport speed. Another consideration is the effect of high speeds on the interaction of the tape edge with the guides. Previous studies of tapes at high speeds have indicated that contact temperatures at the tape edge-guide interface could become high enough to cause substrate melting (Bhushan et al. 1994).

There are two major types of LTM, and each is the result of different sources of disturbance to the tape and drive. Repeatable LTM is that which occurs in the same way on each pass of the tape. This type of LTM is often the result of the rough tape edge impacting the tape guide, causing the tape to move in the lateral direction. Because the tape edge generally maintains a consentient profile the same edge features influence the tape motion on each pass, resulting in a regularly repeating motion pattern. Another source of repeatable LTM is axial misalignment of the tape reels, which results in tape motion and slight tension changes corresponding to the rotational frequency of the reels. This type of LTM repeats itself both from pass to pass and also multiple times within the same pass. Repeatable LTM events are generally of a low enough frequency and magnitude that they can be compensated for through the use of a servo following system. These servo systems use a small servo motor to adjust the position of the head in order to compensate for small tape motions. The system makes use of servo guide tracks which are often pre-written onto the tape in order to generate the position error signal. Despite the ability of the servo system to compensate for some LTM, it is still important to design tapes and decks to minimize LTM in order to avoid overtaxing the servo systems. Because the servo tracks serve at the tape position reference, as opposed to the tape itself, LTM is sometimes considered to be the motion of only the servo track, with the actual motion of the tape being of secondary interest. In this study, however, the term LTM is used to describe actual tape motion, and not necessarily the motion of the servo track.

The second type of LTM is non-repeatable LTM. This LTM is not repeated from one pass to another, and is generally caused by one time or random events, such as a sudden mechanical failure in the tape substrate or a physical bump to the tape drive. These events are often of a higher magnitude and frequency than the repeatable events, making them more difficult to compensate for using servo following techniques.

This study examined the effect of both tape transport speed and tension on the amount of LTM and the coefficient of friction for five different tape samples, including tapes with standard and thin substrates, as well as particle and metal evaporated magnetic layers. The samples were also subjected to a durability test in order to determine if speed and tension had a large effect on the wear characteristics of the tape. The results of this testing were then used to draw general conclusions about which tape characteristics and transport operating parameters are desirable for running magnetic tape at high speeds.

## 4.2 Experimental

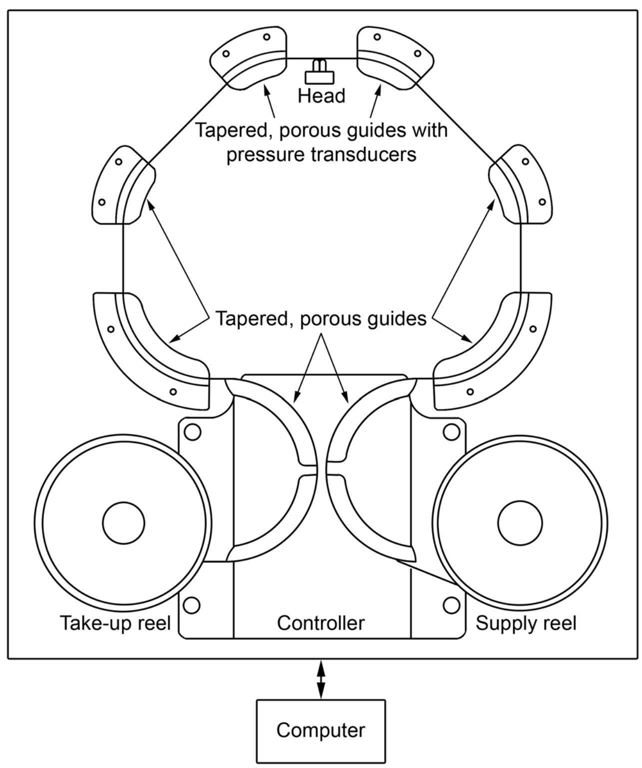



Fig. 4.1 Schematic of Segway Systems / Mountain Engineering MTS linear tape transport with porous air bearings. Guides are tapered at an angle of 0.6° in order to hold tape against bottom flange.

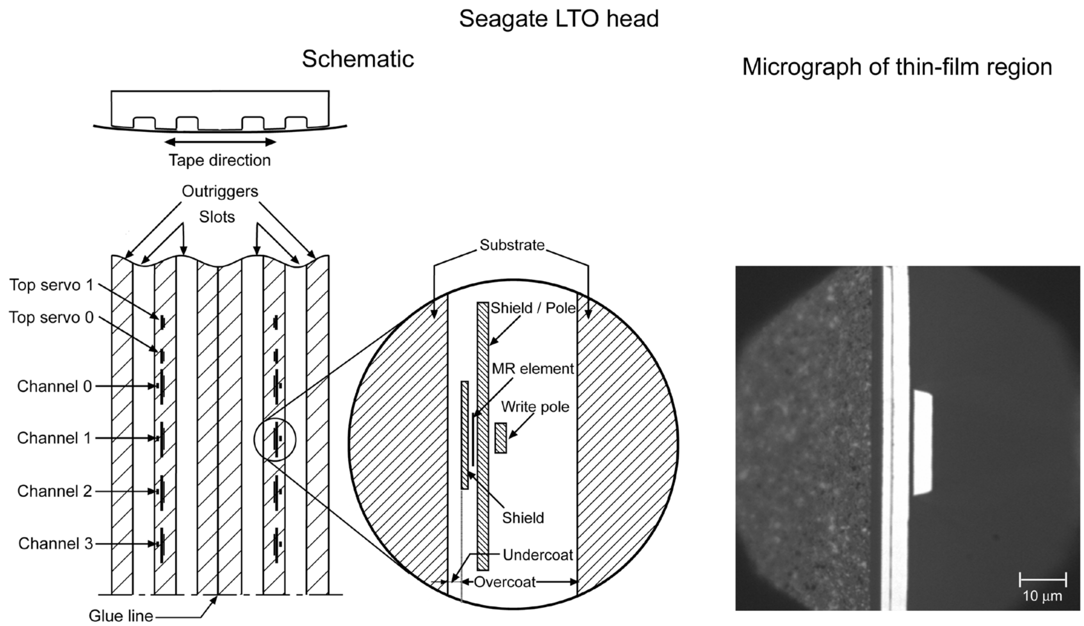



Fig. 4.2 Schematic showing half of the Seagate LTO head used in the study. The head is symmetrical with respect to the glue line. A detailed micrograph of the thin film region is also shown.

### 4.2.1 Tape transport and tape samples

All tests for this study were conducted on a Segway Systems / Mountain Engineering multi-terabyte tape storage (MTS) linear tape transport (Goldale and Bhushan, 2003; Alfano and Bhushan, 2007). The tape guides consisted of porous air bearings and were arranged in an omega pattern, as shown in Fig. 4.1 (Alfano and Bhushan, 2006b). The air bearings allowed compressed air to seep through a porous ceramic surface, creating a cushion of air to suspend the tape above the bearing surface in order to minimize friction and wear. The guides had a single lower flange to guide the bottom edge of the tape and were slightly angled to hold the tape against this bottom flange. The deck controller maintained a constant transport velocity and tension, both of which could be set by the user. The two bearings surrounding the tape head were equipped with pressure sensors to monitor the air pressure needed to suspend the tape above the bearing surface. This information was used by the deck controller to monitor the tape tension and determine if adjustments were needed to maintain the desired tension.

A commercial Seagate LTO head was used for all tests. A schematic of this head is shown in Fig. 4.2 (Alfano and Bhushan, 2006b). The bulk of the head consists of the $Al_2O_3$-TiC substrate, upon which the magneto-resistive stripe, shields and poles, overcoat, undercoat, and gap

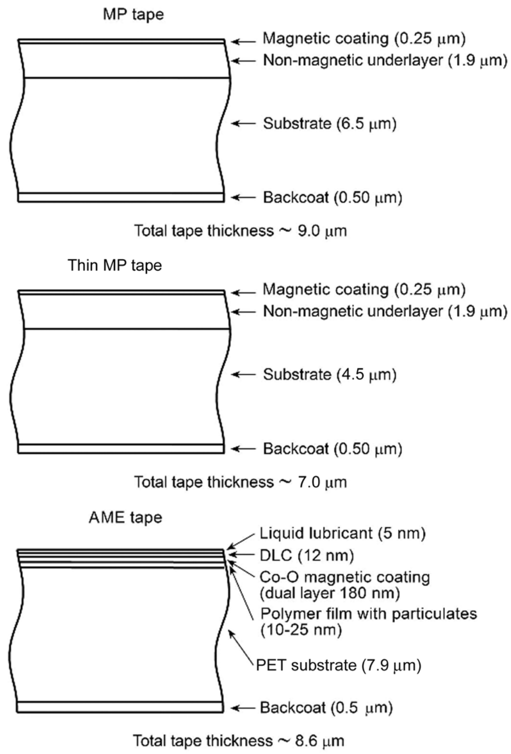



Fig. 4.3 Cross sectional views of magnetic particle (MP) tape, Thin MP tape, and advanced metal evaporated (AME) tape samples used in this study

material are sputter deposited. The head features four vertical slots which allow air to escape while the tape is transporting over the surface, reducing the flying height of the tape above the tape surface. The slots also allow space for debris to collect, so that they will not interfere with the head-tape interface. The read elements had a width of 12 µm, while the write elements were 27 µm wide. Between tests the head was cleaned with isopropyl alcohol to remove deposited tape debris. If staining was observed on the head it was removed by cycling $CrO_2$ tape over the head.

Five different tape samples were tested in this study. These consisted of one commercial metal particle (MP) sample, one experimental Thin MP sample, one experimental negatively-cupped (NC) advanced metal evaporated (AME) sample (AME NC type A), one experimental positively-cupped (PC) AME sample (AME PC type A), and one commercial positively-cupped AME sample (AME PC type B). Cross sections of the different types of tape are shown in Fig. 4.3 (Wright and Bhushan, 2006). Both the MP and Thin MP samples feature a magnetic layer containing passivated iron magnetic particles and head cleaning agents in a polymer matrix of binder and fatty acid ester lubricants. The main difference between the two MP samples is

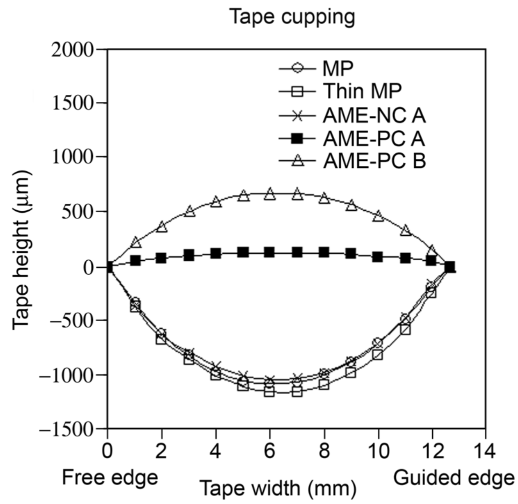



Fig. 4.4 Cupping measurements for tapes used in this study. Positively-cupped (PC) is concave with respect to the head, and negatively-cupped (NC) is convex with respect to the head (Wright and Bhushan, 2006)

the polyethylene (naphthalate) (PEN) substrate thickness, which is 6.5 µm in the standard MP sample and 4.5 µm in the Thin MP sample. The magnetic coating on the AME samples consist of a 180 nm thick layer of evaporated Co-O covering a 7.9 µm thick polyethylene (terephtharate) (PET) substrate. This is then topped with a 12 nm thick layer of diamond-like carbon (DLC) coating to improve durability and protect against corrosion. A lubricant layer 5 nm in thickness consisting of perfluoropolyether (PFPE) coating and a fatty acid esters overcoat was used to further reduce friction and wear on the tape surface.

It was found in previous studies that the cupping of the tape can have a large effect on the performance and durability of that tape (Hunter and Bhushan, 2001; Scott and Bhushan, 2003). Cupping is the tendency of the tape to curl along the machine direction, which is the direction the tape transports through the drive (Bhushan, 2000). Cupping is measured using an optical microscope technique developed by Hunter and Bhushan (2001). With this technique an optical microscope is sequentially focused on different points spanning the tape width, and the focal length needed to bring each point into focus is recorded. These focal lengths can then be converted to distance measurements and the cupping of the tape sample computed. Cupping measurements of the tape samples studied in this test are shown in Fig. 4.4 (Wright and Bhushan, 2006). Tape samples can cup in two different directions. Samples which are concave with

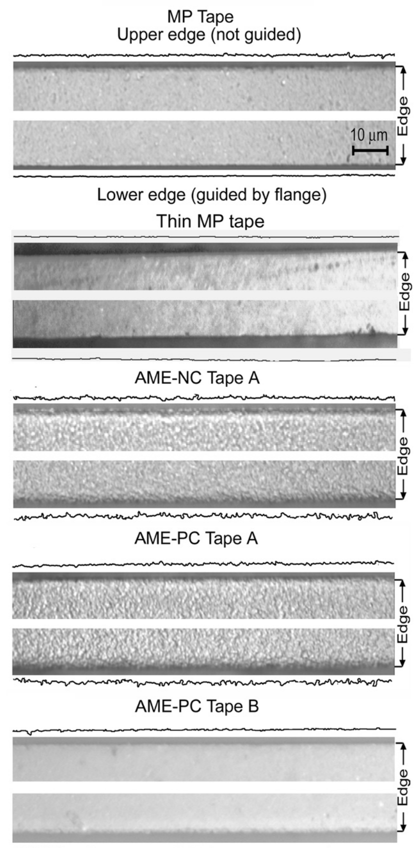



Fig. 4.5 Optical micrographs of MP, Thin MP, and AME tape edges, with types A and B coming from different manufacturers. Example edge contour lines are also shown. Similar edge contour plots were used to compute the relative edge contour length for each tape sample (Wright and Bhushan, 2006)

| Tape Sample | | MP | Thin MP | AME type A-PC | AME type A-NC | AME type B-PC |
|---|---|---|---|---|---|---|
| Cupping Magnitude (μm) | | -1075 [a] | -1075 [b] | 100 [a] | -600 [a] | 700 [a] |
| Relative edge contour length | | 1.033 | 1.024 | 1.036 | 1.025 | 1.025 |
| Tape Thickness (μm) | | 8.9 | 6.9 | 8.6 | 8.6 | 8.6 |
| Bending Stiffness ($\mu$Pa $m^3$) | Machine | 0.2962 | 0.1489 | 0.3071 | 0.2555 | 0.2868 |
| | Transverse | 0.2630 | 0.1382 | 0.3581 | 0.2943 | 0.5007 |
| Elastic Modulus (GPa) | Machine | 4.6 | 4.9 | 5.3 | 4.4 | 4.9 |
| | Transverse | 4.1 | 4.6 | 6.1 | 5.1 | 8.6 |

[a] Alfano and Bhushan, 2007; [b] Wright and Bhushan, 2006; all other data from Petrek and Bhushan, 2008

Table 4.1 Summary of physical properties for tapes tested

respect to the head are considered to be positively-cupped (PC), while samples that are convex with respect to the head are negatively-cupped (NC). It is important to note that for positively cupped samples the tape edges are in contact with the head, while for negatively cupped samples the larger center area of the tape is in contact.

Optical micrographs of the edges of each tape sample are shown in Fig. 4.5 (Wright and Bhushan, 2006). From these images it is clear that the tape edges are not perfectly smooth, and this can have a large impact on the performance of a tape. Edge roughness was quantified using a technique developed by Goldale and Bhushan (2003, 2004). With this technique optical micrographs are processed so that the edge of the tape is identified. The total edge length is then calculated, and compared with the ideal length if the edge were perfectly straight. The ratio between these lengths is known as the relative edge contour length. The higher the relative edge contour length, the rougher the edge. This number is a quantification of only the high frequency edge roughness, and does not include longer wavelength features which cannot be seen in the limited view of the micrographs.

A summary of the mechanical properties of all five tapes is given in Table 4.1 (Petrek and Bhushan, 2008). Bending stiffness is a measure of the resistance a tape gives to being deformed. This was measured using a technique developed by Scott and Bhushan (1997) where

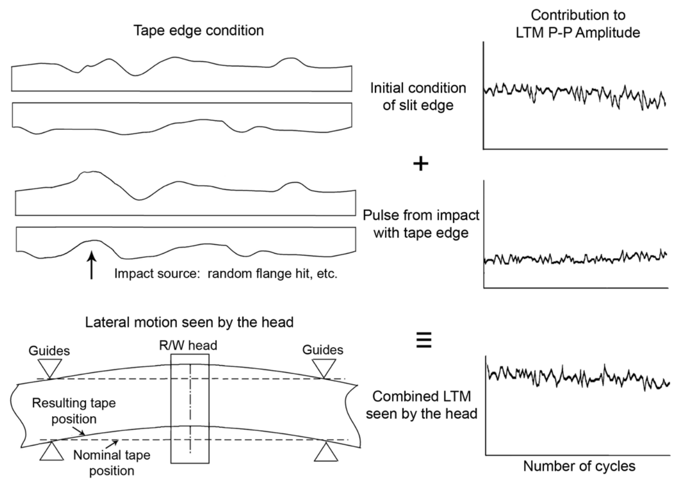



Fig. 4.6 Schematic illustrating the contribution of both tape motion and edge roughness to the measured LTM when using the Fotonic edge probe measurement method. The tape edge roughness contributes error to the LTM measurement when using the edge probe method. (Alfano and Bhushan, 2006)

a loop of tape is pressed into the tray of a microbalance, and the force exerted on the tray is measured for different amounts of tape deflection. By approximating the tape loop as a thin-walled cylinder and using the principle of virtual work, a bending stiffness can be calculated for each sample based on the load-deflection curve. The overall elastic modulus for the sample, including substrate and magnetic layers, can then be computed using the bending stiffness and the tape thickness. The machine direction is the direction which the tape transports through the deck (length) and the transverse direction is the width of the tape, perpendicular to the machine direction.

### 4.2.2 Measurement techniques

To monitor the performance of the different tape samples both LTM and coefficient of friction were measured throughout the test. LTM was measured using both the Fotonic edge probe method and the magnetic signal method. The edge probe method utilizes a Fotonic edge probe (MTI Instruments Inc., Latham, NY, USA) to monitor the position of the tape edge (Taylor et al., 2000;Goldale and Bhushan, 2003). The Fotonic probe consists of a pair of fiber optic cables with prisms on one end. Light is passed down one cable, through the first prism, across an air gap, into the second prism, and then travels down the second fiber optic cable to a photo-

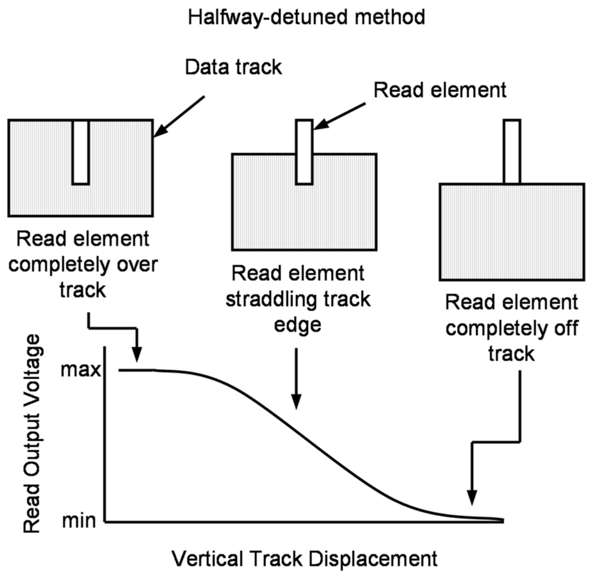



Fig. 4.7 Schematic illustrating the magnetic method of LTM measurement. With the read element straddling the edge of the written data track the read output voltage is proportional to the percentage of the read element that is located on the data track. Changes in head-tape spacing can also affect the read output voltage, which would be misinterpreted as LTM and is a source of error for this measurement method.

detector. The percentage of light reaching the photodetector is proportional to the area in the air gap which is blocked by the tape edge. One main disadvantage of the edge probe technique is that it convolves the tape edge roughness with the LTM (Goldale and Bhushan, 2004; Alfano and Bhushan, 2006a). This is illustrated in Fig. 4.6 (Alfano and Bhushan, 2006b). While this technique is useful for comparing LTM results of a single tape, or for finding trends in changing levels of LTM throughout a single test, its usefulness in comparing LTM for different tapes is limited due to the different edge roughness for each tape.

Another method of LTM measurement is known as the magnetic method, or "halfway detuned method" ( Alfano and Bhushan, 2006a, 2007). In this method a data track is written along the length of the tape. The read element is then repositioned to straddle the edge of the data track. The read output voltage is then proportional to the percentage of the read element which is located over the data track, as shown in Fig. 4.7. As the track moves this percentage changes, and the output voltage can be correlated with a displacement distance measurement. This method is not affected by edge roughness, and LTM measurements made using this method are therefore typically lower than measurements made using the edge probe method. The magnetic method does have several disadvantages, though. First, it assumes that the original data track being followed is straight. Any irregularities in the data track will be misinterpreted as LTM. Second, the method is unable to measure repeatable LTM if the data track is written and read on the same deck. Tape motion occurring the same way in both the read and write cycle are transparent to the magnetic method. Finally, this method is sensitive to head-tape spacing changes, which also affects the read output voltage and would therefore be misinterpreted as LTM.

The coefficient of friction between the head and the tape was also computed. The tension in the tape on each side of the head was calculated based on the plenum pressure needed to hold the tape surface above the porous air bearings. The belt equation was then used to calculate the coefficient of friction based on the difference in these tension signals.

All LTM and coefficient of friction signals were routed to a National Instruments data acquisition (DAQ) board (NI-6023E, National Instruments, Austin, TX, USA). Sampling was triggered via a jump in the Fotonic edge probe signal caused by a small notch cut into the tape edge. One seconds worth of data directly preceding the trigger was then recorded to disk. This consentient trigger method minimized variability in the sampled data that could be caused by recording at different times in the transport cycle, and the retroactive recording ensured that any LTM caused by the edge notch used for triggering was not recorded. The sampling rate was adjusted based on the tape transport speed, in order to minimize differences caused by edge roughness. Sam-

| | Tape Speed (m/s) | | | |
|---|---|---|---|---|
| Tape Tension (n) | | 8 | 10 | 12 |
| | 0.8 | X | | X |
| | 1.0 | | X | |
| | 1.2 | X | | X |

Table 4.2 Testing matrix showing speed/tension combinations

ple rates were 10 kHz at 8 m/s, 12.5 kHz at 10 m/s, and 15 kHz at 12 m/s. The signals were then recorded to disk using LabVIEW software (National Instruments) and processed using MATLAB (Mathworks Inc., Natic, MA, USA).

After each test was completed the edge quality of the lower, guiding edge of each sample was measured. This was done by removing three sections of tape from the worn sample, with at least 10 m of tape separating each section. These worn samples were then mounted to slides, and micrographs were taken using an optical microscope (OPTIPHOT-2, Nikon Corporation, Tokyo, Japan). Image processing was automated using Photoshop (Adobe, San Jose, CA, USA), and an average relative edge contour length was calculated using a custom MATLAB script.

### 4.2.3 Experimental plan

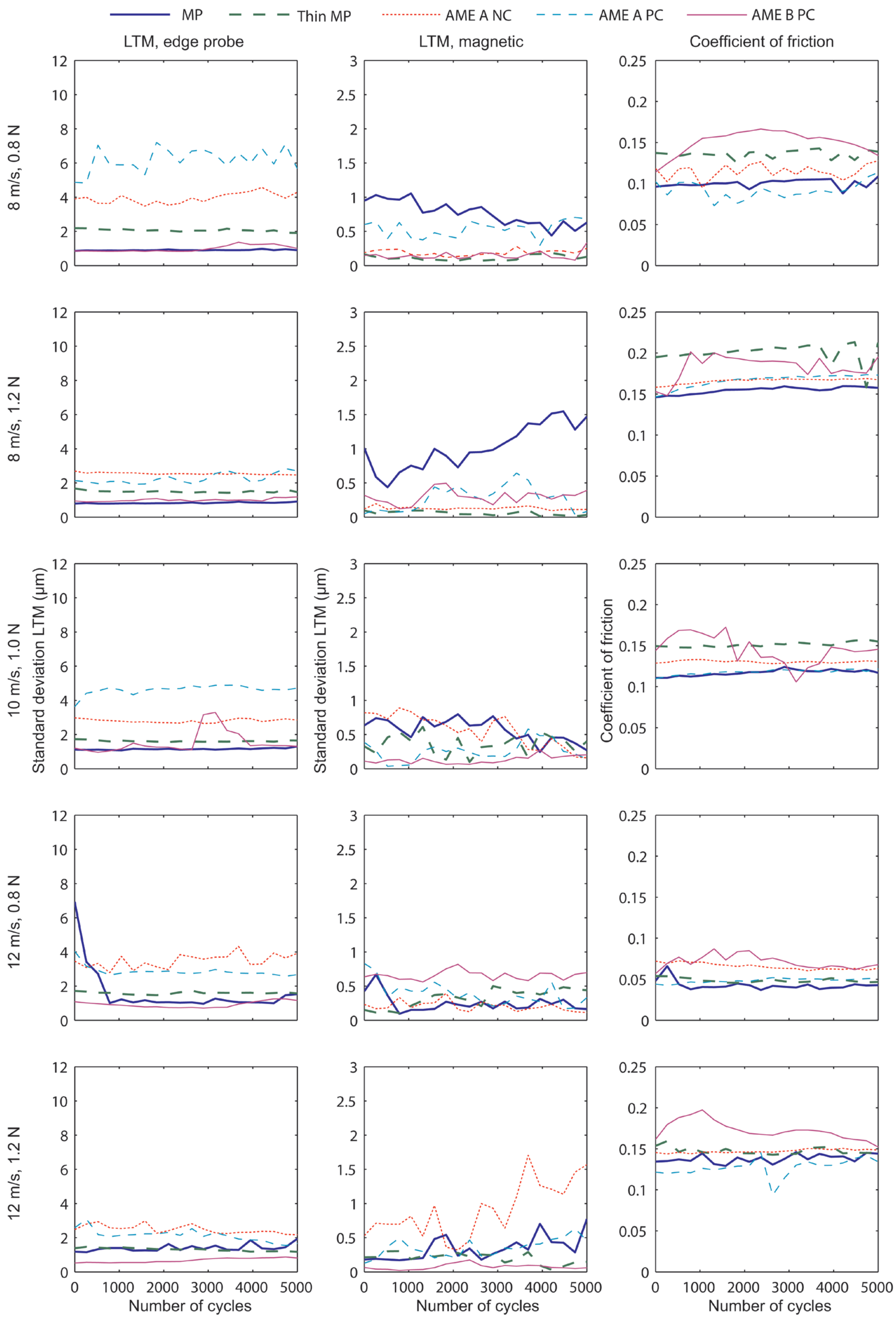
This study was designed to measure the performance of the different tape samples at high speeds and a range of tensions. In order to determine the optimal speed-tension settings several different combinations were studied. Table 4.2 gives the testing matrix. Tension was varied between 0.8 and 1.2 N, and speed was varied between 8 and 12 m/s. Each tape was then run for 5000 cycles, with each cycle consisting of a forward and backward pass.

## 4.3 Results and Discussion

The LTM and coefficient of friction for five different tape samples were monitored over the course of a 5000 cycle durability test. Five different speed-tension combinations were tested in order to determine the optimal setting for using magnetic tapes at high speeds.

LTM and coefficient of friction measurements over the duration of the test are shown in Fig. 4.8a, grouped by testing parameters. By examining the LTM edge probe data it can be seen that all tapes had the lowest amounts of LTM in the high tension cases. Similar results were found in previous studies conducted at lower speeds (Wang et al., 2003; Hansen and Bhushan, 2005). This is likely due to the decreased flexibility of the tape when placed under higher tension, resulting in less tape motion from tape edge - guide impacts. The increased friction between the head and tape at high tensions can also help to dampen LTM, as the higher friction increases the resistance to motion in both the translating and lateral directions. The coefficient of friction plots show clear groupings for each tension/ speed combination. This indicates that a tape's physical properties (cupping, surface roughness, etc.) have less of an effect on coefficient of friction than the speed and tension. MP and Thin MP tapes consistently had the lowest coefficient of friction in all tension/ speed combinations. AME PC type B had the highest coefficient of friction in all cases, most likely due to the large amount of positive cupping which would press the edges of the tape against the head. The small area of these line contacts would not have the benefit of a hydrodynamic air boundary layer to separate them from the head. This dif-

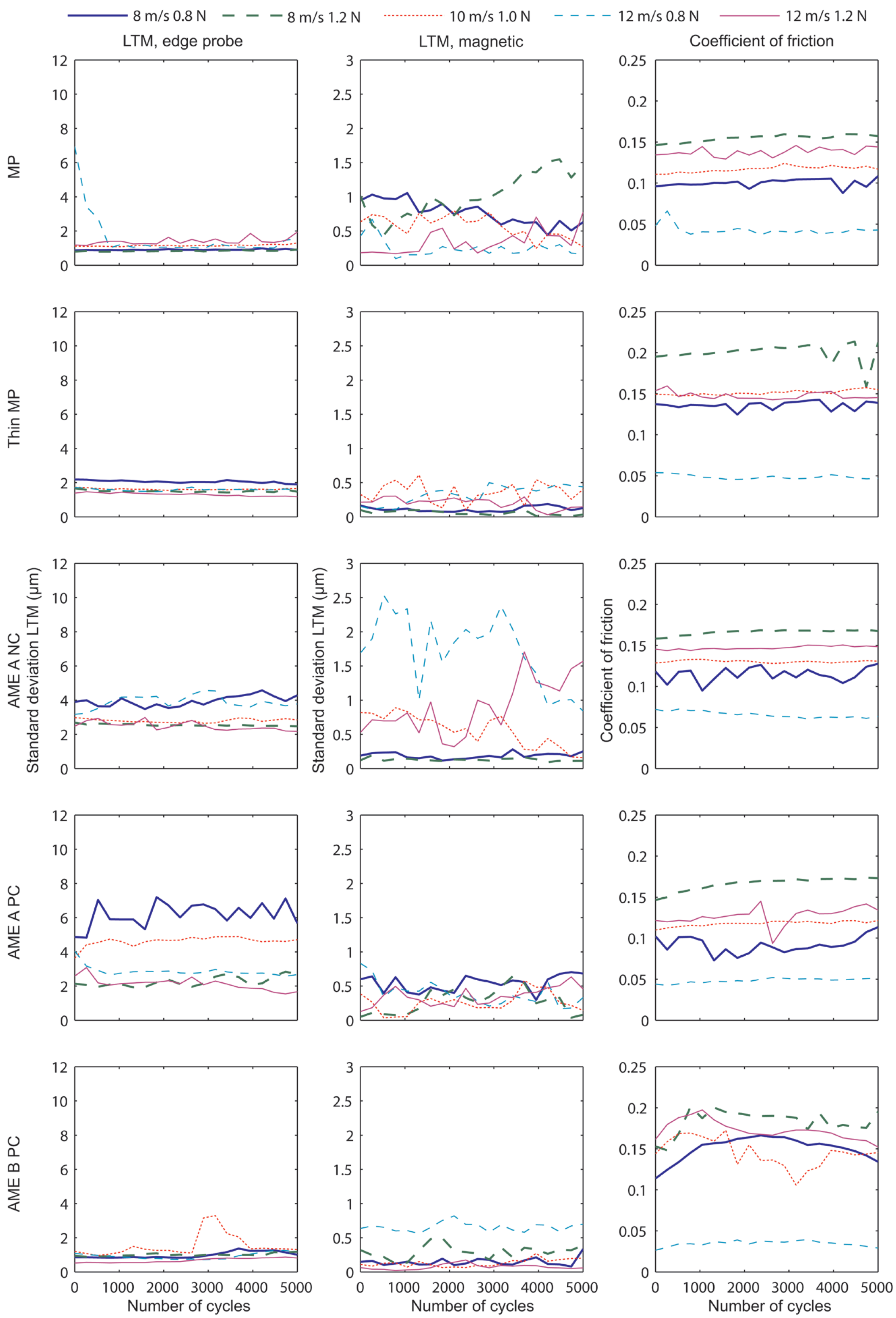
Fig. 4.8a (next page) LTM and coefficient of friction measurements over the duration of the test grouped by testing parameters. In (a) all tapes had the lowest amounts of LTM in the high tension cases, likely due to the increased stiffness of the tape when placed under higher tension. AME PC type B had the highest coefficient of friction in all cases, most likely due to the large amount of positive cupping which would cause the tape edges to be in contact with the head without the benefit of a hydrodynamic boundary layer to reduce the friction. There were no sudden increases in the coefficient of friction for any tape at any parameter combination that would indicate a complete lubricant or protective coating failure.



MP
Thin MP
AME A NC
AME A PC
AME B PC
LTM, edge probe
LTM, magnetic
Coefficient of friction
8 m/s, 0.8 N
8 m/s, 1.2 N
10 m/s, 1.0 N
12 m/s, 0.8 N
12 m/s, 1.2 N
Standard deviation LTM (µm)
Coefficient of friction
Number of cycles


Fig. 4.8a

Fig, 4.8b (next page) LTM and coefficient of friction measurements over the duration of the test grouped by tape type. In (b) MP, Thin MP, and AME PC type B tape had the lowest overall LTM. For all tapes the highest coefficient of friction was seen in the low speed, high tension setup. This combination resulted in an increased normal force between the tape and the head due to the high tension, and a thin hydrodynamic air cushion due to the low speed. The lowest coefficient of friction was seen in the high-speed, low tension case. The high-speed, high-tension cases had roughly the same coefficient of friction values as the low-speed, low-tension cases, indicating that high tension could be used at high speed to minimize LTM without negatively impacting durability. The increased tension would have a negative effect during starting and stopping, though, when there is no hydrodynamic layer to counter the increased friction form tension.



8 m/s 0.8 N
8 m/s 1.2 N
10 m/s 1.0 N
12 m/s 0.8 N
12 m/s 1.2 N
LTM, edge probe
LTM, magnetic
Coefficient of friction
MP
Thin MP
AME A NC
AME A PC
AME B PC
Standard deviation LTM (μm)
Coefficient of friction
Number of cycles


Fig. 4.8b

fers from the negatively cupped samples, which press the center of the tape against the head and would benefit more from hydrodynamic effects. This difference in contact modes has been noted in previous studies comparing the performance of positively and negatively cupped tapes (Goldale and Bhushan, 2005). This same study also proposed that negative cupping was better for MP tapes, as there was less contact between the edge of the tape and the head resulting in less edge damage, and that positive cupping was better for AME tapes so that the DLC coating remained in compression and crack propagation was minimized. There were no sudden increases in the coefficient of friction for any tape at any parameter combination that would indicate a complete lubricant or protective coating failure, which shows that all tapes could be considered good candidates for running at high speed without greatly increased wear.

Fig. 4.8b gives LTM and coefficient of friction measurements over the length of the test, grouped by tape type. MP, Thin MP, and AME PC type B tape had the lowest overall LTM, and the amount of LTM for these tapes was not greatly affected by the tension or speed. The LTM measured for the AME NC and PC type A tapes did change with the testing parameters. These tapes have the lowest magnitude cupping (see Table 1), which may make them less intrinsically stiff than the other tapes and more sensitive to flexibility changes caused by increased or decreased tension, resulting in larger changes in the amount of LTM. All of the tapes showed a consistent pattern relating the coefficient of friction to the speed and tension used. In all cases the highest coefficient of friction was seen in the low speed, high tension setup. This combination resulted in an increased normal force between the tape and the head due to the high tension, and a thin hydrodynamic air cushion due to the low speed. The lowest coefficient of friction was seen in the high-speed, low tension case, due to the decreased normal force caused by the lower tension and the thicker hydrodynamic air cushion caused by the higher tape speed. The high-speed, high-tension cases had roughly the same coefficient of friction values as the low-speed, low-tension cases, indicating that high tension could be used at high speed to minimize LTM without increasing wear. It is important to note, though, that this study only looked at the durability of the tapes in flying operation, where the tape has a constant velocity between the starting and ending points. In the normal operation of a tape drive the tape can be started and stopped at various locations in the cycle. As the tape is stopped or reversed the velocity falls to zero, and the increased coefficient of friction due to high tension is no longer counteracted by the thicker hydrodynamic boundary layer. This could lead to excessive wear of the tape. A possible solution to this problem would be to adjust the tension with the varying speed in the tape drive, so that the tension is decreased during stopping or reversing, but then increased during flying in order to reduce LTM. In all parameter combinations the AME PC type B tape experienced a 10 to 30% increase in coefficient of friction over the first 1000 cycles. This was not seen in the other positively cupped sample, or in either of the other AME samples, suggesting that this trend is due to a lubricant or coating found specifically on the AME PC type B tape.

Both edge probe and magnetic LTM data were given in Figure 8a and 8b. For this study the preferred method of LTM measurement was the edge probe. This is due to the fact that the main disadvantage of the edge probe, the error in LTM measurement caused by edge roughness, does not have a large effect when looking for changes in LTM levels throughout the test or when comparing different tests using the same kind of tape. In both of these cases the tape edge roughness should be consistent, and any error would be equally added in all cases, enabling an accurate comparison of measurements. The magnetic method would normally be useful for making an absolute measurement of LTM. However, this method is very sensitive to head-tape spacing, which can change significantly throughout a test due to tape smoothing or debris formation. It is therefore unclear whether any change in the read output voltage, which would be interpreted as LTM, is due to actual LTM or one of the aforementioned effects. For these reasons, the magnetic method was deemed to be the less reliable of the LTM measurement methods, and further comments on LTM for this study will concentrate on the edge probe results.

In Fig. 4.9 the LTM and coefficient of friction results for all of the different tape samples were averaged together. This was done in order to increase the sample size and highlight any general trends that affect all tape samples. The change in LTM over the course of the 5000 cycle test is shown in Fig. 4.9a. In most cases the measured edge probe LTM was found to increase during the length of the test. This could be due to an accumulation of edge damage on the bottom tape edge, resulting in more edge-guide impact events, and consequently more tape motion. An accumulation of damage on the top tape edge would not increase actual LTM events, due to the fact that there is no flange guiding the upper tape edge. The increased roughness would be seen by the edge probe though, and contribute to an increase in measured LTM. However, this effect should be minor as there should be little damage to the top edge since it is not in contact with a guiding flange. The change in coefficient of friction over the course of the test is shown in Fig. 4.9b. The tests conducted at 10 and 12 m/s showed little change in the coefficient of friction as the number of cycles increased. The low speed tests, however, resulted in a small and gradual increase in the coefficient of friction over the life of the test, indicating that high speeds may help reduce wear. Similar trends in the coefficient of friction were seen in a study conducted at lower speeds by Hansen and Bhushan (2005).

The change in LTM, coefficient of friction, and ending relative edge contour length with respect to speed are shown in Fig. 4.10. LTM and coefficient of friction data were averaged over the entire 5000 cycle test, and tests conducted at the same speed but different tensions were also averaged together. Fig. 4.10a shows that the speed had little effect on the LTM for the Thin MP, AME NC type A and AME PC type B tapes. MP tape showed increasing LTM at increasing speeds. This may be due to an increase in tape edge/ guide impacts due to increasing edge damage at higher speeds (see Figure 10c). The relationship between increasing edge damage and increasing levels of LTM has been noted in previous studies (Wang and Talke, 2005). Fig.

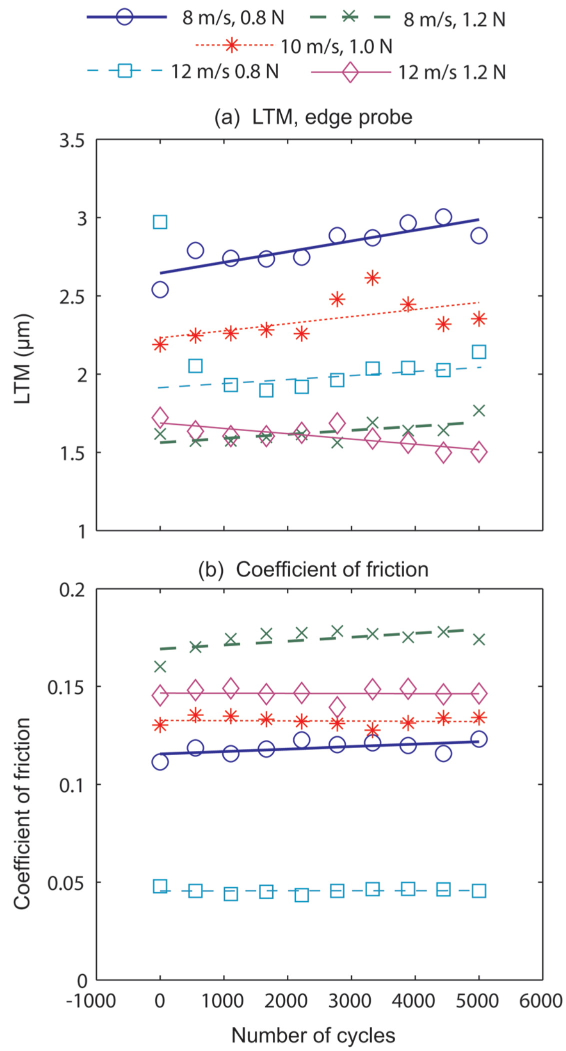
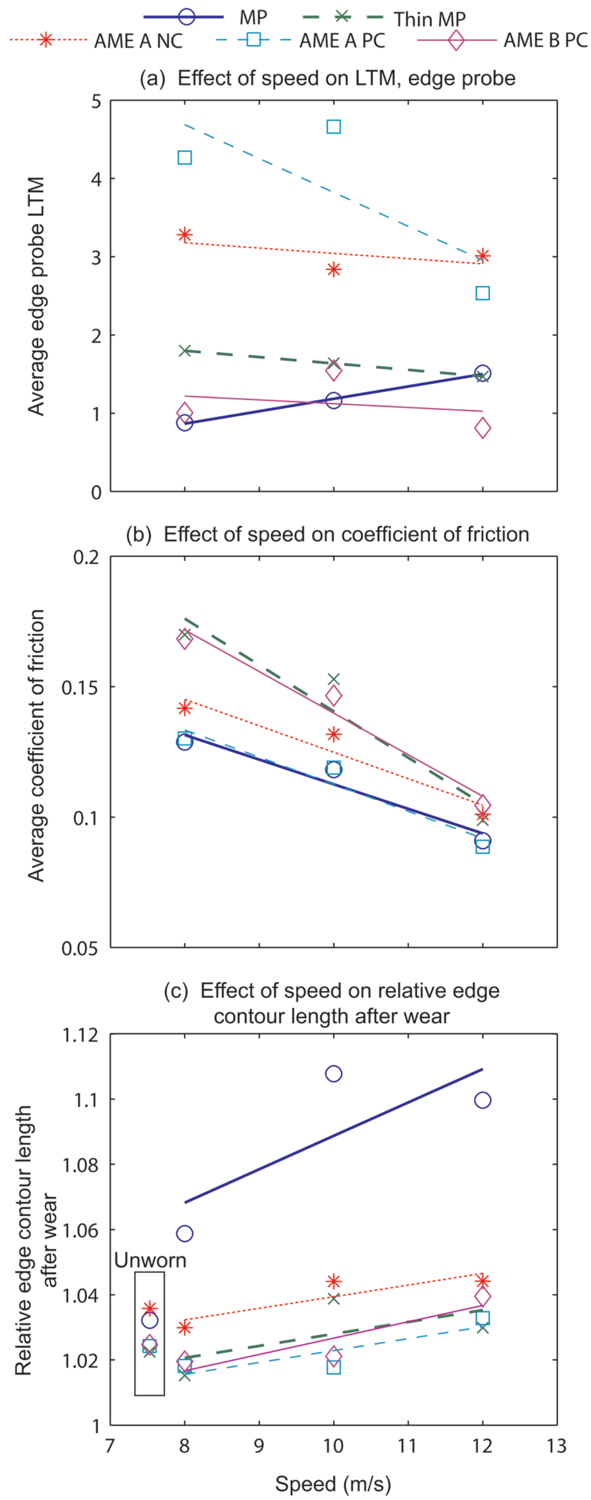



Fig. 4.9 Change in LTM (a) and coefficient of friction (b) for all tapes averaged together throughout the 5000 cycle test, done in order to spot any general trends. As shown in (a), in most cases the measured edge probe LTM was found to increase during the length of the test. This could be due to an accumulation of edge damage, resulting in more edge-guide impact events, and consequently more tape motion. In (b) the low speed tests resulted in a small and gradual increase in the coefficient of friction over the life of the test, indicating that high speeds may help reduce wear

Fig. 4.10 (next page) Effect of speed on LTM (a), coefficient of friction (b), and relative edge contour length (c) after wear. In (a) for the Thin MP, AME NC type A and AME PC type B the speed had little effect on the LTM. MP tape showed increasing LTM at increasing speeds. This may be due to more interaction between the tape edge and guide caused by increased edge damage at higher speeds (see Figure 9c). The plot shown in (b) illustrates that speed has a large effect on decreasing the coefficient of friction , due to the increasing thickness of the hydrodynamic boundary layer at higher speeds. In (c) for most tapes the change in speed had little effect on the ending edge roughness. The exception to this is MP tape, which sustained significant edge damage at all speeds, with more damage occurring at higher speeds.



MP
Thin MP
AME A NC
AME A PC
AME B PC
(a) Effect of speed on LTM, edge probe
Average edge probe LTM
0
1
2
3
4
5
(b) Effect of speed on coefficient of friction
Average coefficient of friction
0.05
0.1
0.15
0.2
(c) Effect of speed on relative edge contour length after wear
Relative edge contour length after wear
1
1.02
1.04
1.06
1.08
1.1
1.12
Unworn
7
8
9
10
11
12
13
Speed (m/s)


Fig. 4.10

4.10b illustrates the effect that transport speed had on coefficient of friction. It can be seen that higher speeds correlated with a decreasing coefficient of friction. This was due to the increasing thickness of the hydrodynamic boundary layer at higher speeds. The relationship between transport speed and ending relative edge contour length for the bottom, guided tape edge is shown in Fig. 4.10c. Edge contour length is a quantitative measurement of edge roughness. An increase in edge roughness compared to the unworn state can indicate extensive edge damage, which may lead to greater amounts of LTM due to increased edge-guide impacts. A decrease in edge roughness may indicate slower wear, casing a rough edge to become smoother. For most tapes the change in speed had little effect on the ending edge roughness, and the edges sustained little damage. The exception to this is MP tape, which sustained significant edge damage at all speeds, with more damage occurring at higher speeds. The reason for this increase in edge damage is unclear, as the other MP tape, Thin MP, did not sustain damage, and neither did the other negatively cupped tapes. One possible explanation is that the thicker, standard MP substrate was not able to deform as easily as the Thin MP substrate, resulting in a greater amount of damage to the magnetic coating.

### 4.4 Conclusions

This study was conducted in order to evaluate the performance of different types of magnetic tapes at high speeds and to identify any potential problems. This is of direct interest to manufacturers as the constant increase in tape drive capacity must be accompanied by an increase in data throughput, which can be accomplished by increasing the tape transport speed. LTM, coefficient of friction, and ending relative edge contour length were measured for five types of tape at five different speed/tension combinations. Due to the comparative nature of this study, Fotonic edge probe LTM measurements were thought to be more accurate than the magnetic method, and all comments on LTM are based on the edge probe measurement data. Using these observations, the following conclusions were made:

- In general, tapes showed the lowest amounts of LTM in the high tension setups. This is due to the increase in force needed to deflect the tape at higher tensions, resulting in less LTM from edge-guide impacts.
- There were no instances of sudden, drastic increases in coefficient of friction that would indicate complete lubricant / coating failure for any tape at and speed or tension. This indicates that the tested samples should be able to operate at any of the tested speed/tension combinations without excessive wear.
- The coefficient of friction between the tape and the head was seen to have a strong relationship with the transport speed, with higher speeds correlating to lower coefficients

of friction. This is due to the increased hydrodynamic boundary layer thickness between the tape and the head.

- The highest coefficient of friction was seen for in the AME PC type B tape. This tape had the highest magnitude positive cupping of the samples tested. This may indicate that the edges of the tape were in contact with the tape head, and that these small-area line contacts did not benefit from a hydrodynamic boundary layer in the way that the negatively cupped tapes did.

- Speed had a greater effect on coefficient of friction than tension. The high speed, high tension case had roughly the same average coefficient of friction as the low speed, low tension case. This indicates that high tension can be used with high speed to reduce LTM without leading to an increase in coefficient of friction and wear. However, this study did not take into account the wear that can occur during starting and stopping. At these points in the transport cycle there would be increased friction at higher tensions without the benefit of a thicker hydrodynamic boundary layer due to the low velocity.

- High speed was found to have little effect on the edge damage for most tapes. The exception to this is the MP tape. As edge damage can lead to an increase in edge-guide impacts and LTM it is suggested that MP tape not be used in high speed scenarios.

- AME PC type B tape showed the lowest overall amounts of LTM, and did not sustain significant edge damage at high speeds. It exhibited higher coefficients of friction than other tapes, but did not show any sudden increases indicating coating or lubricant failure. For these reasons AME tape with a large magnitude positive cupping is suggested for use at high speeds.

Based on these results, any of the tested tapes should operate at high speeds and tensions without excessive wear. High tension is suggested at high speeds to minimize LTM. The normal increase in coefficient of friction often seen at higher tensions is counteracted at high speed by an increase in hydrodynamic effects, which should keep excessive wear from becoming an issue.

# CHAPTER 5

# SUMMARY

As the storage capacity and data throughput for magnetic tape data storage drives increases many challenges must be overcome, including increased sensitivity to LTM and increased wear at higher tensions and speeds. A new method for measuring LTM which overcomes many of the disadvantages of previous methods was described. Examples of how this method could be applied to other systems, both electrical and mechanical, were also described. Using the delay-integration method a more accurate measurement of LTM is possible, which may help to better design drives to minimize unwanted tape motion.

The delay integration method was then applied to the measurement of LTM along an unsupported tape region. As expected, the highest amounts of LTM were seen at the center, where the tape is furthest from either guide. It was also found that tape motion can be minimized by using tape with a large amplitude of cupping, which likely increase the stiffness of the tape and makes it less responsive to edge guiding.

Finally, five different tape samples were tested for durability at high speeds and a variety of tensions. None of the tapes tested showed a complete coating or lubricant failure, indicating that they would be able to withstand high speed and tension conditions. It was also found that higher speeds resulted in a lower coefficient of friction, due to the increased thickness of the hydrodynamic boundary layer. This could allow for tape to be run at higher tensions to minimize LTM without increasing wear. Based on these results, AME tape with a large amount of positive cupping was determined to be the best candidate for high-speed operation.

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