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Modeling chain continuously variable transmission for direct implementation in transmission control

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ABSTRACT

Continuously variable transmissions (CVT) have been widely used in many different areas such as automotive, robotics, manufacturing and aerospace industry. In CVT drives, a properly designed control strategy is needed to ensure the precise control of the speed ratio, and a deep knowledge of the steady-state and transient behavior of the drive is necessary to this purpose. In the framework of belt and chain CVT drives, model-based approaches developed for this purpose are mainly of two types: continuous models and multibody models. Continuous models are much less costly from a computation point of view, while multibody models are usually believed to be more accurate. The aim of this paper is twofold: first the CMM continuum model [Carbone G., Mangialardi L., Mantriota G., ASME Journal of Mechanical Design, **127**, 103–113 (2005)] is compared with a multibody model of the chain-CVT variator. Secondly, the CMM model is proposed for a fast and enhanced characterization of the shifting dynamics of chain CVT. The analysis shows that, except for dynamical effects due to the intermittent contact of the chain pins with the pulleys and caused by the polygonal action of the chain, the CMM and multibody models provide very similar results. Moreover, this study shows, by exploiting the CMM model, that the overall dynamics of the CVT can be described by a relatively simple first order nonlinear differential equation, which can be very easily implemented for CVT real-time control applications. The accuracy of such a simplified approach is then tested against some preliminary shifting experiments under torque load conditions. Results show a very good agreement between theoretical predictions and experimental outcomes, thus making this simplified approach a promising tool to develop advanced real-time control of CVT transmissions for automotive applications.

1. Introduction

Continuously variable transmissions have been widely used in many different areas such as aerospace, robotics, machinery and automotive industries as an alternative to conventional speed changers with constant ratios. This is due to the fact that these systems benefit from advantages such as smoothness of operations, infinite range of gear ratio, easy drivability, powerful acceleration and quiet working. In the automotive industry, these systems have been used increasingly since they enable engines to run at optimal speeds, thus providing considerable fuel savings and therefore lower emission values [1–3] or optimized energy consumption in electric vehicles [4], also improving the drive comfort. CVT transmission can be successfully employed in

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hybrid vehicles as well, where split-path transmissions are employed to manage the power flows between the thermal engine and electric machines, or in hybrid mechanical systems, where a seamless speed variator is used to manage the power flow to and from a high-speed rotating flywheel [5–7]. Moreover, CVT variators are gaining an increasing interest for large power applications, like windmills [8–12], trucks [13], variable speed machinery for manufactory [14,15].

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The control and efficiency are key issues for the success of chain and belt CVTs and therefore a great deal of research has been dedicated to investigate both theoretically and experimentally the mechanical behavior and, in particular, the slip, traction, efficiency and shifting of the variator [16-35,37] . Over the years, two main approaches have been developed to theoretically investigate CVT dynamics. One is based on continuum mechanics [31,32], and recently has led to the development of the so called CMM model of the chain CVT (the acronym CMM originates from the names of the researchers who proposed the model for the first time: Carbone, Mangialardi and Mantriota [33,38]). The second one is based on multibody or combined multibody-finite element techniques [30,35,39-41]. The steady-state and shifting behaviors of the variator have been examined in Refs. [31,33], where it has been shown that, in steady state, the pressure and tension distributions of the belt are not affected by the magnitude of the pulley deformation but only depend upon the value of the force ratio. Moreover, in Ref. [33] the authors have shown that the dynamic behavior of the transmission during slow shifting maneuvers, referred to as “creep mode” is caused by the deflection of the pulleys, which also implies that in the case of rigid pulleys and no-clearance between the pulley and its shaft “creep mode” cannot be observed at all. In Ref. [23], the authors compare the theoretical predictions of the so-called CMM model with the experimental results and a very good agreement between theory and experiments has been found, both in steady-state and during shifting maneuvers. Although some investigations have focused on the dynamical behavior of CVT transmissions [23,33], research is still lacking of studies focusing on the shifting dynamics of CVT under load conditions, which is the real working condition of the transmission.

In this paper the authors first compare two different theoretical techniques (multibody and continuum CMM approaches) in terms of predicted traction, slip performance, chain force and velocity distributions. As multibody models are usually considered to be more accurate (since they more realistically reflect the real geometry of the transmission), the first part of the paper is aimed at pointing out the main similarities and/or differences between the two approaches. The second part of the paper, instead, exploits the CMM model to fully characterize the shifting non-linear behavior of the variator. A very first comparison of the shifting dynamics, under load conditions, between experimental outcomes and theoretical results is also shown.

2. A brief review of the CMM model

The CMM model treats the chain as a one-dimensional continuum body having a locally rigid motion. Once neglected the longitudinal elongation of the chain, the mass conservation law yields:

$$v_r + \frac{\partial v_\theta}{\partial \theta} = 0 \tag{1}$$

where v_r and v_θ are respectively the radial and tangential sliding velocities of the chain (see Fig. 1). In the original version of the CMM model [33], Sattler's sinusoidal approximation of the pulley elastic deflection [43] is employed to calculate the deformed half-groove angle β as a function of the local angular coordinate θ

$$\beta - \beta_0 = 0.5\Delta \sin(\theta - \theta_c + \pi/2) \tag{2}$$

where β_0 is the undeformed half-groove angle. In the latter version of the CMM model [36] a modified Sattler formula is proposed, which also takes into account a uniform deformation Γ of the pulley:

$$\beta - \beta_0 = \Gamma + 0.5\Delta \sin(\theta - \theta_c + \pi/2) \tag{3}$$

which allows to calculate correctly the deformed value of the groove angle. This allows to calculate the local radial velocity of the belt as [33]:

$$v_r = \dot{R} + a\Delta\omega R \sin(\theta - \theta_c) \tag{4}$$