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Mechanics of lateral positioning of a translating tape due to tilted rollers: Theory and experiments

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ABSTRACT

A mechanics based model to describe the lateral positioning of a thin, tensioned, translating tape over a tilted roller is introduced, based on the assumption that the transport velocity of the tape should match the surface velocity of the roller when there is sufficient traction. It is shown that this condition requires the slope of the neutral axis of the tape and the slope of the centerline of the tilted roller to be the same over the wrapped segment. An extension of this model is discussed including the possibility of circumferential and lateral sliding, depending on the velocity difference between the tape and the roller. The new model is incorporated into a generalized model of a tape path that consists of numerous rollers as well as the appropriate boundary conditions for the take-up and supply reel dynamics. The nonlinear equation of motion is solved numerically, and the steady state solution is found by an implicit time stepping algorithm. An experimental setup with one tilting roller, two or three nearly ideally oriented rollers and two reels is used for verification of the model. The effects of roller tilt angle, tape wrap angle, and the lengths of the free-tape spans upstream and downstream of the tilted roller on the steady state lateral tape position are investigated experimentally and by simulations. The experiments show that the circumferential position of the wrap on the upstream side of a tilted roller has the strongest effect on pushing the tape in the lateral direction. The total wrap angle around the roller has a smaller effect. It was also shown that the tape segments upstream and downstream of the tilted roller interact, and the combined effect results in a different overall lateral tape response in steady state.

1. Introduction

Thin substrates used in various industries and manufacturing processes ranging from magnetic tape for recording data, to food wrap, to flexible electronics are collectively known as webs. In a typical web handling process, a web travels between two reels and is supported by a range of guiding elements such as fixed guides, rollers, air reversers, coating nozzles, driers, etc. It is well known that during processing the web unavoidably deviates from its prescribed, linear path. In magnetic tape recording the lateral tape motion (LTM) is a particular challenge that must be overcome to continue scaling tape systems to higher data storage capacities in the future. For example, the International Storage Industry Consortium 2012 Tape Technology Roadmap predicts that the tolerance on the lateral positioning error will have to be reduced to approximately 15 nm by the year 2022 (Anonymous, 2012). The *lateral tape/web motion* can arise from roller tilt, web defects, reel wobble and other factors. Lateral tape motion (LTM) can be suppressed to a certain extent by using flanged rollers, but this could damage the edge of the tape, and introduce high frequency low amplitude lateral tape vibrations. On the other hand, use of flangeless rollers could eliminate these issues, but can also amplify the low frequency LTM (Pantazi et al., 2010). One of the key factors in understanding the effects of imperfections on lateral tape/web dynamics has been mechanistic modeling of the tape/web transport process. In particular, mechanics of a translating tape/web interacting with a roller has been the subject of several critical works.

Shelton and Reid (SR) showed that the lateral web deflections can be modeled using beam theory, and they described the mechanics of a web as it comes into contact with a cylindrical roller (Shelton and Reid, 1971a). Their work, which describes the web dynamics in the free span between two rollers, was the first to identify the boundary conditions between the web and the downstream roller. Sievers extended this work to a system with multiple rollers and used the Timoshenko beam theory (Sievers, 1987). Benson obtained the downstream boundary conditions by

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using the minimum total potential energy principle, and described the mechanics of a spliced web by using the Timoshenko beam theory (Benson, 2002). In the limit when Euler–Bernoulli and Timoshenko beam models are identical, the boundary conditions described by the SR and Benson models are identical. The aforementioned works do not directly model the interaction of a web with a roller. Mechanics of a string traveling over a cylindrical roller was described by Ono (1979) and Moustafa (1975), and over a general axisymmetric roller by Yang (1994). Raeymaekers et al. extended Ono's model by adding the effects of bending stiffness (Raeymaekers and Talke, 2007). However, these models do not consider systems with multiple rollers, and they do not take into account roller misalignment. In Shelton's work the effect of roller misalignment on the free span web dynamics is introduced through the boundary conditions. Eaton described the geometry of the tape over a roller that has an arbitrary tilt with respect to the drive base, but did not consider the tape's flexure over the roller. He described the reel-to-reel dynamics of the tape using the tape geometry over the rollers as boundary conditions of multiply connected tape segments (Eaton, 1998). Brake, 2007; Brake and Wickert, 2008 introduced a framework where various types of guides on a tape path can be modeled by applying concentrated forces and moments. Brake and Wickert (2010) added tape flexure to Eaton's description of the tape geometry over a tilted roller. The present work introduces a new model for the tape-roller interactions and implements this in a general approach for the lateral dynamics of a tape/web traveling between two reels, supported by multiple rollers.

2. Model

The tape mechanics is described with respect to a *tape-based coordinate* system (x,z) that coincides with the neutral axis of the idealized tape as shown in Fig. 1. The origin of the tape coordinate system is located at the tape's tangency point on the supply reel. Fig. 1(b) shows the tape in a configuration that is unwrapped onto a plane.

Each roller is assumed to have a set of *roller coordinate axes* designated as (x_1^r, x_2^r, x_3^r). For the case where the roller is exactly perpendicular to the drive base, (x_1^r, x_2^r, x_3^r) are coincident with the *ground* (*or drive-base*) *coordinate system* (x_1,x_2,x_3). Otherwise, the orientation of the roller coordinate axes is described with respect to the ground system by using the *tilt angle* δ and the *orientation angle* α as shown in Fig. 2a. Note that the tilt angle δ represents a rotation about the x_2 axis. The orientation angle α, which is a measure of the location of the x_1^r axis with respect to x_1 axis, on the (x_1, x_2) plane as shown in Fig. 2, also represents a rotation about the x_3 axis. This notation was first used by Eaton (1998) and then by Brake and Wickert (2010).

It is generally assumed that tape sticks on to the roller if there is sufficient traction in the tape-roller interface (Shelton and Reid, 1971a). Therefore, it is useful to describe the position of a tilted roller with respect to the tape coordinate system. Note that the circumferential centerline of the roller develops a height variation $h_r(\theta)$ with respect to the (x_1, x_2) plane for the case where the roller axis is tilted (Eaton, 1998),

$$h_r(\theta) = -R\sin\delta\cos\theta \tag{1}$$

where R is the radius of the roller as shown in Fig. 2(c), and the circumferential position θ is referred to the x_1^r axis as shown in Fig. 2(b). Also note that the x-axis of the tape-based coordinate system and the circumferential position are in general related as $dx = Rd\theta$. As a result, the slope of the centerline of the tilted roller can be expressed in the tape based coordinate system as follows (Eaton, 1998),

$$\phi_r(x) = \frac{dh_r}{dx} = \sin\delta\sin\theta \tag{2}$$

Eqs. (1) and (2) enable the position and slope of an imperfectly oriented roller to be described with respect to the tape-based coordinate system. The total wrap angle θ_w of the tape around a given

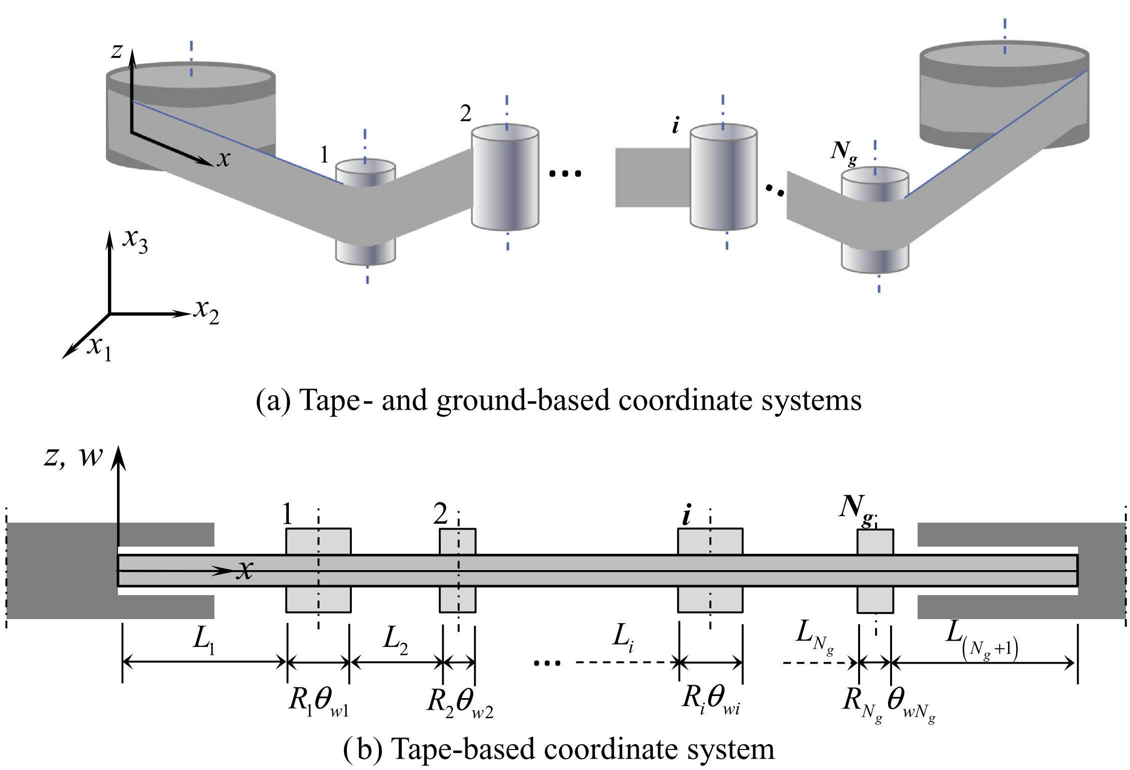

Fig. 1. Schematic depiction of the (a) ground based and (b) tape-based coordinate systems, and the relationship between the two systems.