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Load speed regulation in compliant mechanical transmission systems using feedback and feedforward control actions

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ABSTRACT

The problem of controlling the load speed of a mechanical transmission system consisting of a belt-pulley and gear-pair is considered. The system is modeled as two inertia (motor and load) connected by a compliant transmission. If the transmission is assumed to be rigid, then using either the motor or load speed feedback provides the same result. However, with transmission compliance, due to belts or long shafts, the stability characteristics and performance of the closed-loop system are quite different when either motor or load speed feedback is employed. We investigate motor and load speed feedback schemes by utilizing the singular perturbation method. We propose and discuss a control scheme that utilizes both motor and load speed feedback, and design an adaptive feedforward action to reject load torque disturbances. The control algorithms are implemented on an experimental platform that is typically used in roll-to-roll manufacturing and results are shown and discussed.

1. Introduction

Mechanical transmissions are widely used in various industries where the mechanical power is typically transmitted from motor shafts to load shafts by utilizing transmission systems. Examples include manufacturing, power generation, and transportation systems. Power transmission with speed reduction and variable torque requirement is made possible with mechanical transmission systems. Belt–pulley and gear transmission systems are commonly used. In many applications, a mechanical transmission system containing a combination of belt–pulley and a gear-pair is very convenient over a purely gear transmission system. When the center distance between the driving (motor) shaft and the driven (load) shaft is too large for use of a single gear-pair, using a belt to transmit motion/power may be the only practical alternative. Further, such an arrangement is advantageous because coupling the drive motor directly to the process end mandates very accurate collinearity of the axes and takes considerable amount of time; also, there is no guarantee that collinearity is maintained over extended period of time due to load disturbances. Belt driven transmission systems offer considerable flexibility as small inaccuracies in alignment can be absorbed into compliance of the belt. However, compliance of the belt introduces additional dynamics into the system. The belt driven power transmission system is common in roll to roll manufacturing. The presence of compliance from transmissions and the stiffness of web material [1] will pose different levels of severity in properly transporting the web.

Control of load speed is essential in many applications. When rigid transmissions are employed, there is no dynamic relation between the motor shaft and the load shaft, and typically the motor shaft speed is controlled to control the speed of the load shaft. However, due to the transmission dynamics, resulting from the compliance of belt as well as long shafts in the transmission, regulating load shaft speed is not the same as regulating motor shaft speed. In the presence of such a transmission, practicing engineers are often confronted with the question of whether to use (i) motor speed feedback to control load speed as is done in conventional practice, or (ii) use load speed feedback, or (iii) use a combination of motor and load speed feedback.

There is a large body of literature on the characteristics of belt drives and design of mechanisms using belt drives. Much of this work focused on the mechanism of motion/power transfer, location and extent of slip-arc, nature of frictional contact, efficiency limit of the belt-drive system, and methodology of design/selection of belt-drive components [2–11]. In [12], modeling and control of a belt-drive positioning table is discussed, and in [13], direct

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drive control of X–Y table is presented. However, no specific model is reported for including the effect of compliance of the belt; system identification techniques were used to obtain the system dynamics, to be later used in tuning of the feedback gains. Similarly in [14], a composite fuzzy controller, consisting of a feedback fuzzy controller and a feed-forward acceleration compensator, is proposed to control a belt drive precision positioning table; the effects of belt compliance were not included in this paper. In [15], a robust motion control algorithm for belt-driven servomechanism is reported. In this paper, the belt-stretch dynamics is assumed to contribute a pair of purely imaginary poles to the transfer function of the system; the fact that the belt serves as an interconnection from load-side to the motor-side is ignored in this paper. Modeling of belt–pulley and gear-pair transmission system with gear backlash is given in [16]. Analysis and control of speed drive systems with torsional loads is reported in [17–20].

The following are the contributions of this work: based on the model of the two inertias (motor and load) connected by a belt–pulley and gear-pair transmission system, we have investigated the effect of using either motor or load feedback to control the load speed by utilizing the singular perturbation method. In each case, we consider a PI controller that is typical in the industry for the feedback controller. The small parameter in the singular perturbation method is proportional to the reciprocal of the square root of the belt compliance. The singular perturbation analysis revealed that the controller using pure load feedback results in an unstable system. Therefore, use of pure load feedback must be avoided. To directly control the load speed, we also propose a control scheme that uses both the motor speed and load speed feedback and show that such scheme results in a stable closed-loop system. Since feedback action is not sufficient in rejecting periodic disturbances that commonly act on the load, we also consider an adaptive feedforward compensation action that is based on adaptive estimation of the coefficients of the periodic disturbance as suggested in [21]. This adaptive feedforward action is quite suitable for this application because it preserves closed-loop stability achieved with the feedback controller. Experiments were conducted to evaluate the performance of the various control schemes on an industrial grade transmission system that is common in roll-to-roll manufacturing.

The remainder of the paper is organized as follows. The model of the system is described in Section 2. Sections 3 and 4 describe the motor speed feedback only and load speed feedback only cases, respectively. A control scheme that utilizes both motor and load speed feedback is discussed in Section 5. An add-on adaptive feedforward compensation to reject load speed disturbances is discussed in Section 6. Section 7 provides a description of the experimental platform and a comparison of the results with the various control schemes. Conclusions are given in Section 8.

2. Model of the system

A schematic of the belt–pulley and gear transmission system connecting the motor with the load is shown in Fig. 1. In the schematic, J_i denote the inertias, b_i denote the viscous friction coefficients, R_i denote the radii of the pulleys and gears, θ_i denote the angular displacements of the inertias, τ_m denotes the motor torque, τ_L denotes the torque disturbance on the load, and K_b denotes the stiffness of the belt.

To derive the governing equations for this system we consider the action of the belt in transmitting power. For a given direction of rotation of the pulley, the belt has a *tight side* and a *slack side* as shown in Fig. 1. It is assumed that the transmission of power is taking place on the tight side and the transport of the belt is taking place on the slack side. Under this assumption, the net change in tension on the slack side will be much smaller than that in the tight side and thus may be ignored. The tight side of the belt can then be modeled as a spring with spring constant of K_b. For given angular displacements θ_m and θ_L, the net elongation of the tight side of the belt can be written as $(R_1\theta_m - G_R R_2\theta_L)$. Because of this elongation, the driving pulley experiences a torque of $(R_1\theta_m - G_R R_2\theta_L)K_b R_1$ and the driven pulley experiences a torque of $(R_1\theta_m - G_R R_2\theta_L)G_R R_2 K_b$. Under the assumption that the inertias of the pulleys and gears are much smaller than the motor and the load, the governing equations of motion for the motor-side inertia and the load-side inertia are given by

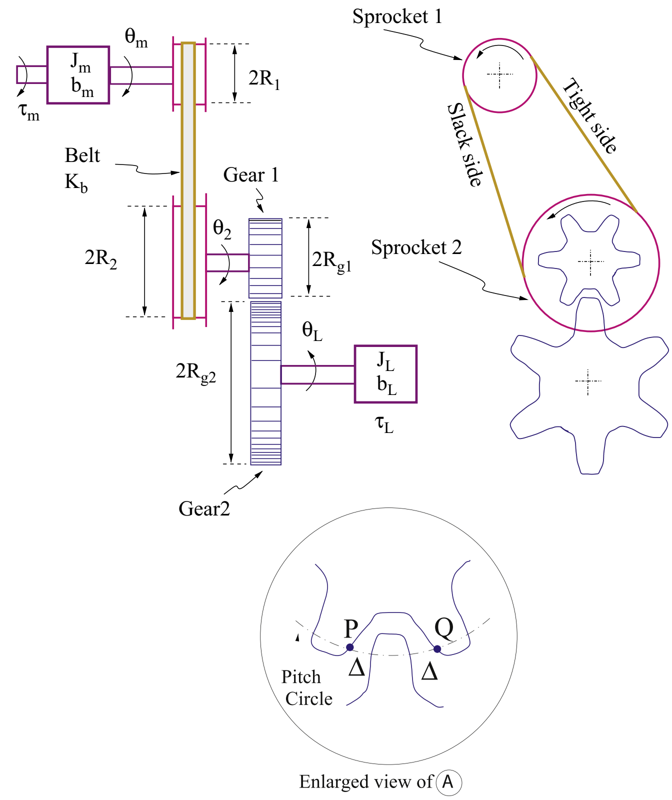

Fig. 1. Schematic of a belt–pulley and gear-pair transmission system.

$$J_m\ddot{\theta}_m + b_m\dot{\theta}_m + R_1K_b(R_1\theta_m - G_RR_2\theta_L) = \tau_m, \tag{1a}$$

$$J_L\ddot{\theta}_L + b_L\dot{\theta}_L - G_RR_2K_b(R_1\theta_m - G_RR_2\theta_L) = \tau_L. \tag{1b}$$

A block diagram representation of the system given by (1) is provided in Fig. 2; note that this block diagram represents the open-loop system and the two “loops” appearing in the block diagram that represent the interconnections in (1). The open-loop transfer functions from the motor torque signal τ_m to the motor speed ω_m and load speed ω_L are given by

$$G_{\tau_m\omega_m}(s) \triangleq \frac{\omega_m(s)}{\tau_m(s)} = \frac{J_Ls^2 + b_Ls + G_R^2R_2^2K_b}{D(s)}, \tag{2a}$$

$$G_{\tau_m\omega_m}(s) \triangleq \frac{\omega_L(s)}{\tau_m(s)} = \frac{G_RR_1R_2K_b}{D(s)}, \tag{2b}$$

where

$$D(s) = J_mJ_Ls^3 + (b_LJ_m + J_Lb_m)s^2 + \left(K_bJ_{eq} + b_mb_L\right)s + K_bb_{eq}, \tag{3a}$$

$$J_{eq} = G_R^2R_2^2J_m + R_1^2J_L, \tag{3b}$$

$$b_{eq} = G_R^2R_2^2b_m + R_1^2b_L. \tag{3c}$$