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THE INFLUENCE OF OPERATING AND DESIGN PARAMETERS ON THE MAGNETIC TAPE/GUIDE FRICTION COEFFICIENT

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Abstract

The friction coefficient between a guide and a tape sample is determined experimentally as a function of nominal tension, speed and guide radius. A comparative study between metal particulate and metal evaporated tape is performed. The tape/guide contact pressure correlated to the experimental results. Tape temperature measurements are compared with the experimentally obtained friction coefficients.

Introduction

The classical belt/pulley equation relates the “tight-side” tension T_1 (upstream of pulley) to the “slack-side” tension T_2 (downstream of pulley) as an exponential function of the product of the friction coefficient μ and the belt/pulley contact angle θ.

$$\frac{T_1}{T_2} = \exp\left(\mu\theta\right) \tag{1}$$

This classical equation, which assumes a constant friction coefficient independent of operating conditions, is often used to measure the “belt/pulley” friction coefficient in applications such as paper, polymer and textile processing. In light of some recent findings that show deviation of the friction coefficient from the classical friction laws [1, 2], a more detailed study about the dependency of the friction coefficient on various operating parameters such as belt tension, sliding speed, pulley diameter, surface finish, etc., seems desirable. Perhaps the most sophisticated application of the “belt/pulley” concept, where accurate knowledge of the friction coefficient is needed, can be found in magnetic tape recording. Magnetic tape is transported from the supply reel to the take-up reel, thereby passing over guides, rollers and a magnetic read/write head.

Lateral tape motion (LTM), defined as the time-dependent displacement of magnetic tape perpendicular to the tape transport direction, can cause track misregistration and limits the recording density. A key issue in analyzing LTM is the friction between tape and cylindrical guides and rollers. By investigating the effect of operating conditions such as tape speed and tape tension in conjunction with design parameters such as roller diameter, surface quality, hardness and coating, the frictional behaviour between tape and roller can be optimized to reduce LTM and tape wear.

Broese van Groenou [3] stated that the friction between tape and guiding pins is determined by the mechanical interaction of the microscopic asperities on the two surfaces in contact. He defined the friction coefficient as the ratio of the shear strength at which the asperities yield irreversibly and normal stress on the asperity. Osaki [4] pointed out tribological obstacles which need to be overcome in order to achieve higher area recording densities in tape drives. The use of metal evaporated (ME) tape, which has superior magnetic characteristics compared to magnetic particulate (MP) tape, allows increasing the area density. However, the smoother surface inherent to ME tapes creates a higher friction coefficient and hence results in unstable tape drive operation. Osaki and Endo [5] investigated the tribology of helical scan tape drive systems and found that a higher static friction coefficient increases the production of wear debris. They concluded that a solid lubricant reduces the friction coefficient but might damage the tape. Panda and Engelmann [6] mention the dependence of the friction coefficient on tape speed and the importance of estimating the correct friction coefficient in the control operation of reel-to-reel tape drives without a tension transducer. No experimental or analytical validation of their hypothesis is provided. Bhushan [7] investigated the friction coefficient between a magnetic tape and a guide and concluded that the friction coefficient depends on the guide radius and the nominal tape tension, but is independent of the wrap angle and the speed. However, the operational test parameters used were not realistic for commercial tape drives. Thus, a more detailed study is desirable. Taylor and Talke [8] reported on roller interactions with a flexible tape medium. They showed that correlation between axial roller run-out and lateral tape motion is a function of the tape/roller friction coefficient.

Apparatus

The experimental set up, shown in Fig. 1, consists of a guide mounted on an adjustable speed DC-motor, and a strain gauge based load cell. A tape sample hangs over the guide surface and is connected to a load cell at one end, while at the other end it is subjected to a known tension by a dead weight (see Fig. 1a)). The load cell is mounted on a sled that slides in a circular groove to allow a variable wrap angle. Fig. 1b) indicates the forces T_1 and T_2 and the wrap angle θ. The set-up is equivalent to a moving tape on a stationary guide. A new tape sample was used for each test since the stationary tape is subject to wear by the rotating guide. Metal particulate tape was used for all the tests except for very few where metal evaporated tape was indicated.

The measured force T_1 combined with the known slack side tension T_2 and the wrap angle θ enable calculation of the friction coefficient μ from eq. (1). The guide is made of aluminum with a ceramic-like coating to increase its surface hardness and withstand the abrasive recording head cleaning particles that are contained within the magnetic coating. The wrap angle can be adjusted from 80° to 100° and the rotational frequency of the guide is adjustable from 0 to 125 Hz, corresponding to a maximum circumferential speed of 11.8 m/s for a guide with a radius of 15 mm.

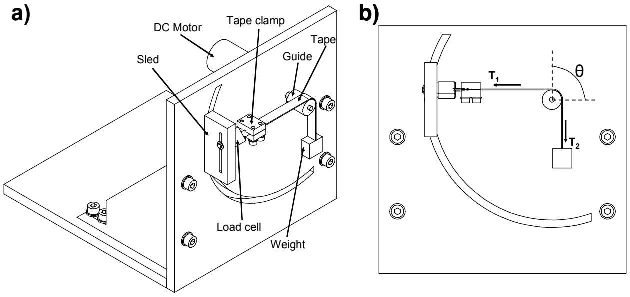
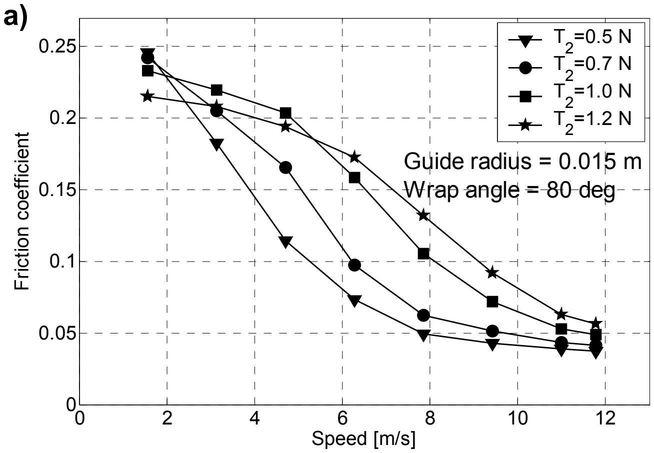


Fig. 1: Experimental set-up

Experimental results

Fig. 2 presents the effect of sliding speed on the friction coefficient for different nominal tape tensions, T_2, from 0.5 N to 1.2 N. The guide radius is 15 mm and the effect of the wrap angle of 80, 90 and 100 degrees is shown in Figs. 2a), 2b) and 2c), respectively. The data was averaged over three repeated measurements.



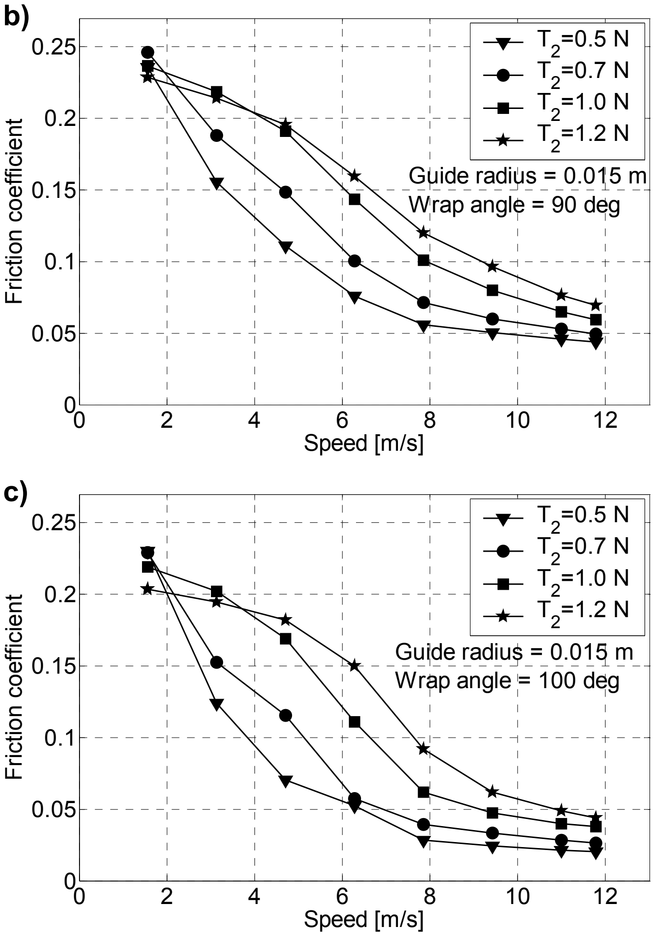


Fig. 2: Friction coefficient versus speed for different nominal tape tensions and for a wrap angle of a) 80 deg, b) 90 deg and c) 100 deg

From Fig. 2 we observe that the friction coefficient decreases significantly with increasing speed, probably due to a formation of an air bearing between the tape and rotating guide. The friction coefficient increases with increasing nominal tape tension. This is because with a higher tape tension it is more difficult to form an air bearing to carry the higher load. Moreover, a higher nominal tape tension increases the contact pressure between the tape and guide (see discussion section) and this may increase the number of contacting asperities per unit area which results in a higher friction coefficient. From Fig. 2 we can also observe that the friction coefficient is almost independent of the wrap angle throughout the speed range. As can be seen from eq. (1) an increase of the wrap angle may increase T_1 for a given T_2 even if the friction coefficient remains constant.

The effect of the guide radius on the friction coefficient is shown in Fig.3. While the wrap angle is maintained at 90 degrees, the guide radius varies from 15 mm in Fig 3 a) to 10 mm in Fig. 3b) and 7.5 mm in Fig. 3c). From Fig. 3 we observe once again that the friction coefficient increases with increasing nominal tape tension, regardless of the guide radius.

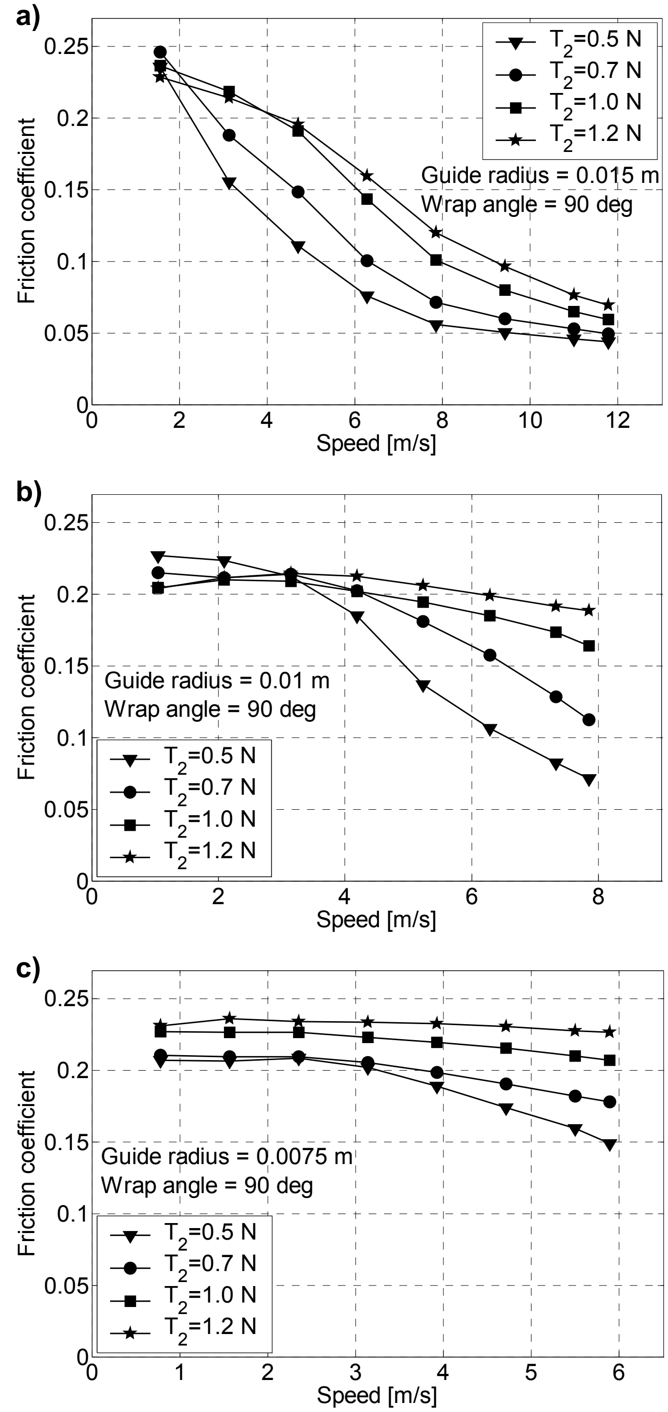


Fig. 3: Friction coefficient versus speed for different nominal tape tensions and for a guide radius of a) 15 mm, b) 10 mm, c) 7.5 mm

Note that due to the upper limit of the rotational frequency of the DC-motor $\omega = 125$ Hz, the maximum linear speeds for the radii 15, 10 and 7.5 mm were about 12, 8 and 6 m/s, respectively. Fig. 4 shows the friction coefficient versus diameter for a sliding speed of 6 m/s. At a sliding speed of 6 m/s and 0.5 N tension, for example, the friction coefficient with a guide radius of 15 mm is only 0.08 compared to 0.11 for a guide radius of 10 mm and about 0.15 for a guide radius of 7.5 mm. Because the guide radius affects the contact pressure between the guide and tape (see discussion section), the friction coefficient will also be affected. In addition, it is more difficult to form an air bearing with smaller guide radii since the same load as in the case of a larger guide is now distributed over a smaller contact area.

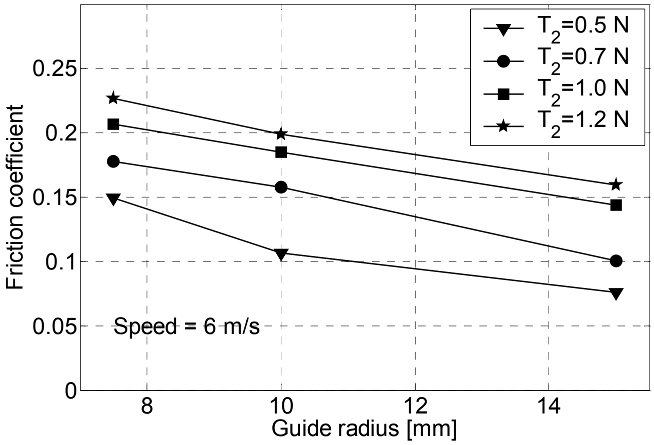


Fig. 4: Friction coefficient versus guide radius for different nominal tape tensions and a tape speed of 6 m/s

Metal particulate (MP) versus metal evaporated (ME) tape

In order to increase the area storage density, tape manufacturers experiment with so called metal evaporated (ME) tape, where high coercivity cobalt atoms are evaporated and deposited on a substrate in a series of vacuum chambers.

Hempstock and Sullivan [9] studied the durability and signal performance of ME and MP tapes and concluded that MP tape exhibits far greater durability than the ME tape, while the latter has superior magnetic characteristics. In another study Hempstock and Sullivan [10] identified the mechanical failure mechanism of an ME tape as a form of delamination wear. Bijker et al. [11] discussed the use of wear protective coatings such as diamond like carbon (DLC) and a so-called super protective layer (SPL) as a potential to improve the wear characteristics of ME tape. They concluded that the protective coatings need further development to withstand abrasive wear.

Fig. 5 compares the friction coefficient versus speed for MP and ME tapes. The rotating guide of our test set-up stalled due to high stiction when attempting to test the ME tape over the full operating range previously used with the MP tape. Thus, to overcome the higher stiction tendency inherent to the ME tape [4], a very low nominal tension of 0.1 N in combination with an 80 degree wrap angle and a guide radius of 15 mm were used for the comparison. A lower friction coefficient is observed in Fig. 4 with the ME tape compared to the MP tape for sliding speeds above 3 m/s where it is likely that an air bearing exists between the guide and the tape due to low tension and large guide radius. With such an air bearing the smooth ME tape surface provides an extremely low friction coefficient. At speeds below 3 m/s, however, the friction coefficient of the ME tape increases more rapidly compared to the MP tape and the ME tape approaches the onset of stiction.

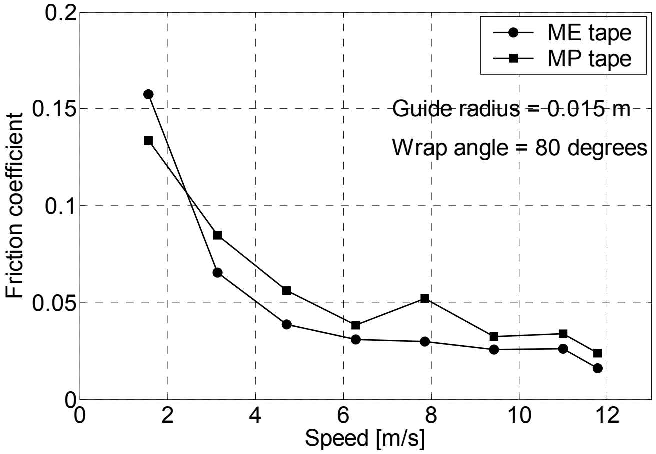


Fig. 5: Friction coefficient versus speed for a guide radius of 15 mm and a nominal tension of 0.1 N for ME and MP tape

Temperature rise

In addition to friction coefficient measurements between the tape and guide we also measured the temperature of the tape with an infrared thermometer at three different angular positions $\pi/2$, $\pi/4$ and *0* degrees, in the direction of rotation as indicated in Fig. 6. We hypothesize that the tape temperature can be correlated to the contact pressure. Tape temperature measurements were taken at several time intervals up to 10 minutes.

After 10 minutes of operation, the temperature almost reached steady state, i.e., the heat due generated to friction equals the amount of energy dissipated by convection and conduction. Tests longer than 10 minutes are not representative since the magnetic coating starts to show degradation due to excessive wear.

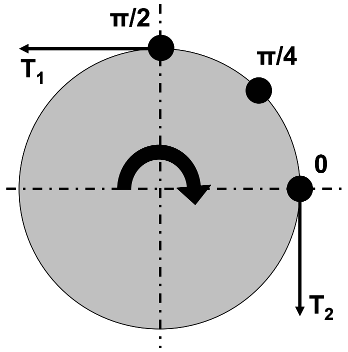
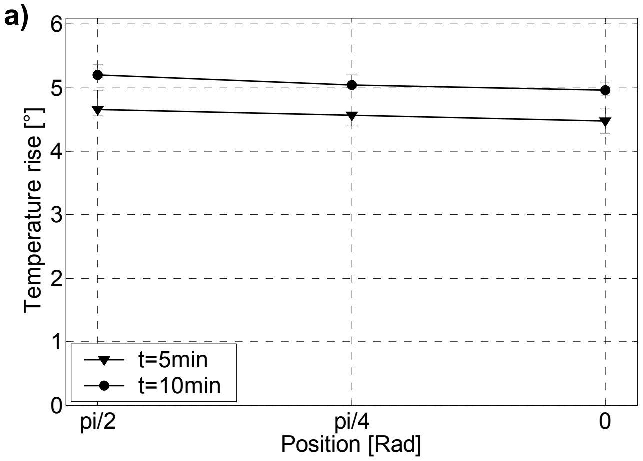


Fig. 6: Schematic of temperature measurements on the tape surface

Fig. 7 shows the temperature rise of the tape above the ambient temperature as a function of time at a rotational frequency of $\omega = 70$ Hz. Results are shown for a guide with a 15 mm radius (Fig. 7 a)), 10 mm radius (Fig. 7 b)) and 7.5 mm radius (Fig. 7 c)). The data were taken at a nominal tape tension of 1 N and averaged over 5 repeated measurements.



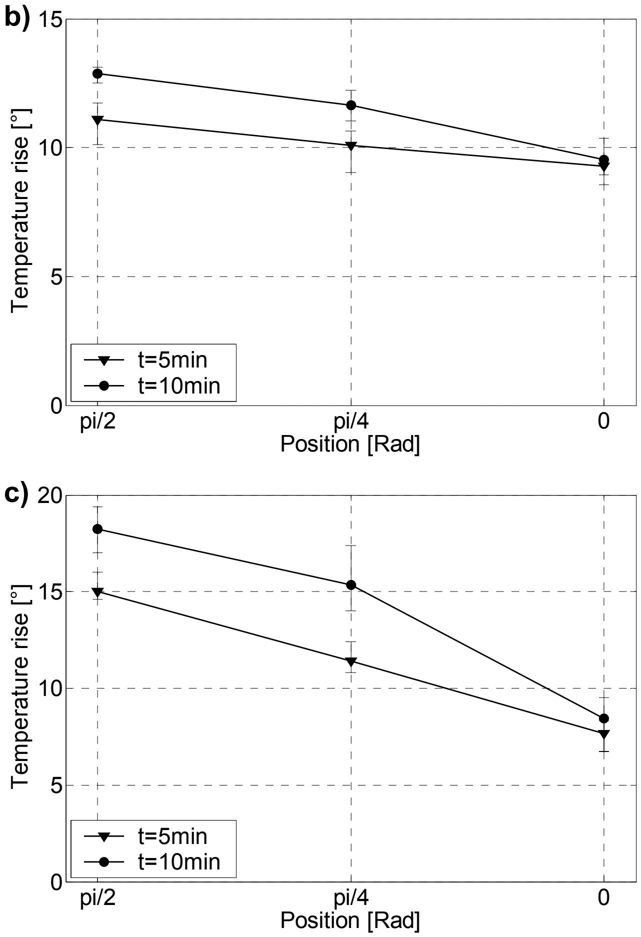


Fig. 7: Tape temperature rise versus position (in the direction of guide rotation) after 5 and 10 min of operation for a guide radius of a) 15 mm, b) 10 mm and c) 7.5 mm. Rotational frequency of $\omega = 70$ Hz, and nominal tape tension of 1 N.

From Fig. 7 we observe higher temperatures and a higher temperature gradient from position $\pi/2$ to 0, as the guide radius decreases. The temperature rise, after 10 min at $\pi/2$, was 18 degrees for a guide with a 7.5 mm radius and only 5 degrees for a guide with a 15 mm radius. Hence, doubling the guide radius reduces the temperature rise by a factor of three.

Fig. 8 shows the temperature rise for the guide with a 15 mm radius spinning at $\omega = 70$ Hz as in Fig. 7a). For this case the nominal tape tension was 0.5 N. Fig. 8 b) shows the temperature for the same guide with a nominal tape tension of 1 N as in Fig. 7a) but when rotating at $\omega = 125$ Hz.

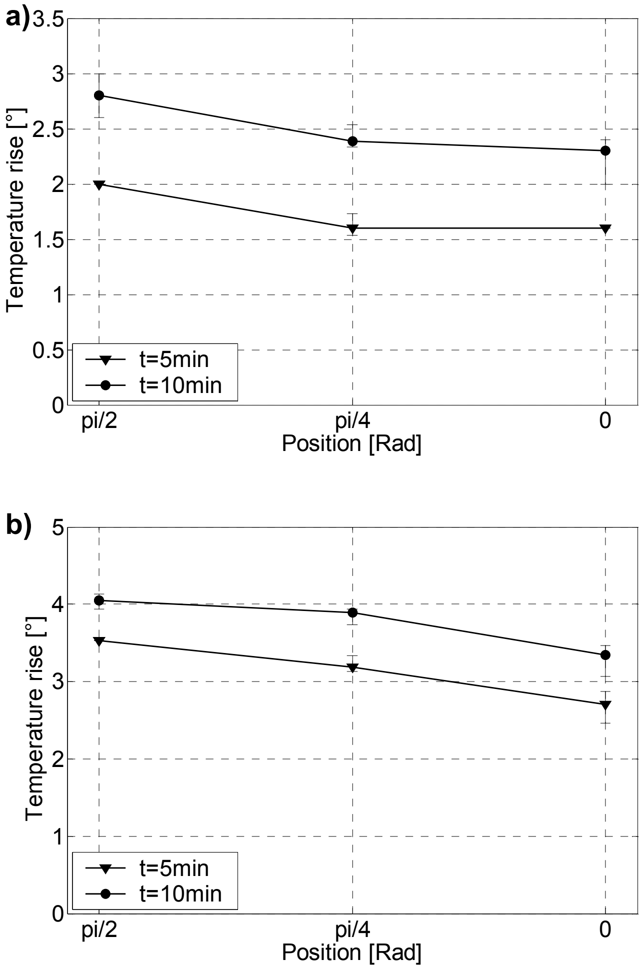


Fig. 8: Tape temperature rise versus position after 5 min and 10 min of operation. Results are for a guide radius 15 mm; a) for ω=70 Hz and 0.5 N tension, b) for ω=125 Hz and 1 N tension

As can be seen from Figs. 8a) and 7a), when comparing the tape temperature rise at position $\pi/2$ for different nominal tape tensions at a constant speed of $\omega = 70$ Hz after 10 min of operation, a 2.8 degree rise and a 5.2 degree rise correspond to the 0.5 and 1 N tape tension, respectively. Thus, an increase in tension by 100% increased the tape temperature by 85%. These results are consistent with the friction coefficient measurements in Fig. 3 a) where a decrease in friction coefficient was observed for decreasing nominal tape tension.

From Figs. 8b) and 7a) we also observe that increasing the rotational speed to $\omega = 125$ Hz (11.8 m/s) from $\omega = 70$ Hz (6 m/s) for the same guide radius and tape tension results in a 25% lower temperature rise at position $\pi/2$ after 10 minutes (4 degrees compared to 5.2 degrees, respectively). This correlates well with Fig. 3 a) where a decreasing friction coefficient was observed for increasing speed under constant nominal tape tension. These results suggest that the friction coefficient can be predicted from the tape temperature.

Discussion

The friction coefficient at the tape/guide interface was observed to be a strong function of speed. This speed dependency is caused by the formation of an air bearing at the tape/guide interface which leads to a reduction in the contact load between tape and guide. The air bearing introduces “load sharing”, where the tape is partially supported by asperity contact and partially supported by the pressure in the air bearing, thereby reducing the friction coefficient significantly.

In the case of low tape speeds (< 4 m/s), a boundary lubrication regime is established and the interaction between the magnetic tape and the guide is dominated by asperity contact. We observed that the guide radius and nominal tape tension have an effect on the friction coefficient and tape temperature rise. Fig. 9 a) shows a free body diagram of a tape element. T is the local tape tension while dT is the increment in tape tension due to the local friction force F_f . The circumferential coordinate is denoted by α , while the wrap angle is represented by θ as illustrated in Fig. 9 b).

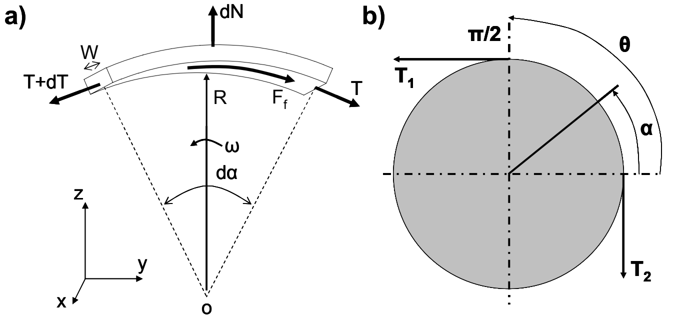


Fig. 9: Free body diagram of a tape element

The contact pressure can be written as [12]

$$P(\alpha) = \frac{T_2 \exp(\mu\alpha)}{wR} \tag{2}$$

where the local friction coefficient μ is assumed to be constant over the tape/guide contact area. w represents the tape width, while R represents the guide radius. The behavior of the contact pressure thus resembles that of the tape temperature rise as would be expected.

For high tape speeds (> 8 m/s), a self-acting air bearing is created between the tape and the guide. Very low frequency coefficients are observed for this regime (e.g. Fig. 3)

For tape speeds between 4 m/s and 8 m/s a transition regime is established where an air bearing exists in competition with partial asperity contact. Lacey and Talke, 1992, modeled this phenomenon with a combined experimental and numerical approach [13]

Conclusion

The experimental results show that:

- the tape/guide friction coefficient decreases as the guide radius increases. The contact pressure between tape and guide is inversely proportional to the guide radius at low tape speeds (< 4 m/s). The true area of contact between tape and guide is proportional to the contact pressure. Hence, the friction coefficient will increase with decreasing guide radius. For high tape speeds (> 8 m/s), an air bearing is formed while for intermediate tape speeds (between 4 m/s and 8 m/s), asperity contact coexists with an airbearing.
- the temperature measurements correlate well with the friction coefficient results. It is possible to deduct information about the friction coefficient from tape temperature measurements.
- the tape/guide friction coefficient decreases for increasing tape speed and increases for increasing nominal tape tension.
- the tape/guide friction coefficient is independent of the wrap angle.

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