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Physics-based modeling of a chain continuously variable transmission

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ABSTRACT

This paper focuses on a physics-based model of a chain CVT. The study starts from kinematics of an infinitely small chain segment, and then investigates the fundamental dynamics of the chain segment. A speed-dependent continuous friction model is employed that accounts for both micro-slip and macro-slip conditions. Pulley axial dynamics is studied and is coupled with chain segment radial movement. The classical pulley deformation (Sattler's model) is included in the model. Simulation results show that pulley deformation plays an important role in defining the chain CVT dynamics. Unlike a rigid pulley, sliding angle with a deformable pulley is not a constant. Internal forces like chain tension and normal contact force are not monotonic function of angular position within the wrap. The simulation results compare well, qualitatively and quantitatively, with data published in literature and clamp force ratio (KpKs) values from dynamometer testing.

1. Introduction

Continuously variable transmission (CVT) is widely accepted as an efficient powertrain solution because it enables an engine to run more optimally. There are two major types of CVTs: push belt and pull chain. While a push belt CVT delivers smooth riding, its torque capacity is in general limited. Pull chain CVTs can be designed for high torque applications. A large amount of research work is done using a hybrid approach combining analytical and experimental study [1–3]. For example, Ide et al. [1] studied effect of ratio changing speed of metal belt CVT on vehicle response. They developed a well-known KpKs (clamp force ratio) contour map and ratio changing dynamics. Srnik and Pfeiffer [4] developed a multi-body dynamics model to study chain CVT. Good results using multi-body dynamics model of push belt CVT have also been published recently [5,6]. The first attempt of a physics based model, to the best of our knowledge, was from Carbone et al. [7–11]. They developed a CMM model and studied several key dynamic features of the CVT. Pennestri et al. [12] developed a theoretical model to study CVT transient dynamics. More recently, Srivastava and Haque [13], and later Bhate and Srivastava [14,15] did similar modeling to study transient ratio changing behavior.

However, chain deformation and pulley axial dynamics is usually not considered in previous researches [7–11,13–15]. Further, a constant friction coefficient was typically assumed although previous study has indicated otherwise [16]. This study not only considers rotational dynamics of chain and pulley, but also pulley axial dynamics. The rotational and axial dynamics are coupled as in a physical system. Chain deformation, although assumed small, is used to calculate the tension force at tight span, and as another coupling element between driving and driven pulley.

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2. Chain as a continuous body

In this study, we assumed a chain as a continuous body. By doing that, the model cannot capture the polygonal effect. As the chain pitch becomes ever smaller, this assumption should be reasonable, especially because high frequency speed oscillation is not within the scope of this study. In addition, we made the following assumptions:

1) Chain elastic deformation is small and concentrated on tight span, which is the lower span in Fig. 1 when both driving and driven pulley rotate clockwise.
2) Tight span tension force is identical for driving entry and driven exit.
3) Chain acceleration could result in tension force difference on slack span.

The continuous chain is schematically shown in Fig. 1. Here, R_1 and R_2 are nominal pitch radius; ε is the chain angle; d_c is the center distance of two pulleys; α_1 and α_2 represent the wrap angles of driving and driven pulley; θ_{10} and θ_{20} are the initial angular position of chain element on driving and driven pulley; K_{chain} and C_{chain} are the chain elasticity and damping term; T_0 is the tension force at tight span; and $T_{\alpha 1}$, $T_{\alpha 2}$ represents the slack span tension force respectively. Geometric constraints define the following relationships:

$$\sin\varepsilon = \frac{R_2 - R_1}{d_c} \quad (1)$$

$$\alpha_1 = \pi - 2\varepsilon, \quad \alpha_2 = \pi + 2\varepsilon. \quad (2a–b)$$

The chain length L is calculated by,

$$L = R_1\alpha_1 + R_2\alpha_2 + 2d_c\cos\varepsilon \quad (3)$$

Since all elastic deformation is lumped at the tight span, we have:

$$T_0 = (L - L_{ini})K_{chain} + C_{chain}\dot{L} \quad (4)$$

Here L_{ini} is the initial chain length. If we assume $d_c \gg R_2 - R_1$, we can approximately define $\dot{L}$ as,

$$\dot{L} = \dot{R}_1\alpha_1 + \dot{R}_2\alpha_2 \quad (5)$$

At this point, given R_1, R_2, L_{ini}, d_c, K_{chain} and C_{chain} together with specified initial $\dot{R}_1$ and $\dot{R}_2$, the initial T_0 can be calculated straightforwardly from Eqs. (1)–(5). Further, we physically couple input and output pulley through the chain tension force. At tight span, we assume chain speed is identical at driving and driven side where $\dot{\theta}_{10}$ should also be specified as an initial condition.

$$\dot{\theta}_{10}R_1 = \dot{\theta}_{20}R_2 \quad (6)$$

At slack span, the tension force discrepancy could accelerate chain,

$$T_{\alpha 2} - T_{\alpha 1} = \sigma_e L_{ini}\dot{v} \quad (7)$$

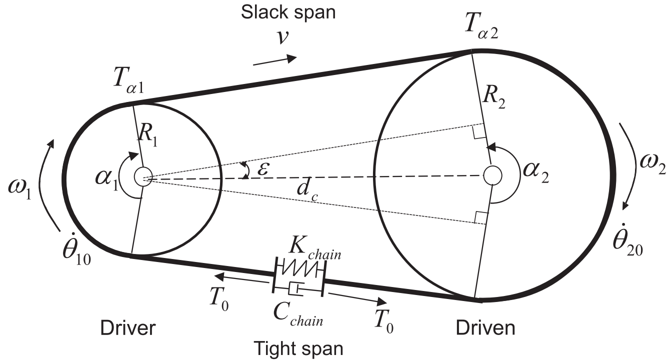

Fig. 1. CVT chain as a continuous body.