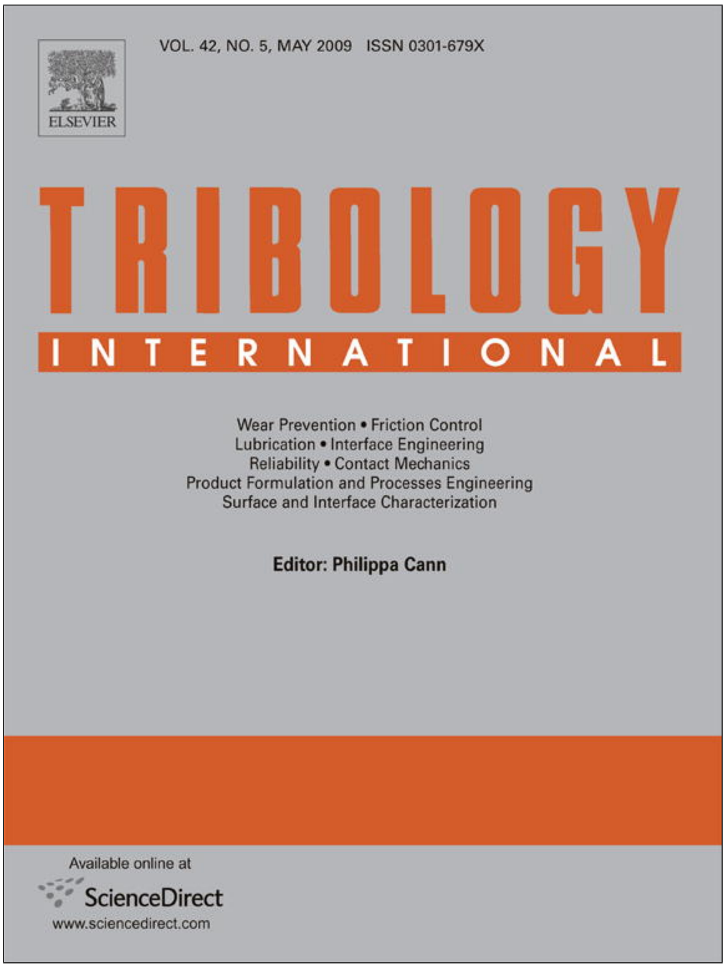
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Attenuation of lateral tape motion due to frictional interaction with a cylindrical guide

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A B S T R A C T

Lateral tape motion (LTM) is a function of tape path and tape properties, design parameters such as speed, tension, and friction between tape and tape path components. This investigation deals with the LTM of a tape moving over the surface of a cylindrical guide. Starting from the equation of motion for a moving tape on a cylindrical guide surface, the effects of friction, tape properties and design parameters are examined by calculating the ratio of LTM before and after a cylindrical guide. Attenuation of LTM is found to be mainly dependent on the guide radius and the wrap angle.

1. Introduction

Lateral tape motion (LTM) is the time-dependent displacement of magnetic tape perpendicular to the tape transport direction. In general, a servo loop controls the magnetic read/write head actuator and compensates the lateral displacement of the tape. LTM with a frequency higher than the bandwidth of the servo actuator (typically >1 kHz) is generally referred to as high-frequency LTM. LTM can cause track misregistration between the read/write head and a previously written track, thereby limiting the recording density that can be achieved [1]. Currently, the track density of typical magnetic tape drives is approximately 55 tracks/mm (1400 tracks per inch (tpi)) [2].

To decrease the lateral displacement of a moving tape [3], it is important to first characterize LTM. In commercial tape drives and tape manufacturing equipment, tape is guided over rollers and guides, which interact with the tape surface through frictional contact. Rollers and guides in tape drives are typically small in diameter, on the order of tens of mm, due to stringent space constraints in a tape drive. On the other hand, rollers and guides in tape manufacturing process equipment can be much larger in diameter, since spatial constraints are less important.

The lateral motion of a string or web has been studied in the past. Swope and Ames [4] analyzed the oscillations of a string that is being wound on a bobbin. They assumed a perfectly flexible string without lateral bending stiffness and solved the governing equations analytically. Shelton and Reid [5,6] studied the lateral dynamics of a moving web and derived the differential equations for the lateral dynamic motion of a massless moving web. Wickert and Mote [7] investigated the vibration and stability of an axially moving continuum, casting the equations of motion in a canonical state space form. Garziero and Amabili [8] 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 [9] used Euler–Bernoulli beam theory to predict the lateral motion of a long warped web that is transported between two rollers.

The effect of guides on the LTM in a tape path has been studied by only a few researchers. Ono [10] 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 was governed by a second-order differential equation similar to that for one-dimensional heat flow. Cheng and Perkins [11] studied the vibrations of a friction-guided translating string. Zen and Muftu [12] investigated the stability of an axially accelerating string subjected to frictional guiding forces. They found that friction adversely affects stability. In addition, Chen [13] presented an analysis of the natural frequencies and stability of a string traveling between two fixed supports and in contact with a stationary load system. The analysis contains parameters such as dry friction, inertia, damping, and stiffness.

More recently, work has been published that describes the behavior of a tape rather than a string interacting with a guide. Taylor and Talke [14] investigated the interactions between rollers and flexible tape and showed that friction between the tape and

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the roller affects the lateral displacement of tape. In addition, they correlated LTM with the axial run-out of a roller. Raeymaekers and Talke [15] derived the equation of motion for an axially moving tape on a cylindrical guide surface and compared the effect of bending stiffness of tape to a string model without bending stiffness. No published work seems to exist that describes the effect of guides in a tape path, or how it can be used to attenuate LTM.

In this paper, we have studied the effect of friction and other design parameters on the lateral motion of magnetic tape as it moves over a stationary cylindrical guide. We have included the effect of bending stiffness in our analysis, since the moment of inertia of the tape for the transverse direction is very large. Bending stiffness is the major difference between a simplified string model and an actual magnetic tape.

2. Analytical background

The equation of motion for a tape traveling over a stationary cylinder (Fig. 1) is given by the following fourth-order partial differential equation [15]:

$$-EI\frac{\partial^4 z}{\partial s^4}+T\frac{\partial^2 z}{\partial s^2}-\frac{\mu_z T}{a}\left(1-\frac{\mu_\varphi}{\mu_z}\right)\frac{\partial z}{\partial s}-\frac{\mu_z T}{\bar{v}_0 a}\frac{\partial z}{\partial t}=0 \qquad (1)$$

where μ_φ is the friction coefficient in the circumferential direction and μ_z is the friction coefficient in the lateral direction. E is the Young's modulus, I is the area moment of the cross-sectional area of the tape, z is the lateral position of the tape (along the $\boldsymbol{k}$-axis), s is the coordinate along the centerline of the tape, T is the tape tension per unit width, a is the guide radius, $\bar{v}_0$ is the tape velocity and t represents time. Inertia terms are not included in Eq. (1) since for a typical tape transport speed $\bar{v}_0 = 4\,\mathrm{m/s}$ and tension $T = 1\,\mathrm{N/m}$, we can neglect the inertia terms $\rho w \bar{v}_0^2$ versus the tension T for a 9-μm-thick magnetic tape (mylar-PET) with $\rho = 0.012\,\mathrm{kg/m^2}$ and $w = 12.7\,\mathrm{mm}$. The tension term is three orders of magnitude larger than the inertia term.

The tape first makes contact with the guide at point s_1 and loses contact with the guide at point s_2. The fourth-order derivative in Eq. (1) denotes the bending stiffness of the tape. For the limiting case when the guide becomes a roller, $\mu_\varphi = 0$ and $\mu_z \to \infty$ since there is no relative sliding (slip) between the tape and an ideal roller. Furthermore, if the friction coefficient for the circumferential and lateral direction are the same, i.e., if $\mu_\varphi = \mu_z$,

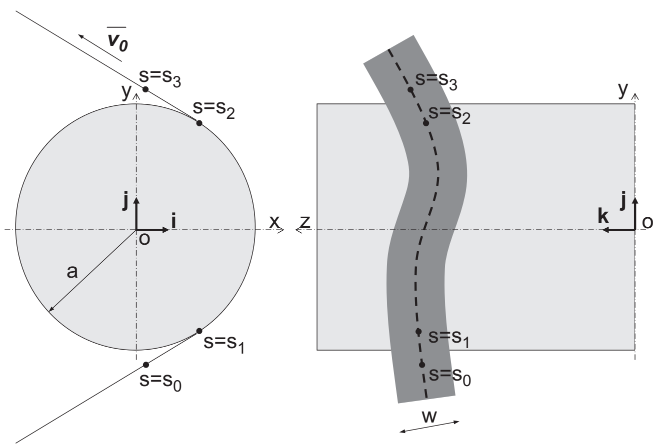

Fig. 1. Axially moving tape over a cylindrical guide surface.

Eq. (1) becomes

$$-EI\frac{\partial^4 z}{\partial s^4}+T\frac{\partial^2 z}{\partial s^2}-\frac{\mu_z T}{\bar{v}_0 a}\frac{\partial z}{\partial t}=0 \qquad (2)$$

If $I = 0$ and $\mu_\varphi = \mu_z = 0$, which physically represents a frictionless string moving over a cylindrical guide surface, Eq. (2) reduces to

$$\frac{d^2 z}{ds^2}=0 \qquad (3)$$

The solution of Eq. (3) is a linear function of z in terms of s, i.e., the tape (string) moves as a straight line over the guide between points s_1 and s_2. Since Eq. (1) is difficult to solve in closed form, numerical analysis was used to study the effect of friction and design parameters on the lateral motion of the tape [15]. To solve Eq. (1), an implicit Euler finite difference scheme was implemented. As illustrated in Fig. 1(a) and (b), we assume that the tape is wound on a reel with zero run-out at s_3, i.e., $z(s_3,t) = 0$. At s_0, the lateral displacement $f_0(t)$ is assumed to be known from experimental measurements, i.e., $z(s_0,t) = \mathrm{LTMB}(t)$. In addition, we postulate that the tape moves like a rigid body between s_0 and s_1 and s_2 and s_3, where it is not supported by the guide. The distances $|s_0 s_1|$ and $|s_2 s_3|$ are taken much shorter than the distance $|s_1 s_2|$. This assumption becomes more accurate for increasing guide radii. Hence, using LTM B as input to our model (Eq. (1), see also [15]), we can simulate the LTM in the middle of the cylindrical guide and compare it to experimental results measured with our experimental set-up. Although LTM B can be a function of the guide properties, we used one baseline case as input to all our simulations. This allows us to study the effect of different guides on LTM, independent from the input to the model.

To verify our model, we have first compared the values of the numerically simulated LTM in the middle of the cylindrical guide with experimentally measured LTM values at the same position. Using a stationary guide and an LTM edge sensor [1], we have measured LTM on the guide surface. Fig. 2 illustrates our experimental set-up. A simple tape path was created where the tape is transported from the supply reel to a take-up reel. A cylindrical guide is positioned between supply and take-up reel (Fig. 2(a)). The cylindrical guide is provided with a cut-out, in which an LTM sensor (LTM A) is positioned (Fig. 2(b)).

Fig. 3(a) shows simulated and experimentally measured values of lateral tape displacement in the middle of the cylindrical guide, while Fig. 3(b) shows the simulated and experimentally determined frequency spectrum at the same position. In our simulation (Eq. (1)), we have used the following parameters: $E = 7\,\mathrm{GPa}$, $w = 12.7\,\mathrm{mm}$, $\bar{v}_0 = 4\,\mathrm{m/s}$, $a = 10\,\mathrm{mm}$, $T = 1\,\mathrm{N}$, $\mu_\varphi = \mu_z = 0.2$ and tape thickness $b = 9\,\mu\mathrm{m}$, typical values for state-of-the-art magnetic tapes.

From Fig. 3 we observe very good agreement between experimental measurements and numerical results, especially in the frequency region below 1.5 kHz. The increased deviation between experimental measurements and the numerical predictions for increasing frequencies is most likely related to the presence of the cut-out in the stationary guide for positioning of the lateral tape displacement sensor.

3. Amplitude ratio

To characterize and quantify the effect of a tape guide on LTM, we have introduced the amplitude ratio ζ, defined as the output amplitude of the LTM divided by the input amplitude, i.e.,

$$\zeta=\frac{\mathrm{LTM_{out}}(f)}{\mathrm{LTM_{in}}(f)} \qquad (4)$$

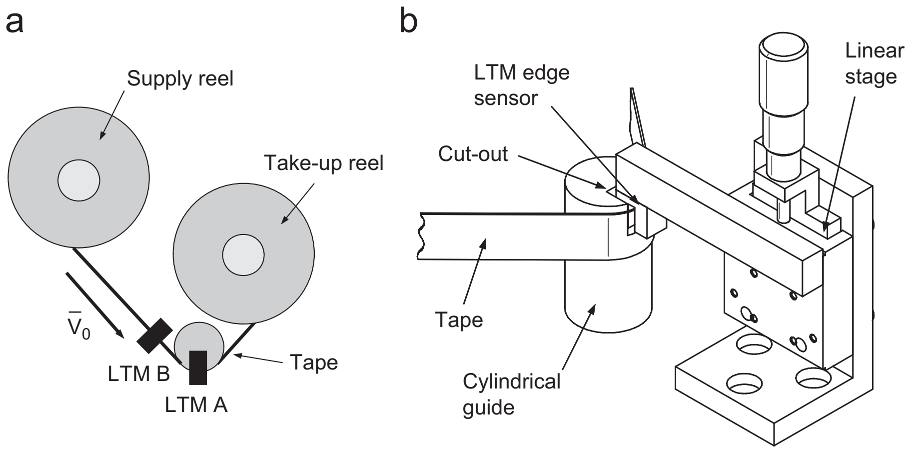

Fig. 2. Experimental set-up: (a) tape path and (b) measurement of LTM in the middle of the cylindrical guide.

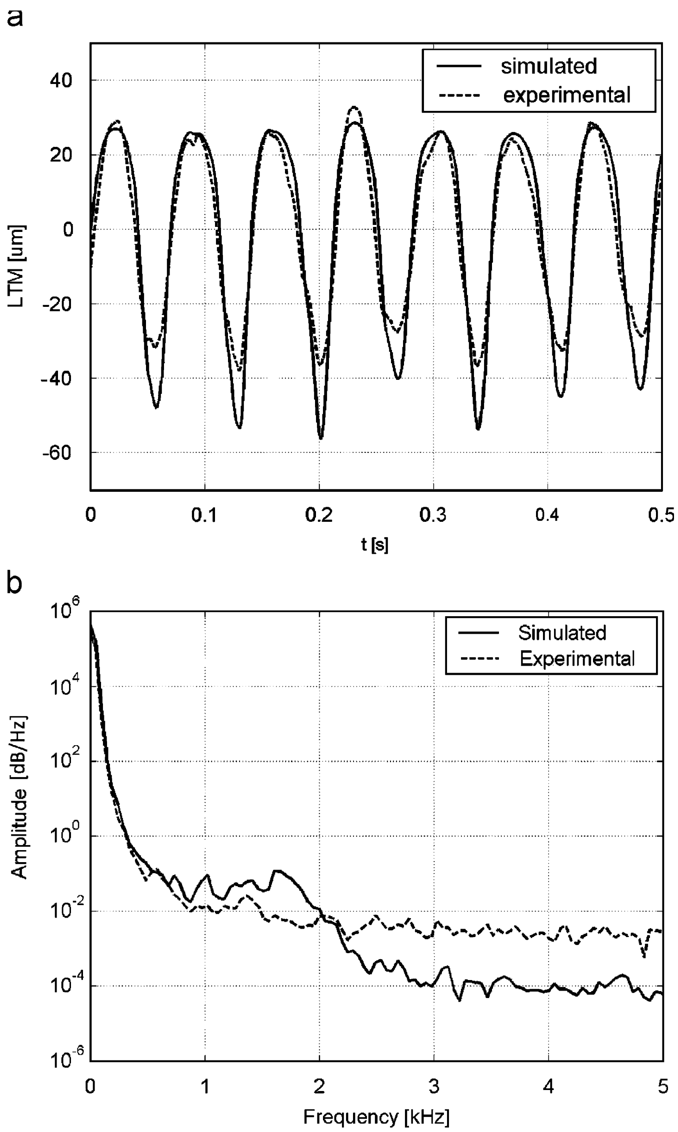

Fig. 3. Comparison of experimental measurements and numerical predictions in the middle of a cylindrical guide (a) in time domain and (b) in frequency domain.

The amplitude ratio ζ can be physically interpreted as a transfer function which gives information about the attenuation or amplification of LTM as a function of the frequency f. A normalized sine wave was used as input LTM (Fig. 4). Although Fig. 3(b) only shows very good agreement between model and experiments in the 0–1.5 kHz range, we have varied the frequency of the input LTM within a range of 0–10 kHz, for the sake of completeness. Simulating the output LTM, we have determined the amplitude ratio as a function of the frequency.

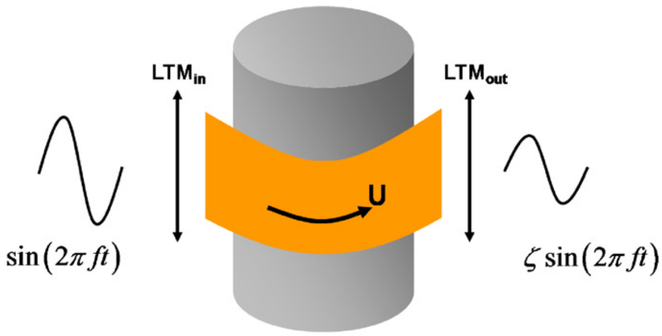

Fig. 4. Amplitude ratio.

4. Results

In this section, we have presented the results for the case of a commercial tape drive, where guides are subject to tight space constraints, and where guide radii are typically on the order of 10 mm. In addition, we have presented results for dimensions that are in line with those used in tape manufacturing process equipment, where guide radii of 100 mm are used.

The influence of the guide radius on the amplitude ratio ζ is depicted in Fig. 5 for a typical friction coefficient $\mu_\varphi = \mu_z = 0.2$, a wrap angle of 90°, a tape thickness of 9 μm, a tape speed of 4 m/s and a nominal tape tension of 1 N.

We observe that the amplitude ratio is a strong function of the guide radius a. The reason for this is the following. As the guide radius increases, the contact length between the magnetic tape and the guide increases. This causes an increased friction force which will dampen out lateral tape vibrations.

Fig. 6 shows the influence of the wrap angle on the amplitude ratio ζ for a friction coefficient $\mu_\varphi = \mu_z = 0.2$, a nominal tape tension of 1 N, a tape speed of 4 m/s, a tape thickness of 9 μm and a guide radius of 10 mm with a nominal tape tension of 1 N.

We observe that the amplitude ratio decreases with increasing wrap angle. Physically, the effect of increasing the wrap angle is

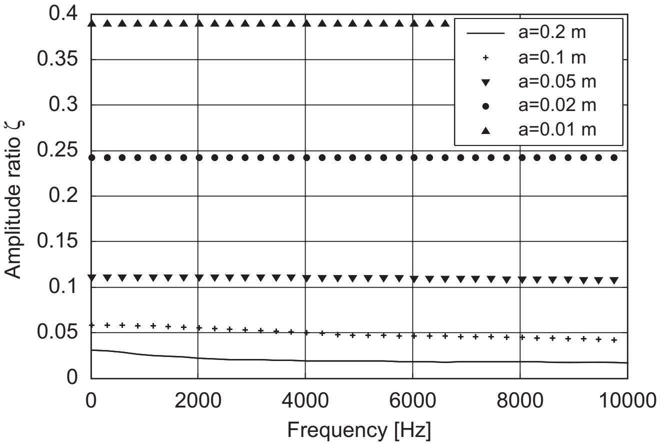

Fig. 5. Influence of the guide radius on the amplitude ratio as a function of frequency.

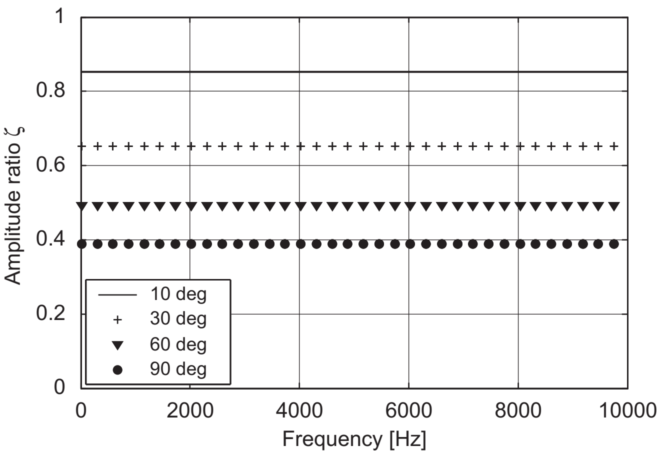

Fig. 6. Influence of the wrap angle on the amplitude ratio as a function of frequency.

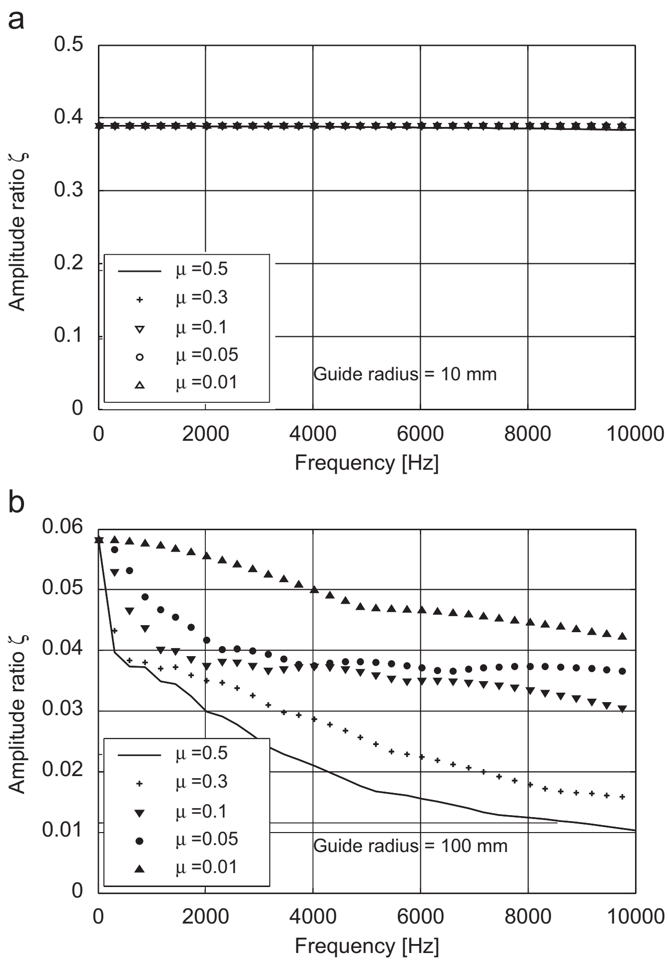

Fig. 7. Influence of friction coefficient on amplitude ratio as a function of frequency for a guide of radius (a) 10 mm and (b) 100 mm.

similar to increasing the guide radius. Both parameters affect the tape/guide contact length. An increased contact length yields an increased friction and thus reduced LTM.

Fig. 7 shows the influence of the friction coefficient $\mu = \mu_\varphi = \mu_z$ on the amplitude ratio ζ (a) for a guide radius of 10 mm and (b) for a guide radius of 100 mm. A wrap angle of 90° was maintained together with a nominal tape tension of 1 N, a tape speed of 4 m/s, a tape thickness of 9 μm and a friction coefficient.

We observe that the amplitude ratio is independent of the friction coefficient for a guide of radius 10 mm (Fig. 7(a)), but is a stronger function of the friction coefficient for a guide radius of 100 mm (Fig. 7(b)). It is apparent that the amplitude ratio is dominated by the wrap angle and the guide radius, i.e., by the tape/guide contact length.

In Fig. 8, the influence of tape speed on the amplitude ratio ζ is shown. Fig. 8(a) shows the amplitude ratio versus the frequency for a guide radius of 10 mm, while Fig. 8(b) shows the amplitude ratio for a guide radius of 100 mm. The same conditions were used as in Fig. 7(a) and (b).

We observe that for a guide radius of 10 mm, the amplitude ratio is almost independent of the speed; since the effect of the friction coefficient on the amplitude ratio is small compared to the effect of the guide radius and the wrap angle, the friction coefficient was kept constant as a function of tape speed. However, the friction coefficient is expected to decrease with increasing tape speed due to the formation of a partial air bearing between the tape and the guide surface [16]. For the guide radius of 100 mm, the amplitude ratio is one order of magnitude smaller than for the 10 mm case, i.e., LTM is reduced more significantly. The attenuation is not a strong function of the frequency.

Fig. 9 illustrates the influence of the nominal tape tension on the amplitude ratio ζ. The same conditions were used as in Figs. 7 and 8. Fig. 9(a) shows the amplitude ratio versus frequency for a guide radius 10 of mm, while Fig. 9(b) shows the amplitude ratio for a guide radius of 100 mm.

We observe that the amplitude ratio ζ is almost independent of tape tension for the 10 mm guide. However, for the 100 mm guide the amplitude ratio decreases for increasing tape tension (Fig. 9(b)). If the tape tension T increases, the "belt-wrap force" N increases as $N = 2T\sin(\theta/2)$, where θ denotes the wrap angle, and $0 \leqslant \theta \leqslant 2\pi$. An increased "belt-wrap force" creates stronger asperity contact and hence more friction. Thus, LTM will be attenuated.

Fig. 10 shows the influence of tape thickness. Fig. 10(a) shows the amplitude ratio versus frequency for a guide radius of 10 mm, while Fig. 10(b) shows the amplitude ratio for a guide radius of 100 mm. The wrap angle is 90°, the tape speed is 4 m/s and the friction coefficient $\mu_\varphi = \mu_z = 0.2$.

Similar to the previous results, we observe that the amplitude ratio is nearly independent of the tape thickness for the 10 mm

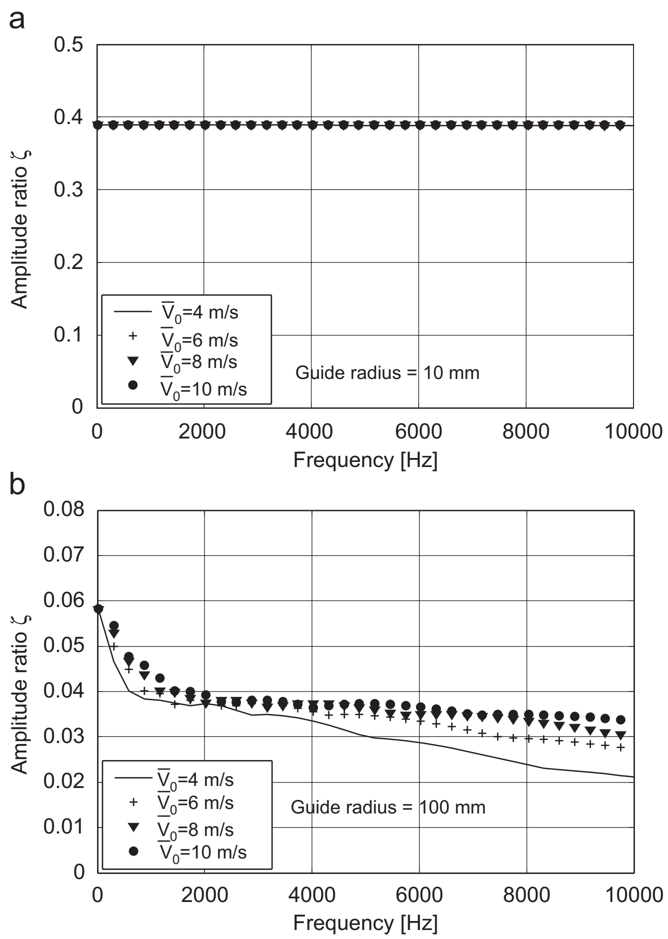

Fig. 8. Influence of tape speed on amplitude ratio as a function of frequency for a guide of radius (a) 10 mm and (b) 100 mm.

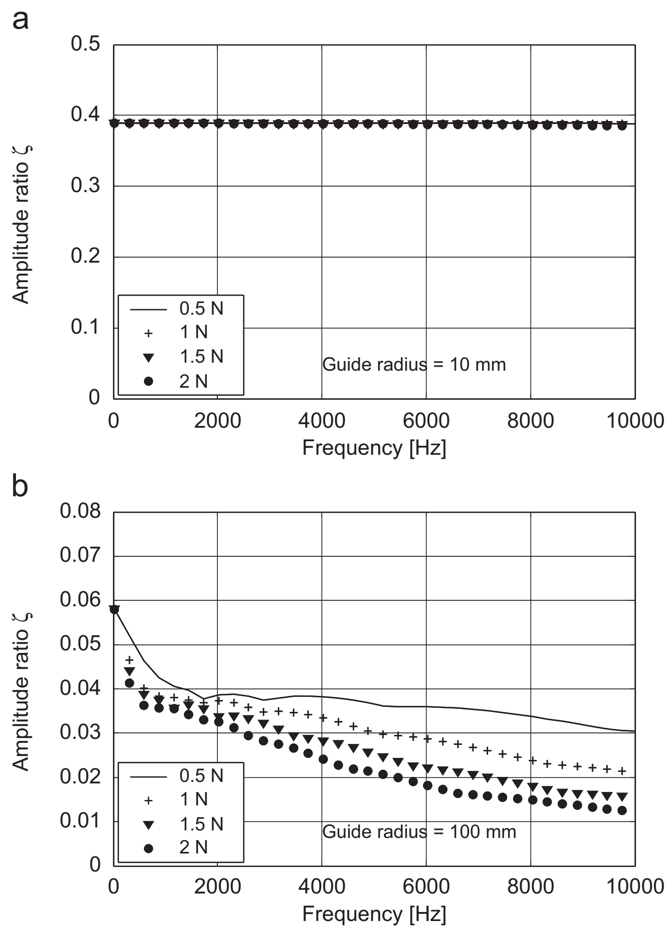

Fig. 9. Influence of nominal tension on amplitude ratio as a function of frequency for a guide of radius (a) 10 mm and (b) 100 mm.

radius guide, while it decreases with decreasing thickness for the 100 mm guide radius.

5. Discussion

We observed that the amplitude ratio ζ is inversely proportional to the tape/guide friction coefficient μ, the wrap angle θ, the nominal tape tension T and the guide radius a, and proportional to the tape speed V and tape thickness b. Hence, the amplitude ratio ζ can be defined in terms of tape design parameters as

$$\zeta = A\frac{w_V w_b V b}{w_\mu w_\theta w_a w_T \mu \theta a T} + \varepsilon, \qquad (5)$$

where A is a proportionality constant, w_μ, w_θ, w_a, w_T, w_V and w_b are weight factors for the individual parameters. From the model it is clear that w_θ, $w_a \gg w_T$, w_V, w_b, and w_μ. ε is a correction factor that accounts for the error of the model.

It is apparent that an increase in the guide diameter or wrap angle increases the contact length and friction force. This, in turn, attenuates the LTM more strongly. In the case of commercial tape drives, the guide diameter cannot be increased arbitrarily due to space constraints. In tape manufacturing process equipment, where spatial constraints are less critical, there is greater design freedom to increase the diameter of the guides, which would reduce LTM. However, increased friction force due to increased contact length may lead to increased tape wear, and the balance between those effects must be found. It should also be noted that the main frequency range of interest with respect to design of tape drives is 0–3 kHz.

The tape industry is moving towards using thinner tapes to increase the volumetric storage density of a tape cartridge. Thinner tapes require lower tape tension to keep the stress in the tape constant. Increased storage density also calls for higher data rates (higher tape speeds). Our results show that the tape speed V, the tape thickness b, the nominal tape tension T and the friction coefficient μ have only a secondary effect on the amplitude ratio for small guide diameters.

From the results presented, it is apparent that LTM can be reduced by positioning guides in the tape path before the tape passes over the read/write head. The guides would serve as "mechanical LTM-filters". This would allow increased track density and storage capacity of magnetic tape. Furthermore, reducing LTM during the tape slitting process would produce tapes with improved edge quality, i.e., straighter edges. Straight edges are important for tape edge guiding [17,18], and are thus of primary concern in the tape manufacturing process.

6. Conclusion

The simulation results show that guide radius, wrap angle, friction coefficient, tape thickness, tape tension and tape speed affect the amplitude ratio ζ, i.e., the ratio that describes the

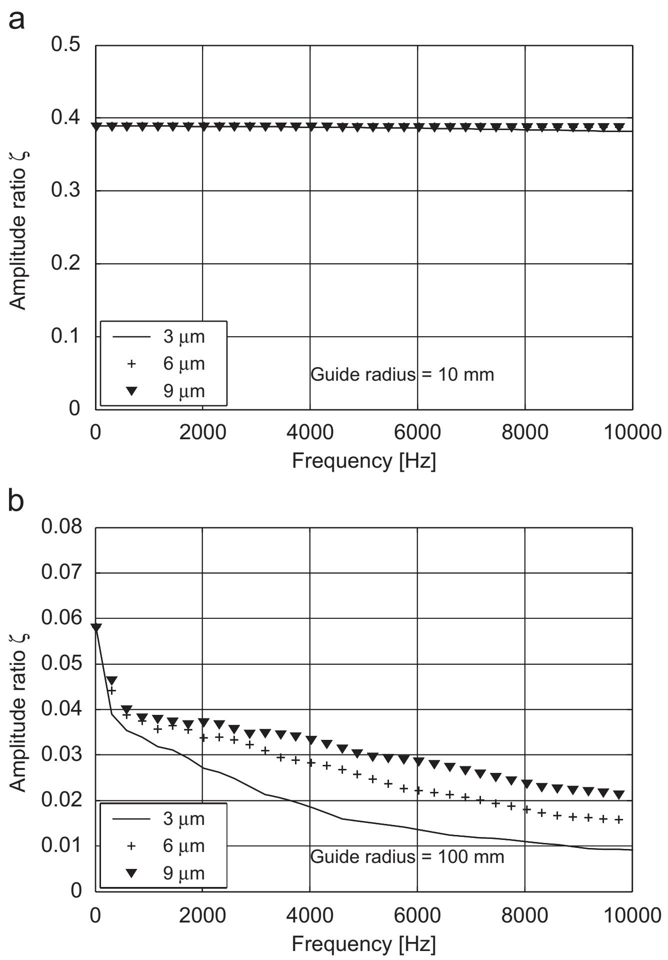

Fig. 10. Influence of tape thickness on amplitude ratio as a function of frequency for a guide of radius (a) 10 mm and (b) 100 mm.

attenuation of LTM due to the frictional contact between a guide and a magnetic tape. We conclude that:

1. The guide radius as well as the wrap angle (tape/guide contact length) influences the amplitude ratio most significantly.
2. The nominal tape tension, friction coefficient, tape thickness and tape speed affect the amplitude ratio; however their influence is negligible with respect to the influence of the guide radius and the wrap angle.
3. The results of this investigation can be used to minimize LTM at the magnetic read/write head by positioning cylindrical guides in the tape path.

References

[1] Taylor RJ, Strahle P, Stahl J, Talke FE. Measurement of cross-track motion of magnetic tapes. J Inf Storage Proc Syst 2000;2:255–61.
[2] Dee RH. Magnetic tape: the challenge of reaching hard-disk-drive data densities on flexible media. MRS Bull 2006;31:404–8.
[3] Richards DB, Sharrock MP. Key issues in the design of magnetic tape for linear systems of high track density. IEEE Trans Magn 1998;34(4):1878–82.
[4] Swope RD, Ames WF. Vibrations of a moving threadline. J Franklin Inst 1963;275:36–55.
[5] Shelton JJ, Reid KN. Lateral dynamics of an idealized moving web. J Dyn Syst Meas Control—Trans ASME 1971;3:187–92.
[6] Shelton JJ, Reid KN. Lateral dynamics of a real moving web. J Dyn Syst Meas Control—Trans ASME 1971;3:180–6.
[7] Wickert JA, Mote CD. Classical vibration analysis of axially moving continua. J Appl Mech—Trans ASME 1990;57:738–44.
[8] Garziera R, Amabili M. Damping effect of winding on the lateral vibration of axially moving tapes. J Vib Acoust—Trans ASME 2000;122:49–53.
[9] Benson RC. Lateral dynamics of a moving web with geometrical imperfection. J Dyn Syst Meas Control—Trans ASME 2002;124:25–34.
[10] Ono K. Lateral motion of an axially moving string on a cylindrical guide surface. J Appl Mech—Trans ASME 1979;46:905–12.
[11] Cheng SP, Perkins NC. The vibration and stability of a friction-guided, translating string. J Sound Vib 1991;144(2):281–92.
[12] Zen G, Müftü S. Stability of an axially accelerating string subjected to frictional guiding forces. J Sound Vib 2006;289:551–76.
[13] Chen JS. Natural frequencies and stability of an axially-traveling string in contact with a stationary load system. J Acoust Vib—Trans ASME 1997;119(2):152–7.
[14] Taylor RJ, Talke FE. Investigation of roller interactions with flexible tape medium. Tribol Int 2005;38:599–605.
[15] Raeymaekers B, Talke FE. Lateral motion of an axially moving tape on a cylindrical guide surface. J Appl Mech Trans ASME 2007;74(6):1053–6.
[16] Raeymaekers B, Etsion I, Talke FE. The influence of design and operating parameters on the magnetic tape/guide friction coefficient. Tribol Lett 2007;25(2):161–71.
[17] Bhushan B, Hinteregger HF, Rogers AEE. Thermal considerations for the edge guiding of thin magnetic tape in a longitudinal tape transport. Wear 1994;171:179–93.
[18] Taylor RJ, Talke FE. High frequency lateral tape motion and the dynamics of tape edge contact. J Microsystem Technol 2005;11:1166–70.