Measurement and Sources of Lateral Tape Motion: A Review

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The sources of lateral tape motion in a tape drive are reviewed. Currently used measurement methods and models for lateral tape motion are analyzed and compared. The effect of roller run-out, tape edge contact, and tape tension transients on lateral tape motion is discussed. A dual stage actuator tape head is investigated to improve track-following capability and increase the track density on a magnetic tape. [DOI: 10.1115/1.3002332]

Keywords: magnetic tape recording, lateral tape motion, magnetic storage

1 Introduction

The storage market is presently dominated by hard disk drives. However, magnetic tape has maintained its cost-per-gigabyte advantage with respect to hard disk drives and remains the primary choice for backup and mass data storage applications [1,2].

Tape research can be divided into four main fields [1]: (a) head technology, (b) recording media technology, (c) tape transport technology, and (d) recording channel electronics technology. In this paper, we focus on tape transport technology and review the present understanding of lateral tape motion and its effect on track density. Currently used instrumentation to measure lateral tape motion is described. In addition, the primary sources of lateral tape motion are discussed. Finally, the concept of active friction guiding and the design of a dual stage actuator tape head are discussed.

2 Recording Density

In Fig. 1, the areal density in commercial tape products is shown as a function of their introduction year. As can be seen, the areal density has increased at an approximately 60% compound annual growth rate (CAGR) [1–5].

This increase in areal density in tape drives occurred mainly due to increases in the linear bit density. More recently, increases in track density have been implemented. Track densities presently approach 100 tracks/mm. Significant improvements in the areal density could be made by increasing the track density even further, as shown by both the 1 Tbyte and 8 Tbyte demonstrations [3,4].

It has been reported in the literature that tape media can be manufactured to accommodate areal densities of up to 15 Gbit/in.^2 [6,7]. To operate tape media with this density, lateral tape motion (LTM) needs to be better controlled along with obtaining a better understanding of the sources of tape dynamics. In particular, the lateral tape motion at the read/write elements must be attenuated to reduce track misregistration.

3 Tape Transport Technology

3.1 Lateral Tape Motion. Magnetic tape is transported from a supply reel (cartridge) to a take-up reel. Along this path, the tape is guided by stationary guides or rotating rollers. Several researchers have studied the dynamic behavior and vibrations of a moving string or web between rollers. Swope and Ames [8] characterized and analyzed the oscillation of a string that is wound on a bobbin. In their analysis, they assumed a perfectly flexible string without lateral bending stiffness and derived and solved the governing equations. Shelton and Reid [9] studied the lateral dynamics of a moving web and derived the differential equations for the lateral dynamic motion of a massless moving web [10]. Wickert and Mote [11] studied the vibration and stability of an axially moving continuum, with the equations of motion cast in a canonical state space form. Young and Reid [12] investigated the lateral and longitudinal motion of a moving web and concluded that the lateral and longitudinal web dynamics are critical with respect to web edge alignment. Lee and Mote, Jr. [13] investigated the transverse motion of a translating tensioned Euler–Bernoulli beam moving at constant velocity between two supports using a fourth order model. Garziera and Amabili [14] studied the effect of damping on the lateral vibration of an axially moving tape. The tape was modeled as a string; i.e., bending stiffness was neglected and only the lateral vibrations were investigated. Benson [15] used the Euler–Bernoulli beam theory to predict the lateral motion of a long warped web that is transported between two rollers. Yerashunas et al. [16] modeled a web as a viscoelastic beam under axial tension. This model treats the web position between rollers as a function of both space and time. However, the lateral displacement of the web guided over a roller was not investigated. Zen and Muftu [17] modeled a web as a tensioned string translating between two rigid supports. They found that friction adversely affects stability.

The effect of guides on the lateral tape motion in a tape path has been studied by only a few researchers. Ono [18] described the lateral displacement of an axially moving string on a cylindrical guide surface. Bending stiffness was not included in his model. He showed that the lateral motion is governed by a second order differential equation similar to that for one dimensional heat flow. More recently, O'Reilly and Varadi [19] studied the dynamics of a closed loop of inextensible string, which undergoes an axial motion and of which one point is in contact with a singular supply of momentum. Taylor and Talke [20] investigated the interactions between rollers and a flexible tape and showed that friction between the tape and the roller affects the lateral displacement of tape.

Displacements of the tape perpendicular to the transport direction occur due to internal and external forces acting on the tape. The lateral displacement z of a point on the centerline of a section of a tape between two rollers or guides is most commonly described as an Euler–Bernoulli beam [9,10],

$$EI\frac{\partial^4 z}{\partial s^4} - T\frac{\partial^2 z}{\partial s^2} + \rho\left(U^2\frac{\partial^2 z}{\partial s^2} + 2U\frac{\partial^2 z}{\partial s\,\partial t} + \frac{\partial^2 z}{\partial t^2}\right) = q(s) \qquad (1)$$

where E is the Young's modulus of the tape, I is the area moment of the tape cross-section, U is the tape speed, T is the tape tension, ρ is the linear density of the tape, s is the coordinate along the tape centerline, t is the time variable, and $q(s)$ is an external load that may be applied to the tape edge. In addition, the lateral displacement z of a point on the centerline of a section of a tape, which is

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Contributed by the Tribology Division of ASME for publication in the Journal of Tribology. Manuscript received July 5, 2007; final manuscript received September 8, 2008; published online December 2, 2008. Assoc. Editor: Jane Wang.

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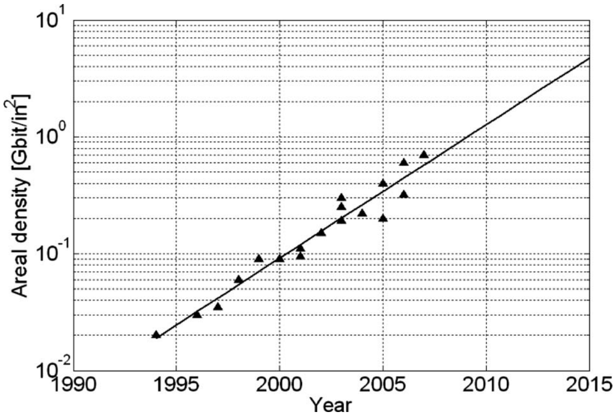

Fig. 1 Evolution of the areal density

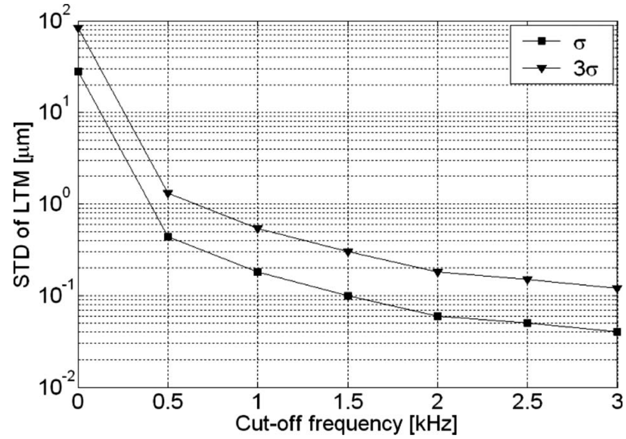

Fig. 3 Standard deviation of LTM versus cutoff frequency

in contact with a guide, can be described as [21]

$$EI\frac{\partial^4 z}{\partial s^4} - T\frac{\partial^2 z}{\partial s^2} + \frac{\mu_z T}{a}(1-\nu)\frac{\partial z}{\partial s} + \frac{\mu_z T}{Ua}\frac{\partial z}{\partial t} = 0 \tag{2}$$

where $\nu=\mu_\varphi/\mu_z$ is the ratio of the friction coefficients in the circumferential and vertical direction, respectively. a is the radius of the cylindrical guide. When $\mu_\varphi=0$ and $\mu_z\to\infty$, Eq. (2) describes the lateral motion of a tape moving over a roller, i.e., a rotary guide. In Eqs. (1) and (2), the fourth order derivative represents the bending stiffness of the tape. If the bending stiffness is neglected, i.e., $I=0$, Eqs. (1) and (2) become identical to the equations of motion for a string derived by Swope and Ames [8] and Ono [18], respectively.

A servo system can be used to control the lateral position of the tape head actuator and to compensate for the lateral displacement of the tape up to a limiting bandwidth [22]. The bandwidth of the actuator is a function of the actuator mass and the power available [1]. Lateral tape motion with a frequency higher than the bandwidth of the servo actuator, typically around 1 kHz, is referred to as high frequency lateral tape motion [23,24]. Lateral tape motion can cause track misregistration between the read/write head and a previously written track. This limits the maximum recording density achievable. Lateral tape motion can be characterized by its 3σ value, where σ represents the standard deviation of the lateral displacement. Lateral displacements of the tape on the order of 10% of the width of a track have been reported to cause read/write errors [25]. Thus, for a typical tape drive with a track width of 10 μm, 3σ of the high frequency lateral tape motion must be smaller than 1 μm. For a track width of 1.5 μm [3], 3σ of the high frequency lateral tape motion must be smaller than 0.15 μm to avoid track misregistration.

Figure 2(*a*) shows a typical lateral tape motion signal from a commercial tape drive, while Fig. 2(*b*) shows the 1 kHz high pass filtered lateral tape motion signal of Fig. 2(*a*). The tape drive operated at 4 m/s and a nominal tape tension of 1 N. We observe peak-to-peak LTM values of 100 μm in (Fig. 2(*a*)) and peak-to-peak high frequency LTM values of 2 μm (Fig. 2(*b*)). The amplitudes of the high frequency components of the lateral tape motion are significantly smaller than those of the low frequency components.

Figure 3 shows the standard deviation σ of the lateral tape motion signal shown in Fig. 2 after high pass filtering at cutoff frequencies ranging from 0 kHz to 3 kHz. A state-of-the-art commercial tape drive uses tapes with a track width of approximately 14 μm. Servo actuators for these tape drives typically have a bandwidth of approximately 1 kHz. From Fig. 3 we find that 3σ of the high frequency lateral tape motion (>1 kHz) is equal to 0.54 μm. For those conditions, it is unlikely that lateral tape motion will cause read/write errors since 0.54 $\mu\text{m}<1.4$ μm (10% of the track width). In the case of a tape with a track width of 1.5 μm [3], we observe from Fig. 3 that the track-following servo needs to have a bandwidth of 3 kHz to accommodate a 1.5 μm track width because 3σ of the lateral tape motion must be smaller than 0.15 μm to avoid track misregistration. However, state-of-the-art servo actuators only offer a bandwidth up to approximately 1 kHz. To increase the track density, the amplitude of lateral tape motion should be reduced. At the same time, the bandwidth of the servo actuator must be increased.

3.2 Measurement Methods. A number of methods have been reported in the literature for measuring the lateral displacement of a magnetic tape. The lateral displacement of the tape as a function of time and displacement can be identified in Eqs. (1) and (2) as $\partial z/\partial t$. The most commonly used measurement methods are reviewed and discussed in this section.

The first method to measure lateral tape motion is the use of an optical edge probe [24,26], as illustrated in Fig. 4(*a*). Here, the

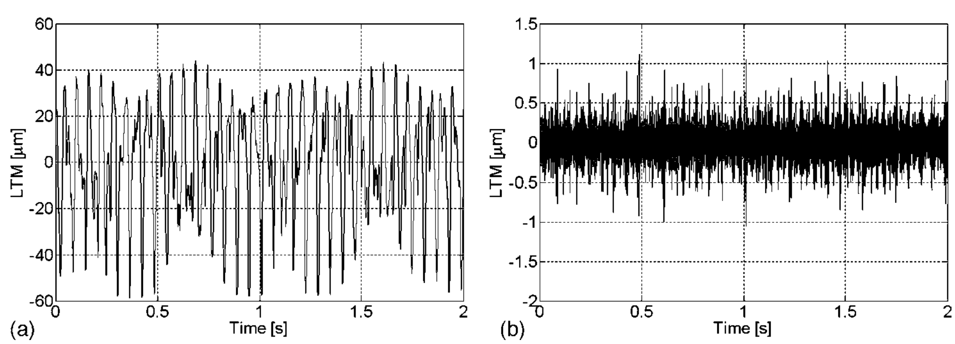

Fig. 2 (*a*) LTM signal and (*b*) 1 kHz high pass filtered LTM signal

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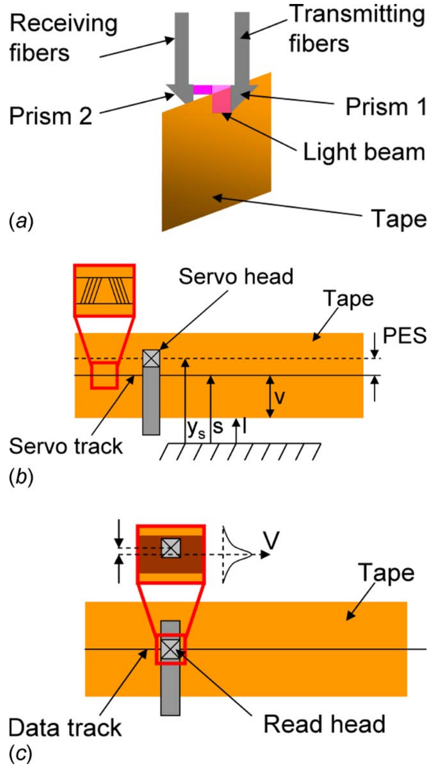

Fig. 4 LTM measurement: (*a*) optical edge sensor, (*b*) PES signal, and (*c*) magnetic signal

path of a light beam emitted through light transmitting fibers is deflected by 90 deg by a prism and is partially obstructed by the tape. The portion of light that is not obstructed by the tape enters the receiving fibers and is a measure for the lateral position of the tape [27]. A similar method has been reported using infrared light instead of the visible light range [28,20]. The technique allows lateral tape motion measurements at any position along the tape path and yields repeatable results. However, the measurement is not a true measurement of the lateral tape motion since tape edge imperfections [29] are "seen" as lateral motion rather than tape edge defects. Since most imperfections are smaller than the lateral displacement of the tape, this effect is of minor importance.

An alternative to optical lateral tape motion measurements is to use the position error signal (PES) [30], as illustrated in Fig. 4(*b*). The position of the servo head is indicated by $y_{\mathrm{sh}}(t)$, while the position of the servo track is denoted by $y_{\mathrm{st}}(t)$. In addition, $y_{\mathrm{edge}}(t)$ indicates the position of the tape edge and $y_{\mathrm{var}}(t)$ is the so-called servo track variability, defined as the difference between the servo track position and the tape edge position, $y_{\mathrm{var}}(t)=y_{\mathrm{st}}(t)-y_{\mathrm{edge}}(t)$. The PES$(t)$ is defined as the difference between the servo head position and the servo track position, i.e., $\mathrm{PES}(t)=y_{\mathrm{sh}}(t)-y_{\mathrm{st}}(t)$. The lateral tape displacement derived from the position error signal incorporates the geometric imperfections (nonstraightness) of the servo track. Hence, the measurement depends mainly on the "straightness" of the servo track. Using system identification methods, one can separate the effect of servo track variability and the effect of the lateral tape motion on the PES. The PES yields a reliable measure for the lateral tape motion, but it can only be determined at the read/write head [30].

In a recent paper, Alfano and Bhushan [25] proposed a method for the measurement of lateral tape motion based on the magnetic read-back signal (Fig. 4(*c*)). The magnetic read element is narrower than the track width. When the read element is positioned in the middle of the data track, the read-back voltage is assumed to be at maximum value. The magnitude of the read-back voltage is a function of the lateral position of the magnetic read element with respect to the data track, y_m. Hence, the read-back voltage can be used to measure lateral tape motion. This lateral tape motion measurement is independent of the tape edge quality or the straightness of the servo track but is now dependent on the straightness of the data track. The lateral tape motion during the writing of data cannot be assumed to be zero. Thus, the lateral tape motion derived from the read-back signal consists of both contributions of LTM while writing and reading the data.

Other less frequently used methods to measure LTM have been proposed in the literature, e.g., the "videographic method" [31]. The videographic method works as follows. First a reference line is created on the tape surface by means of a razor blade. The razor blade is pressed against the tape, resulting in a longitudinal scratch along the length of the tape. By centering a camera on the longitudinal scratch, LTM could be recorded and monitored.

3.3 LTM Sources. Sources of lateral tape motion have been extensively discussed in the literature (see, e.g., Refs. [30,32,33]). The main sources of lateral tape motion are run-out of tape reels and rollers [20], tape tension transients resulting from torque changes in the supply and take-up reel motors [28], and contact between the tape edge and a flange of a roller/guide or reel [34,35].

3.3.1 Roller Run-Out. Commercial tape drives use rollers with rolling-element bearings. Imperfections and manufacturing tolerances cause run-out of the bearings. Run-out consists of repeatable run-out z_{R}, occurring at the frequency of rotation ω_R, and nonrepeatable run-out z_{NR}. The sum of both components is defined as the total indicated run-out (TIR) [20],

$$z_{\mathrm{TIR}} = z_{\mathrm{R}}(\omega_R) + z_{\mathrm{NR}} \tag{3}$$

The repeatable run-out can be obtained by averaging the run-out of a roller over N rotations, i.e., $z_{\mathrm{R}}=1/N\sum_{i=1}^{N} z_i$. The nonrepeatable run-out can then be obtained by subtracting the repeatable run-out from the run-out of a single rotation [36], i.e.,

$$z_{\mathrm{NR}} = z_{\mathrm{TIR}} - \frac{1}{N}\sum_{i=1}^{N} z_i \tag{4}$$

Taylor and Talke [20] measured the total indicated axial run-out of a roller and the lateral tape motion close to that roller. They found a maximum correlation of 81% between roller run-out and lateral tape motion when bandpass filtering between 0.4 kHz and 1.7 kHz. After applying a perfluoropolyether lubricant on the roller surface, the maximum correlation between the axial roller run-out and the LTM decreased to 41%. It was also found that the correlation coefficient between the lateral tape motion and the axial run-out of the roller was lower for a grooved than a smooth roller. Grooved rollers inhibit the formation of an air bearing between the roller and tape, thereby increasing the frictional coupling between axial roller run-out and lateral tape motion. Thus, axial roller run-out is a source of lateral tape motion. The resulting lateral tape motion for a section of tape in contact with a roller is the sum of the total indicated axial roller run-out and the lateral tape displacement from Eq. (2), assuming that frictional coupling between tape and guide would be perfect.

To reduce lateral tape motion, it is desirable to reduce axial run-out of rollers. Another approach would be to replace rollers with stationary guides. This would eliminate axial roller run-out but would increase wear between guide and tape. From this consideration, pressurized or self-acting air bearing guides would provide a good alternative [24,37].

In the case of a pressurized air bearing, the traveling tape is supported by hydrostatic pressure from an externally pressurized porous foil bearing and by hydrodynamic pressure due to web movements. The design of pressurized porous air bearing guides was described in the literature by Stahl and Gavit [38], among others. More specifically, they designed a low-flow-rate porous

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ceramic air bearing system that eliminates the friction associated with contact guiding systems. Hashimoto [39–41] presented an extensive numerical analysis of web handling by means of porous foil bearing guides. He concluded that a porous foil bearing is advantageous in terms of controlling the spacing between web (tape) and guide. He also found that the width of the web has significant effects on the pressure distribution between the web and the porous air bearing guide. Tape drives with pressurized air bearing guides instead of rotating guides exhibit significantly lower LTM than tape drives with rotating guides [24]. However, pressurized air bearing guides require an external air source, which is costly and introduces reliability problems.

An alternative approach to the use of externally pressurized bearings is the use of self-acting foil bearings. In Ref. [37], laser surface texturing (LST) of the guide surface was proposed as a means of establishing an efficient low speed air bearing between a guide and a magnetic tape. Laser surface texturing creates so-called dimples on the guide surface, which reduce the friction between the tape and guide. In addition, laser surface texturing was found to cause the transition speed from boundary lubrication to full fluid lubrication to move to lower tape speeds than for untextured surfaces; i.e., dimples enhance the formation of an air bearing at low speeds by increasing the average pressure of the air bearing.

3.3.2 Tape Edge Contact. Another important source of lateral tape motion is tape edge contact [34,35]. Equation (1) contains the effect of edge contact on lateral tape motion through its right hand side term, which allows the inclusion of edge contact forces in the model. In particular, if in Eq. (2) the right hand side could be replaced by an edge force, edge contact between a tape and a flange as the tape moves over the guide surface can be modeled.

Edge contact has been studied by different researchers. Lakshmikumaran and Wickert studied edge buckling of imperfectly guided webs and developed a "free sliding" model and an "edge guided" model for web buckling [42]. Furthermore, Kartik and Wickert [43] examined the vibration of a web with edge imperfections, guided by a partially elastic base, similar to a porous foil bearing. They found that the vibrations of a web, for a certain wavelength of edge imperfections, can be reduced drastically by choosing the position of the guides appropriately. The effect of tape edge contact on edge quality and tape wear has also been studied. Goldade and Bhushan [26,29] found that tape edge contact can damage the tape edge, creating polymeric debris that affects tape guiding. Since tape edge wear and LTM are functions of the magnitude of the tape edge contact force [35], it is important to be able to quantize the magnitude of the contact force during tape edge/flange contact. A measurement method based on acoustic emission (AE) sensors was proposed by Raeymaekers and Talke [35]. The experimental setup is shown in Fig. 5. The AE sensor was mounted above a roller with only a bottom flange. The AE sensor serves as the top flange of the roller and detects contact between the tape edge and the flange, which is replaced by the AE sensor. It was found that increased tape tension and reduced tape speed reduce tape/flange impact forces [35].

To eliminate flanges but still control LTM, an "active guiding" system would be highly desirable [34,35]. The concept of such a friction guiding has been described by Kartik and Wickert [44]. The tape was modeled as a beam that is transported over the rollers. The rollers have subambient regions, which create friction beyond what can be achieved by a normal wrap pressure. The increased friction helps to control and constrain the position of the tape laterally. Also, Cheng and Perkins [45] examined the lateral response of a string that slides through an elastically supported dry friction guide and suggested ways to minimize vibration by adjusting various design variables. Figure 6 outlines the active guiding concept. Figure 6(*a*) shows a "normal" tape operation. In Fig. 6(*b*), the tape has moved higher than its normal position. By tilting the guide (angle α), the tape is forced to move down on the guide surface, as indicated by the arrow. Figure 6(*c*) illustrates the

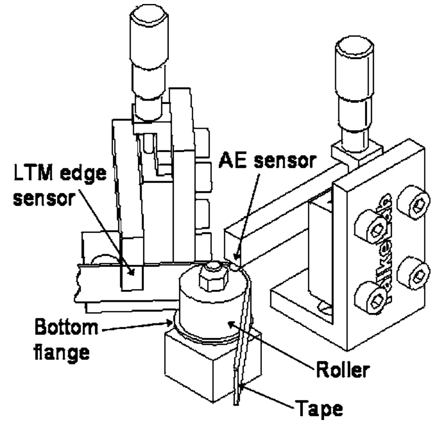

Fig. 5 Experimental setup for tape edge contact force measurement with acoustic emission

reverse case. The guides could be controlled by a servo loop, which receives lateral tape motion information from sensors positioned upstream of the guides.

3.3.3 Tape Tension Transients. Tape tension transients are another source of lateral tape motion. The reels of a tape drive are driven by separate motors, and fluctuations in their torque change the tension in the tape. Referring to Eqs. (1) and (2), it is clear that the tension T plays an important role in the lateral displacement of a tape, as it moves through the tape path.

Figure 7(*a*) shows a tension measurement method based on the magnetic signal. This method was introduced by Smith and Sievers [46], who attempted to measure tape tension variations using a commercial flutter meter and the digital read-back signal of a tape drive. The difference between write and read-back signals, with respect to "bit distance" dx, was used to predict information regarding tape tension fluctuations. This approach can only be used if the velocity of a tape drive is constant or if velocity changes during writing and reading are identical.

Imaino [47] proposed a noncontact method for measuring tension in a magnetic tape. A pulsed laser was used to photoacoustically generate an antisymmetric flexural acoustic wave within a tensioned tape sample, as shown in Fig. 8. The out-of-plane motion created by this wave was detected with a laser Doppler vibrometer (LDV). The time between the generation of the flexural wave and its detection and the known separation between pulsed laser and the sensed position of the LDV yield the propagation velocity of the wave. The Rayleigh–Lamb wave equation

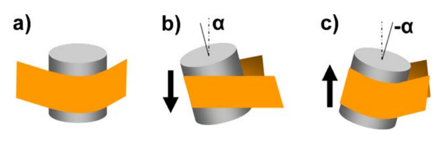

Fig. 6 Active guiding concept

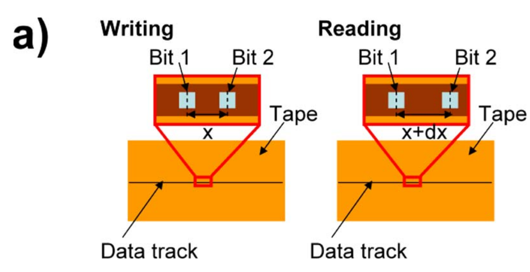

Fig. 7 Noncontact tape tension measurement by Smith and Sievers [46]

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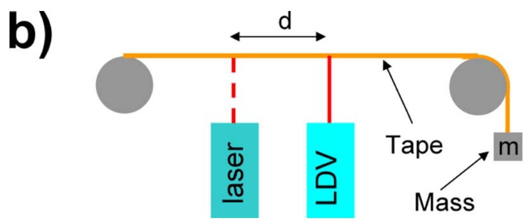

Fig. 8 Noncontact tape tension measurement by Imaino [47]

[48,49], in combination with the experimentally determined wave propagation speed, yields the tape tension when the flexural stiffness of the tape is known.

Raeymaekers et al. [28] introduced a noncontact high bandwidth tape tension sensor, which uses a laser and a photodiode to measure tape tension. The principle of the optical tension measurement is illustrated in Figs. 9(*a*) and 9(*b*). A laser beam is directed at the tape surface, where the tape moves over the edge of the tape head. The light reflected from the tape is captured by a photocell. At low tension T_1 (Fig. 9(*a*)), the reflected light beam diverges less than at high tension T_2 (Fig. 9(*b*)); i.e., as the tape tension increases, the divergence of the reflected light increases. Hence, the amount of light seen by the photocell changes with tape tension and is a measure of the tension change in the tape. It was observed that the absolute value of the tape tension signal correlates well with the absolute value of the lateral tape motion.

Since the magnetic tape is not straight [50], a tension gradient is created across the width of the tape when the tape is tensioned in a tape drive. To relate the direction of tension changes to the direction of lateral tape motion changes, knowledge of the tension gradient in the tape is needed. Hu and Hollman [51] used a tension sensor based on a miniature metal diaphragm pressure transducer built into a glass cylinder with radius R. The transducer was translated along the width of the tape to measure the air bearing pressure p between the tape and cylinder at different track locations. The tape tension T per unit tape width can then be estimated using $T \sim pR$ [52]. Since the tape tension can be measured at only one location at a time across the width of the tape, superposition of individual tension signals is required and is likely to cause errors in the measurements.

An improved sensing device that simultaneously measures tape tension at different locations across the width of a tape would be highly desirable. Position dependent tension values would allow the calculation of the curvature of the tape. To instrument such a device poses several challenges. Ultrasmall pressure sensors need to be positioned within a 12.7 mm ($\frac{1}{2}$ in.) distance, directly above each other, to simultaneously measure the air bearing pressure at different locations across the tape width. Piezo-based microelectromechanical system (MEMS)–type pressure sensors would be most suitable for this application because of their small form factor and high resolution. Tension sensors of the latter type could be included in the servo loop, which controls the lateral position of the read/write head, thereby accounting for LTM due to tension transients and tape curvature.

In future tape drives, reduction in tape thickness is likely to

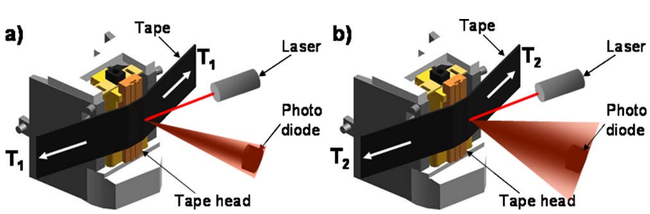

Fig. 9 Noncontact tape tension measurement by Raeymaekers et al. [28]

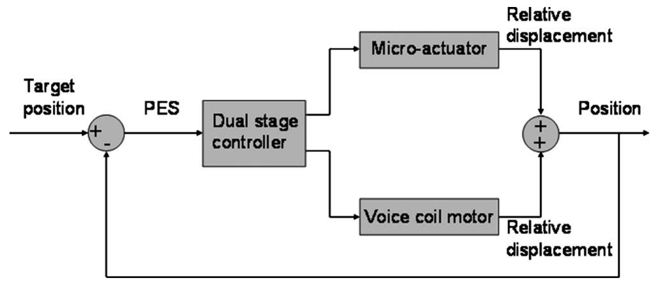

Fig. 10 Schematic of a dual stage actuator tape head

occur to increase the volumetric storage density. Reducing the tape thickness requires a reduction in the nominal tape tension, which will increase the susceptibility to increased lateral tape motion due to the reduction in the lateral bending stiffness of the tape. Additionally, decreasing the tape tension will increase the frequency and magnitude of tape edge contact, thereby increasing high frequency lateral tape motion in the tape path [34]. While a thinner tape is beneficial in terms of volumetric storage density, it poses additional problems in designing the tape path and increasing the track density of a tape.

3.4 Dual Stage Actuator Tape Head. In most modern tape drives, timing-based servo loops are used [53,54] to control the lateral position of the read/write head. To increase the track density of the magnetic tape, the servo bandwidth of the head actuator must be increased. This would allow the head to follow higher frequency components of lateral tape motion that are presently not followed by the head.

To increase the servo bandwidth and to improve the track-following capability of a tape head, a dual stage actuator tape head can be used [55]. Such a head consists of a voice coil motor (VCM) for "coarse" positioning and a micro-actuator for "fine" positioning of the read/write elements on the tape. One possible design of a micro-actuator uses a "stacked-type" piezo crystal mounted on the VCM. The micro-actuator moves the read/write elements, while the VCM moves the whole tape head. Figure 10 illustrates the concept of a dual stage actuator tape head.

If the mass of the micro-actuator is small, it allows following the lateral tape motion up to a higher frequency than with only a voice coil motor, which follows low frequency LTM (<1 kHz). Including a micro-actuator allows expanding the bandwidth of the servo actuator significantly. A dual-stage controller allows a synergetic operation of both actuators. It is anticipated that future tape drives will likely incorporate dual stage actuators in order to increase the track density in tapes.

4 Conclusion

Lateral tape motion is currently one of the main limitations for increasing track density on a magnetic tape. We conclude that:

1. Roller run-out, tape edge contact, and tape transients are the most important sources of lateral tape motion.
2. To increase the track density on a tape, the amplitude of lateral tape motion should be reduced. At the same time, the bandwidth of the servo actuator must be increased.
3. New methods need to be developed to increase the track density on magnetic tapes. A dual stage actuator tape head is proposed in this paper, which promises a substantial increase in the servo bandwidth, thereby enabling a higher recording (track) density.

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