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TECHNICAL PAPER

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Non-contact tape tension measurement and correlation of lateral tape motion and tape tension transients

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Abstract Non-contact tension measurement of magnetic tape is performed. Light from a focussed light source is directed at a tape surface and the light reflected from the tape is captured by a photo cell. As the tape tension varies, the divergence of the reflected light bundle changes, i.e., the amount of light seen by the photo cell is a measure for the tension in the tape. Using this non-contact tension measurement approach and a high frequency lateral tape motion sensor, we have investigated the correlation between high frequency tension changes and high frequency lateral tape motion. Strong correlation is observed between the absolute values of tension and lateral tape motion.

1 Introduction

Lateral tape motion (LTM) is defined as the time-dependent displacement of magnetic tape perpendicular to the tape running direction (cross-track) and is measured using tape edge sensors (Taylor et al. 2000). Using a servo system, the read/write head can follow the LTM up to a cut-off frequency imposed by the bandwidth of the head actuator. State of the art actuators have a bandwidth up to 500 Hz. High frequency LTM is referred to as the LTM which cannot be followed by the read/write head actuator, i.e., LTM with a frequency greater than 500 Hz.

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High frequency LTM is a key problem in tape technology, since it limits the maximum achievable track density in a tape drive (Richards et al. 1998). To reduce high frequency LTM, it is important to identify and control all sources of LTM. The most important sources of high frequency LTM are edge contact between tape and tape drive components, non-repeatable roller axial run-out, air induced flutter and tape tension transients (Elrod and Eshel 1965, Taylor and Talke 2005, Hansen and Bhushan 2005). Figure 1a shows a typical unfiltered LTM signal while Fig. 1b shows the same signal, 500 Hz high pass filtered. We observe that the unfiltered signal shows a lateral displacement on the order of 60 μm while the high frequency components are on the order of 5 μm.

Currently, the track density used in a typical magnetic tape drive is 39 tracks/mm (1,000 tracks/in. (tpi)). In order to increase the track density of magnetic tapes to 195 tracks/mm (5,000 tpi), high frequency LTM must be reduced to 1 μm.

The effect of tape tension transients on high frequency LTM is currently not well understood. It is apparent, however, that tape transients lead to transverse motion of the tape in the wide span between supports due to tape curvature (Bhushan 1992). Tape tension in a tape drive is generally measured using pressure transducers (Hu and Hollman 1984). However, the bandwidth of these sensors is limited to below 100 Hz and improved tension sensing devices are necessary to investigate the relationship between tension changes and high frequency LTM.

Smith and Sievers (1985) attempted to measure tape tension changes using a commercial flutter meter and the digital read-back signal of a tape drive. The difference between write and read-back signal, with respect to 'bit distance', was used to provide information regarding tape tension. However, this approach is only correct if the velocity of the tape drive is constant or if velocity changes in time during writing and reading are the same.

Boyle and Bhushan (2005) investigated LTM as a result of an impact on the tape. Tape tension, however,

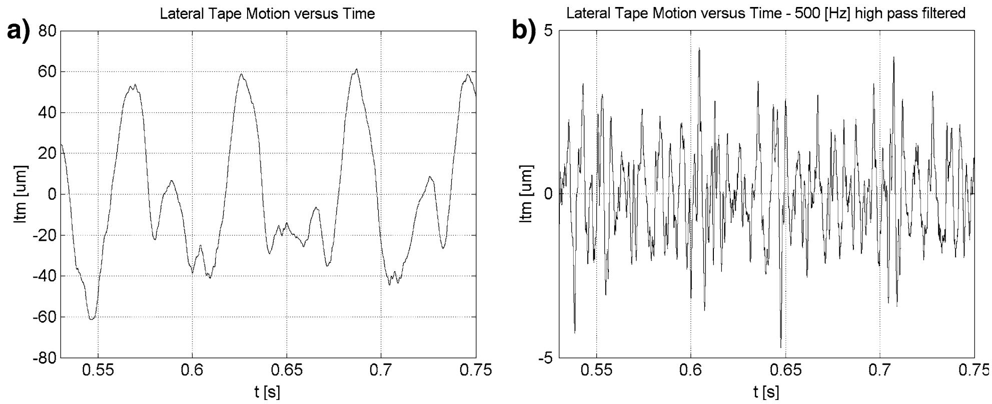


Fig. 1 Lateral tape motion versus time

was not measured. Imaino (2004) developed a non-contact method to measure tension in a magnetic tape using photoacoustically generated antisymmetric Lamb waves detected with a laser Doppler vibrometer.

In this paper, an optical non-contact high bandwidth tension sensor for magnetic tape is developed and the correlation between LTM and tension transients is investigated. The use of an optical light reflection method similar to the one described here was first proposed by J. Eaton (personal communication).

2 Tension sensor

The concept of a non-contact tension measurement uses the following approach. A tape moves over a solid surface that contains an edge, such as shown in Fig. 2. The solid edge can be created by adding an edge element in the tape path or configuring the magnetic head to contain a solid edge. A laserbeam is directed at the magnetic tape surface as it moves over the edge. The light reflected from the tape is captured by a photo cell. Since the radius of curvature of the tape over the edge of the solid surface decreases with increasing tape tension, the divergence of the reflected light bundle increases with increasing tension, i.e., the amount of light seen by the photo cell is a function of tape tension. Thus, measurement of the change of light reflected from a tape surface can be used as a measure of the tension change in the tape.

The principle of the optical tension measurement is illustrated in Figs. 2 and 3. At low tension (Fig. 2), the reflected light beam diverges less than at high tension (Fig. 3). This measurement approach is limited because it needs an edge in order to function. The method, however, is non-dependent on the 'sharpness' of the edge and the type of tape. The method is not strictly "non-contact" because it needs an intrusion in the tape path. However, in our work we use a magnetic read/write head as contact edge. Thus, no extra hardware has to be added to the tape path and the tape is partially separated from the head by a hydrodynamic air lubrication film. A typical calibration curve of the photo cell voltage versus the tape tension is shown in Fig. 4. The entire tension deviation range encountered in a tape drive is contained within the linear range of calibration. The sensor has to be calibrated for each type of tape due to different reflectivity of each tape and for each magnetic read/write head due to variation in the contour.

3 "Artificial" disturbance

To investigate the correlation between dynamic tension changes and LTM changes, the following approach was used. An eccentric tape pack was first created by

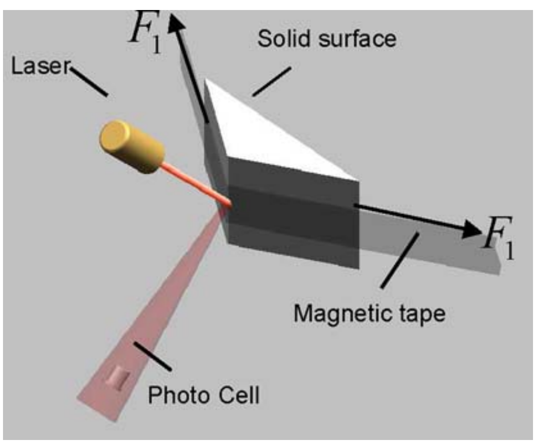


Fig. 2 Divergence of light beam as a result of tension F1

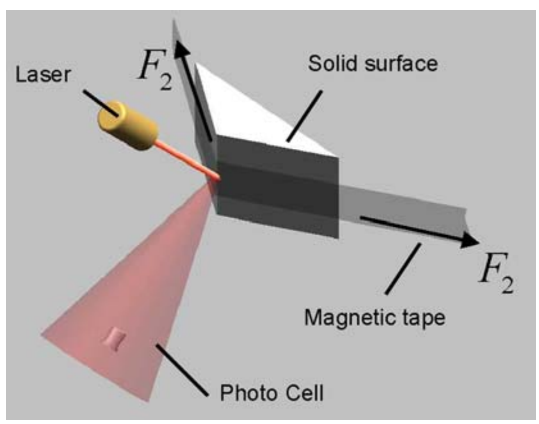


Fig. 3 Divergence of light beam as a result of tension F2

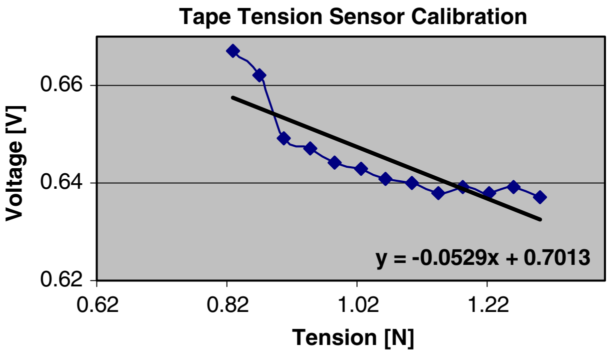


Fig. 4 Typical calibration curve

inserting a thin rod into the tape pack during winding. Using this eccentric pack, large tension disturbances were created in the tape at the reel rotation frequency. Figure 5 shows a schematic of the test set-up used. The tape path was configured with an actual tape head to simulate a commercial tape drive. A smooth roller was positioned before and after the tape head to insure a proper wrap angle. Two LTM edge sensors (Taylor et al. 2000) were mounted in close proximity of the head to measure the lateral displacement of the tape. The tension sensor was directed at the edge of the head. Tape speed was set at 4 m/s and a nominal tape tension of 1 N was used. The ''artificial'' disturbance created a tension force of about 0.5 N.

4 Results

In Fig. 6a, the LTM signal and the tension changes are shown. A magnification of a short section of Fig. 6a is depicted in Fig. 6b, c the cross-correlation coefficient ϕ between tension change and LTM signal is calculated as

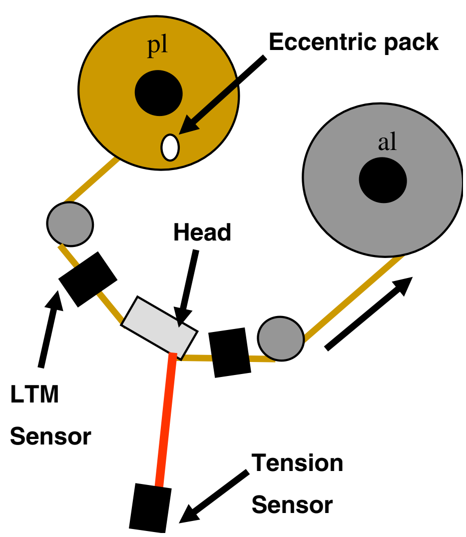


Fig. 5 Schematic of test-set up

$$\varphi[n] = \frac{1}{2N+1} \sum_{m=-N}^{N} f_1[m+n] f_2[n] \quad (1)$$

where f_1 and f_2 are the two signals to be correlated and the data set is of length $2N$. We observe that the maximum correlation between tension change and LTM is approximately 40%.

From the curves shown in Fig. 6b we observe that an increase in tape tension always causes a change in LTM. The direction of this change is sometimes towards larger LTM values and sometimes towards smaller LTM values. The same behaviour is observed if the tape tension is decreased, i.e., a tension decrease causes always a change in LTM, but this change can be towards larger or smaller LTM values as pointed out by the arrows in Fig. 6b. Hence, four different cases must be taken into account when considering the correlation between tension changes and LTM changes:

1. Tension increases, tape moves down.
2. Tension increases, tape moves up.
3. Tension decreases, tape moves down.
4. Tension decreases, tape moves up.

From the above consideration, it is apparent that the correlation between the absolute values of the tension and LTM signal must be investigated rather than the correlation of the actual signals. The use of absolute values is justified since we are interested in the relationship between tension transients and LTM changes regardless of their direction. In other words, we are primarily interested in investigating whether tension changes induce LTM changes; the direction of these changes is immaterial.

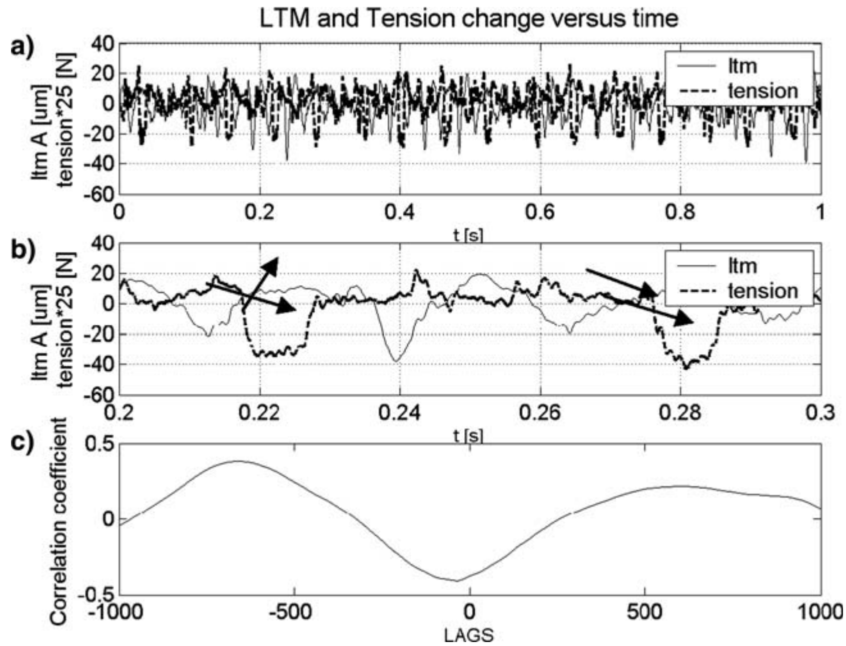
Figure 7 shows the correlation between the absolute values of both the tension changes and the LTM changes for the data shown in Fig. 6. We observe a direct relationship between tension change and LTM. This is further supported by the increase of the maximum correlation coefficient between the two signals (63%), which is higher than the correlation coefficient between the actual signals (40%). Thus we conclude that tension changes cause LTM changes.

5 Natural disturbance

The ''artificial'' disturbance was used to amplify the effect of tension transients in order to get a first indication of the interaction between LTM changes and tension transients. In a commercial tape drive, however, the tension disturbances are much smaller than those created with the eccentric pack. In order to see the effect of small tension transients, we used the same test set-up as displayed in Fig. 5 but now with a regular tape pack, without eccentricity, and hence without the large tension disturbance. Figures 8 and 9 show the results from this test.

In Fig. 8a, the LTM signal and the tension changes are shown. A magnification of a short section of Fig. 8a

Fig. 6 LTM and tension, artificial disturbance



is depicted in Fig. 8b. In Fig. 8c the correlation coefficient between tension changes and the LTM signal is plotted. We observe that the maximum correlation between the tension change signal and LTM is now only 30%, significantly smaller than with the artificial disturbance previously investigated.

Figure 9 shows the correlation between the absolute values of both the tension change signal and the LTM change signal for the data shown in Fig. 7. We again observe a direct relationship between the tension change and the LTM. The maximum correlation between the two signals is now 67%, which is on the same order of magnitude than with the artificial disturbance. Thus, the results support our earlier conclusion that tension changes cause LTM changes.

6 Dependence of LTM on tension transient frequency

In order to study the frequency dependency of the correlation between LTM and tape tension transients, frequency bands of 400 Hz were defined and the data was bandpass filtered between these bands. The maximum correlation coefficient between tension changes and

Fig. 7 Artificial disturbance, absolute values

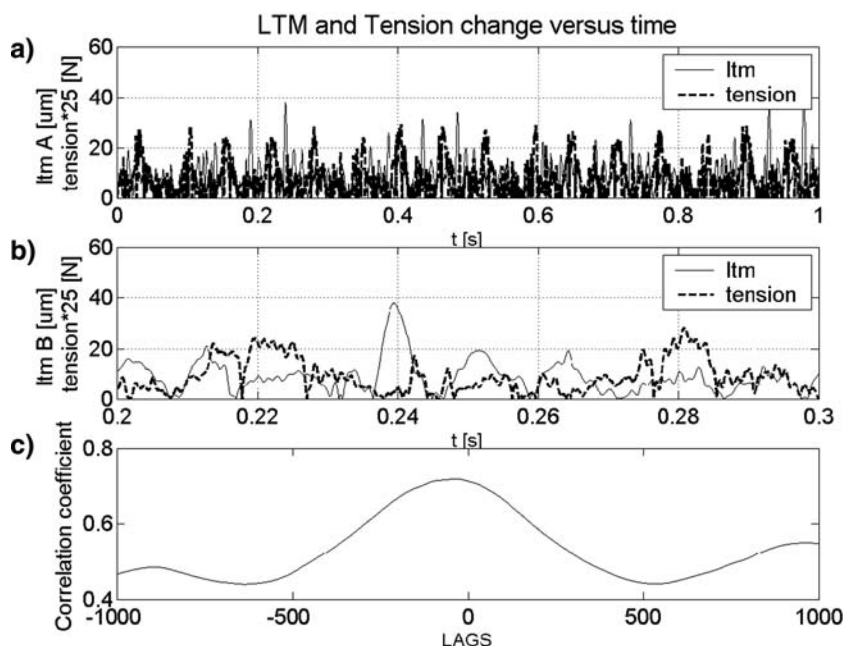
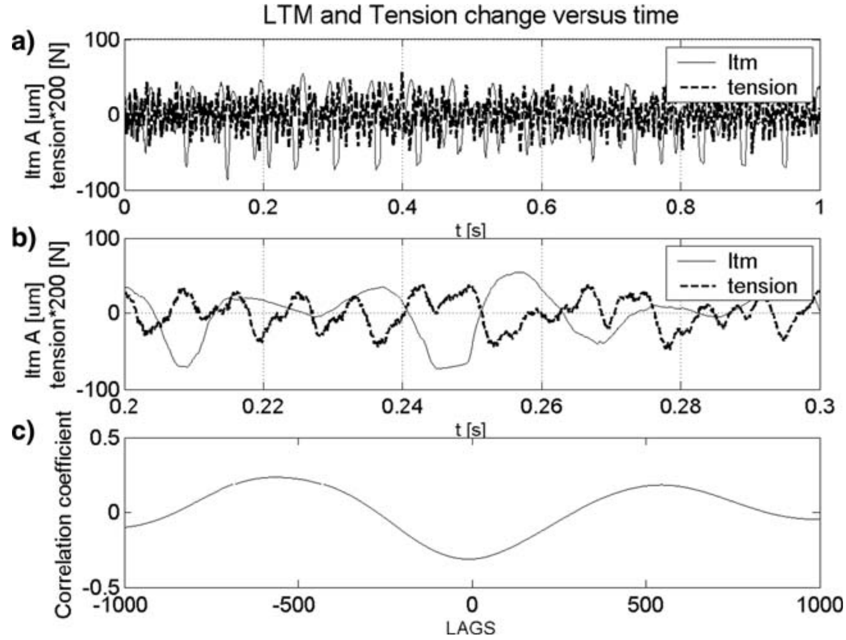


Fig. 8 Tension and LTM, natural disturbance



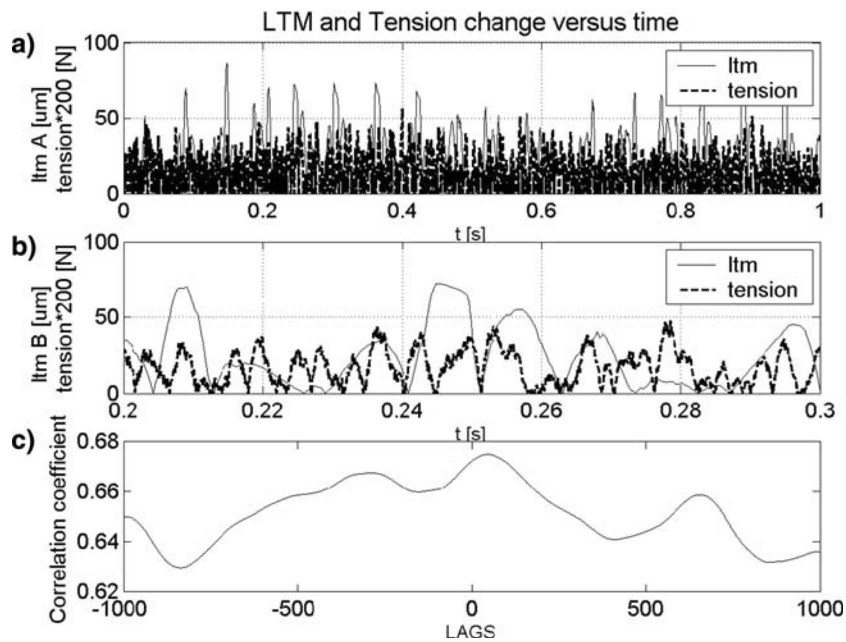
LTM changes was calculated for each frequency band and plotted for both the case of an artificial disturbance and the case of a natural disturbance (Figs. 10, 11).

We observe from Figs. 10 and 11 that the maximum correlation between tension changes and LTM changes decreases with increasing frequency. This trend is likely related to the effect of tape inertia: as the frequencies of tension changes increase, the tape should react faster to those changes. However, the reaction of the tape is limited by its inertia, and thus, the correlation between tension changes and LTM changes as a function of frequency decreases.

7 Discussion

The reason why tension changes cause LTM changes seems to be related to the straightness of the tape. If one edge of a tape is shorter than the other, the tape is curved (Bhushan 1992). Curvature can be characterized by the radius of curvature, denoted as r in Fig. 12. In the tape industry, tape curvature is often referred to as the deviation of tape from straightness and is defined as the maximum deviation h over a unit length (generally taken to be 1 m of tape length; Elrod and Eshel 1965), as shown in Fig. 12.

Fig. 9 Natural disturbance, absolute values



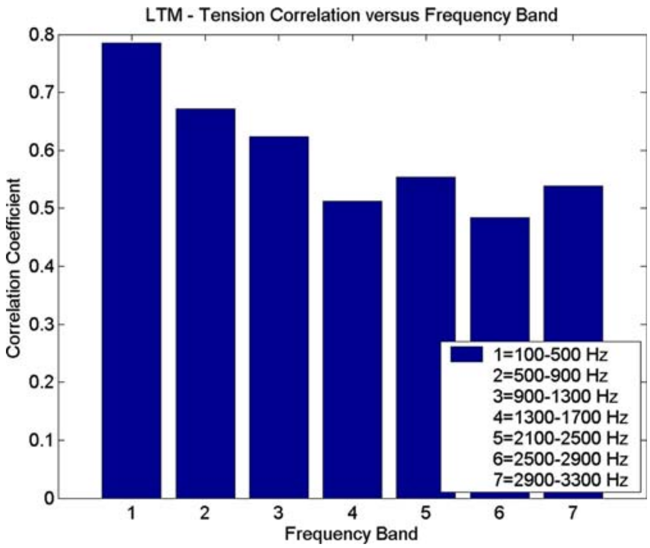


Fig. 10 Frequency study with an artificial disturbance

Hu and Hollman (1984) examined the case of a curved tape segment and noted that a tension gradient will develop across the tape width as a result of uneven stretching. Bhushan (1992) concluded that uneven tension across the tape width can cause tape vibration over the guide bearings. Our experimental results showed that a correlation exists between tape tension transients and LTM, although no prediction could be made about the direction of the motion resulting from a tension transient. Therefore it is interesting to characterize the direction of the tape motion with respect to tape curvature and to determine the stress distribution across the tape width.

Figure 13 shows the four cases that influence the correlation between tension transients and LTM. Figure 13a shows a positive curvature while Fig. 13b shows a negative curvature. Both the effects of tension increase and decrease are illustrated. If tension increases for a positive curvature, the tape straightens out. This causes the tape to move upwards. If the tension decreases the opposite is true, i.e., the tape move downwards. If tension increases for a negative curvature the tape will straighten out, causing a downward lateral tape displacement. A tension decrease will cause the tape to move upwards.

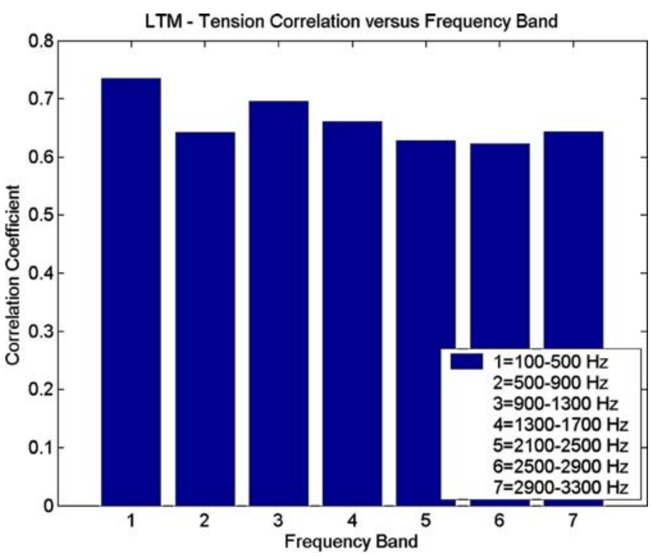


Fig. 11 Frequency study with a natural disturbance

By applying tension at both ends of the tape segment, the curved tape is pulled straight. The tension in the tape, however, will not be uniform but characterized by a gradient along the cross-track direction. We can model the tape as a static beam, which is depicted in Fig. 14, representing a tape segment. cc represents the centerline of the tape while nn denotes the neutral line when bending. e is the distance between both lines but is negligible since h is small.

The radius of curvature r is defined as

$$r = \frac{L^2}{8h} - \frac{h}{6} \tag{2}$$

where h denotes the absolute curvature of the tape segment with length L (Bronshtein et al. 2004). Since h is much smaller than r $(r/h \gg 10)$, we can assume a linear stress distribution (Timoshenko 1970). The resulting stress distribution in the tape is shown in Fig. 15 and consists of two parts; a constant part due to the nominal tension N applied by the tape drive on the tape and a linear part due to the straightening of the curved tape.

The resulting stress distribution in the tape can hence be written as (Timoshenko 1970)

$$\sigma_x = \frac{My}{EI} + \frac{N}{A}, \tag{3}$$

where $A = t \times w$, the cross-sectional area of the tape and y is the vertical coordinate, with $y = 0$ defined as the center line of the tape. $I = tw^2/12$ is the moment of inertia of the cross-sectional area. The Young's modulus E is on the order of 9 GPa (Bhushan and Tao 2004).

The bending moment M can be calculated as follows.

$$M = \int_{w/2}^{w/2} \sigma_x y \, \mathrm{d}A \tag{4}$$

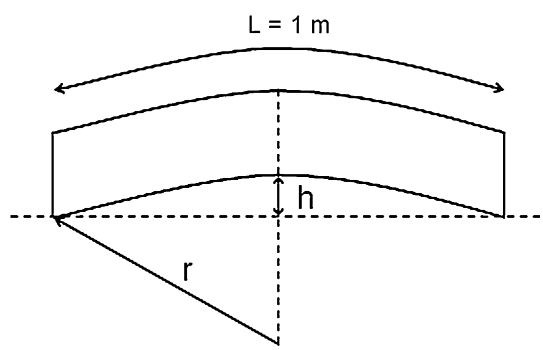


Fig. 12 Tape curvature

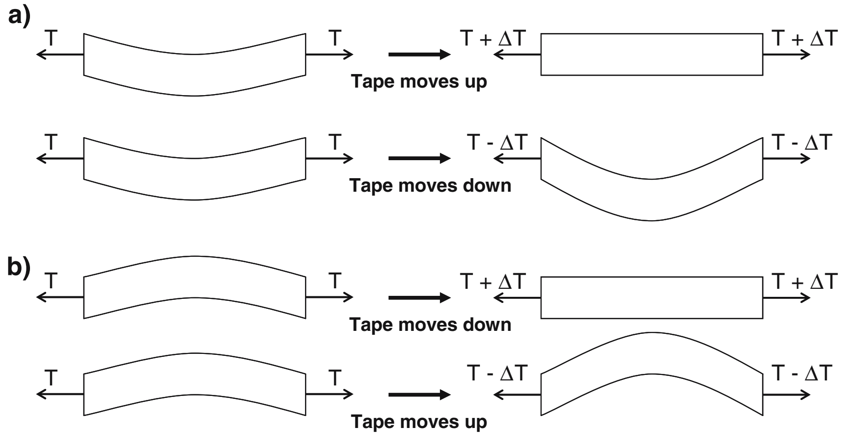


Fig. 13 Tape motion as a result of tension transients

$$= 2\int_0^{w/2} \frac{N}{A} th\, \mathrm{d}y \tag{5}$$

where $\sigma_x = N/A$ and $y = h$ if we assume the curvature to be constant in the lateral direction.

Solving (5) and substituting the result in (3) finally yields the resulting stress distribution as a function of y:

$$\sigma_x = \frac{Nhy}{EI} + \frac{N}{A}. \tag{6}$$

Once the curvature of the tape is known along the length of the tape (h), the direction of the lateral tape displacement (direction of LTM) can be obtained from Fig. 13. The resulting stress distribution can be calculated from (6). To illustrate the effect of tape curvature on the non-uniform tension gradient, we plotted the cross-track tension distribution for $h = 0.5$, $h = -0.5$ and $h = 0.9$. From Fig. 16 we observe that a larger curvature will create a larger tension gradient along the tape width. Since tape straightness is related to LTM, magnetic tape with a larger curvature (either positive or negative) will be more likely to induce LTM.

As new tape systems are developed, thinner tapes would allow an increase in the tape windings per cartridge, and therefore a greater capacity per cartridge. Thus, thinner tapes require increased attention to the stress distribution and the inherent parameters governing the bending stiffness and system tension considerations. If the same nominal tension N would be applied to thinner tape, the internal stresses would increase. The second factor in (6) would increase because A becomes smaller. Additionally, since I will decrease, the bending stiffness EI will decrease and the first factor in (6) will increase too. Making tape thinner thus affects both the constant and the linear part of the stress distribution along the tape width. It is thus apparent that tension transients and LTM will become increasingly more important in future high performance tape drives.

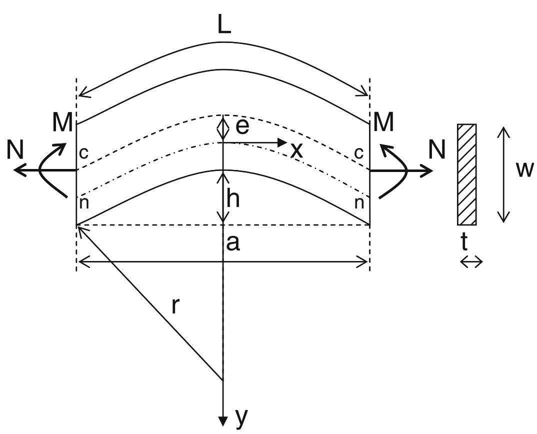


Fig. 14 Tape segment

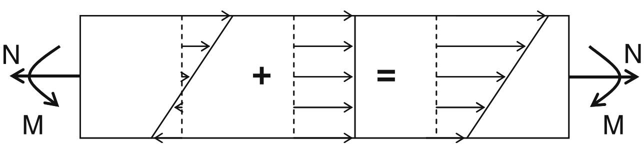


Fig. 15 Non-uniform stress distribution

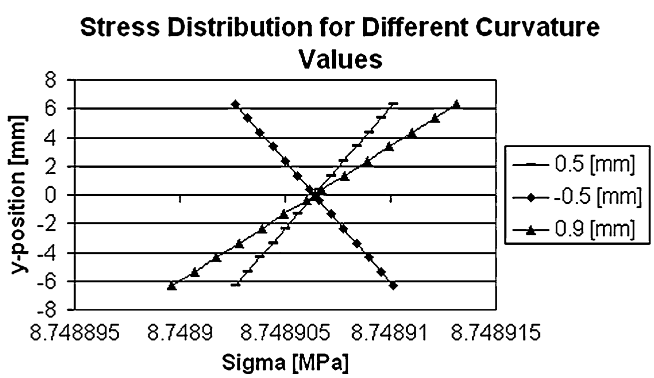


Fig. 16 Stress distribution for different curvature values

8 Conclusion

A non-contact optical method was implemented to measure tape tension and study the effect of tension changes on LTM. Based on our experimental results, the following conclusions can be drawn:

1. The measurement of the change in reflected light intensity from a tape surface due to a tension variation is a viable method to study the effect of tension change on LTM.
2. A sound correlation exists between the absolute values of tension change and the lateral tape displacement signal.
3. Tape curvature from the slitting process coupled with tension changes from the drive system causes lateral motion of the tape.

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