

Dynamic Performance of a Metal V-belt CVT during Rapid Shift-ratio Conditions for Control Applications

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ABSTRACT

This paper presents a detailed continuous one-dimensional transient-dynamic model of a metal V-belt continuously variable transmission (CVT) for control applications. The simulation model developed captures the power transmission characteristics and inertial dynamics of a metal pushing V-belt CVT. The torque transmitting mechanism of a metal V-belt CVT under the conditions of high load torque, constant driven pulley axial force and a constant driver pulley input torque was studied. The results discuss the performance of a metal V-belt CVT system model under transient and steady state operating conditions. The model proposed in this work expounds a relationship between the transmission ratio change and pulley actuation force, which will serve as a powerful tool for the development of fast and reliable CVT controllers to meet the objectives of reduced losses, higher torque capacity, higher vehicle fuel economy and better acceleration performance.

INTRODUCTION

In keeping with the recent global trend of environmental awareness and emission control, automobile manufacturers have become increasingly aware of the need to make modern vehicles more efficient, cost effective and sustainable. Improvement of pre-existing drive-train technologies is a critical first step towards cleaner and more energy efficient vehicles. One such promising concept is the Continuously Variable Transmission (CVT), which enhances the fuel economy and acceleration performance of a vehicle by better matching the engine operating conditions to the variable driving scenarios. CVTs are being actively pursued as

an alternative to conventional transmissions due to the advantages of better fuel efficiency (3-5% increase [13]), and continuous smooth acceleration. Although the CVT offers distinct advantages over conventional automatic transmissions its complete potential has not been achieved in a mass production vehicle.

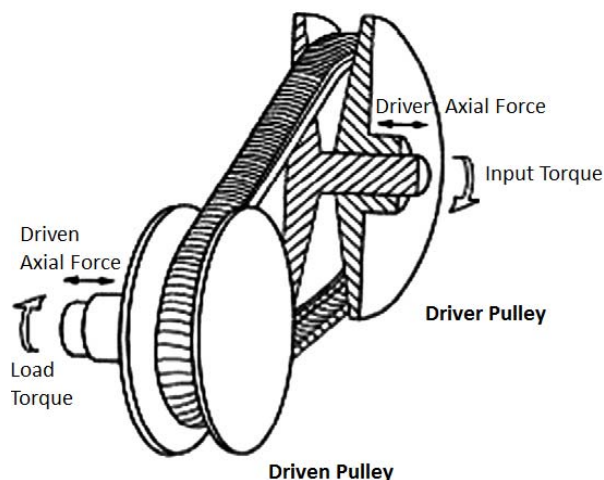


Figure 1 – CVT configuration [10]

The CVT being a nonlinear mechanism is capable of exhibiting varied behavior under different operating conditions. The model presented in this paper outlines a detailed continuous one-dimensional transient-dynamic model of a metal V-belt CVT valid for both transient and steady state operating conditions. A comprehensive equation is derived which reveals an insightful relationship between the transmission ratio of the system and the axial force on the driver pulley and can be further utilized to design fast and reliable transmission ratio shifting strategies.

A basic CVT system comprises of two variable diameter pulleys connected by a metal V-belt which transmits power. Figure 1 shows the schematic of a basic CVT system. By exerting an axial force on the movable pulley sheave, the belt pitch radius on either pulley can be continuously varied. A continuous band of transmission ratios is obtained between fixed limits dictated by the maximum and minimum belt pitch radius attainable on the pulleys.

Torque is transmitted from the pulley on the engine side (i.e. driver pulley) to the pulley on the final drive side (i.e. driven pulley) by means of a metal pushing V-belt. Figure 2 shows the belt structure of a metal pushing V-belt. The metal V-belt consists of approximately 300-400 metal elements which are held in place by two continuous multilayered bands. Compressive force in the belt elements and tensile force in the band pack aids in torque transmission.

Different aspects of the CVT including dynamic performance, loss mechanisms, operating regimes, slip behavior and friction characteristic, vibrations etc have been researched over the past couple decades. Most of the existing models, apart from some exceptions are steady state models based on the principle of quasi-static equilibrium [1-3].

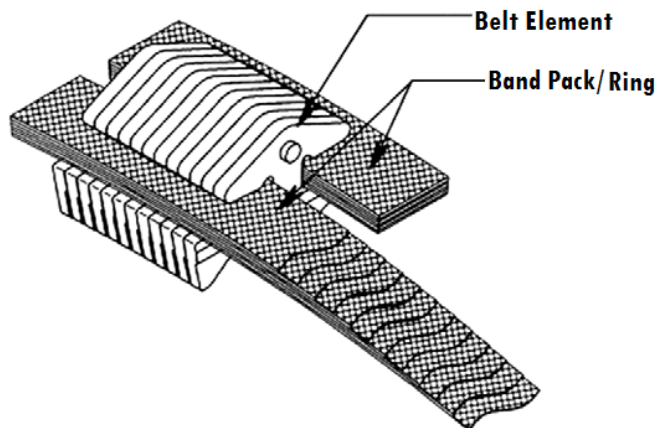


Figure 2 – V-belt structure [10]

Steady state models fail to accurately capture the inertial effects of the belt. A model to study the CVT transient dynamics during gear ratio shifting was developed by Carbone et al [4]. Non-dimensional equations were defined to theoretically determine the dynamic response of the system. Inertial coupling between the belt and the pulley during transient state was not modeled adequately. Later the influence of pulley deformation was studied by Carbone et al [5] on the shifting mechanism of metal V-belt CVT. Pulley deformation was described by sinusoidal function. The behavior of the CVT under slow and fast shifting maneuvers was studied. Pulley bending was modeled based on Sattler's model. Fujii et al [6] and Kitagawa et al [7] investigated the belt element compression force and band tensile force in metal V-belt CVT. The contribution to torque transmission of the element compression and band tension was experimentally studied. Srivastava et al [8,9] developed a detailed transient dynamic model of a metal pushing V-belt CVT to investigate the dynamic

interactions occurring between at the belt element-band interface and the element-pulley interface of a CVT system. The effect of pulley deformation, friction characteristic at the belt-pulley interface was modeled. Genetic algorithm was also used to capture a set of specific initial conditions under transient operation in order to successfully meet the load conditions [14]. Later Bhate et al [12] developed a transient-dynamic model for control applications and the performance of the CVT was analyzed. A relation between the rate of change of radius and axial force was developed under the constraint of constant driver pulley speed. Slip between the band pack and belt element and pulley bending was ignored. The work in this paper is an extension of [12], subject to a change in the operating criterion of the CVT system and the results of the model simulation.

NOMENCLATURE

F_z	Pulley axial force
F	Normal force between band pack and the element
I	Pulley rotational inertia
N	Normal force between the pulley and the element
Q	Compressive force in the belt element
r	Pulley radius
T	Tensile force of the band pack
v	Slip parameter
α	Wrap angle
β	Half sheave angle of the pulley
β_s	Pulley half-sheave angle in the sliding plane
θ	Element angular location on the pulley wrap
μ_a	Coefficient of friction between the element and the band pack
μ_b	Coefficient of friction between the element and the pulley
σ_b	Linear mass density of band pack
σ_e	Linear mass density of belt element
τ_{id}	Driver input torque
τ_{in}	Driven load torque
φ	Slope angle of the belt element
ψ	Sliding angle of the belt
ω	Angular speed of the pulley
d	Centre distance between driver and driven pulley
ξ	Slip angle

SYSTEM MODELING

The CVT model presented in this paper is an extended modification of the work done by Bhate et al [12]. The CVT system is subject to a constant input torque at the driver pulley, constant driven pulley actuation force and a constant load torque on the driven side. The model development and analysis includes the following assumptions.

- Belt elements and bands are inextensible, continuous and belt length is constant
- Bending and torsional stiffness of the belt is neglected
- The offset in the band and the belt element pitch radius is neglected (an approximation based on the observations of Srivastava et al. [9])
- Pulley deformation effects are neglected (reasonable assumption for control applications)
- The friction coefficient between the belt and the pulley remains constant

The CVT model developed predicts the behavior of the system independent of the belt element position; it is not limited to one cycle of the belt element. As illustrated in Figure 3, let the points P , Q , R and S represent the entry and exit points to the driver and driven pulley.

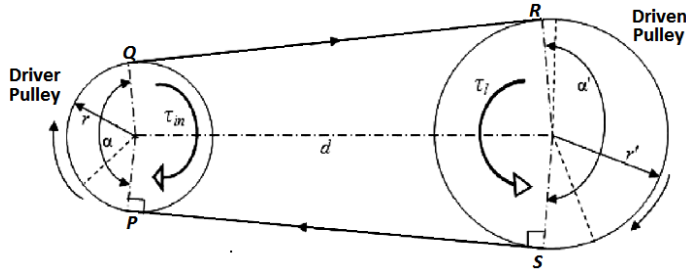


Figure 3 – Belt drive geometric description

To ensure continuity of the simulation when the belt element exits a pulley, the magnitude of band tension and belt element compression at the point of entry of the pulley are required to continue the simulation. In this model it is assumed that the values of these parameters are equal to those of the belt element exiting the preceding pulley at that instant, i.e. if the belt element exits at Q it is assumed that the band tension and belt element compression at P are equal to those at S . This assumption is reasonable given that the free section of the V-belt does not contribute significantly to the inertial dynamics of the CVT system. When the belt pitch radius attains maximum permissible value, the transmission ratio remains constant and any subsequent change can occur only with a change in the operating conditions. Figure 4 is the kinematic description of the belt [4],[8]. The plane ADE (refer 3D view, (a)) represents the actual sliding plane of the belt. $\hat{\theta}$ is the belt speed ($\hat{\theta} = \nu\omega$), ν is the belt slip parameter. $\nu > 1$ implies that belt moves faster than the pulley. ω_s denotes the local sliding velocity of the belt, ($\omega_s = \hat{\theta} - \omega$). β is the pulley wedging angle, whereas β_s is the wedging angle in the sliding plane. The plane of rotation is ABE. The sliding angle of the belt is denoted by ψ . The pulley movable

sheave moves only in the axial direction (e_z) however the effects due to pulley deformation and sheave translation inertia are not accounted for in this model. The kinematic description involves two coordinate systems (refer 2D view, (b)); (n, τ) attached to the belt and describes its path (ρ is the radius of curvature of the belt element) and (e_r, e_θ, e_z) which is a rotating coordinate system attached to the centre of the pulley O . The centre of curvature of the belt path changes with time and is labeled C .

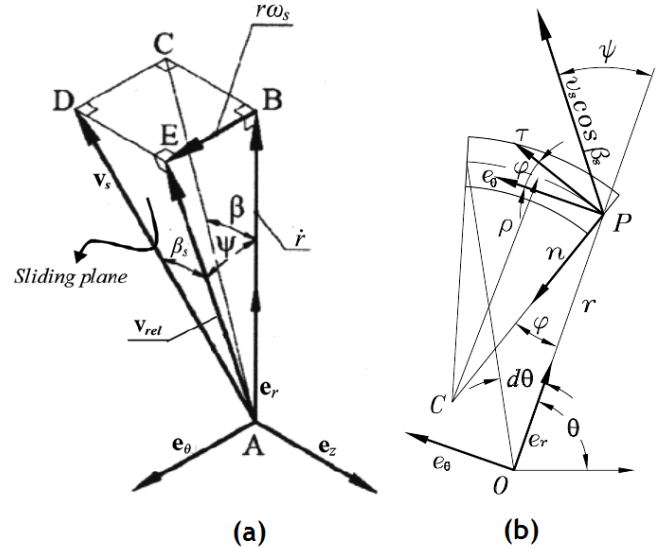


Figure 4 – Kinematic description of the belt [4],[8]

The following equations could be readily obtained from the kinematic description of the belt,

$$\tan\beta_s = \tan\beta \cos\psi \quad (1)$$

$$\tan\psi = \frac{r\omega_s}{\dot{r}} \quad (2)$$

$$\tan\varphi \approx \varphi \approx \frac{\dot{r}}{r\dot{\theta}} \quad (3)$$

Figure 5 and Figure 6 [12] depict the forces acting on the driver band pack and the belt element respectively. Summing the forces in the normal and tangential directions yields equations that describe the dynamic interaction between the belt (both band and element) and pulley.

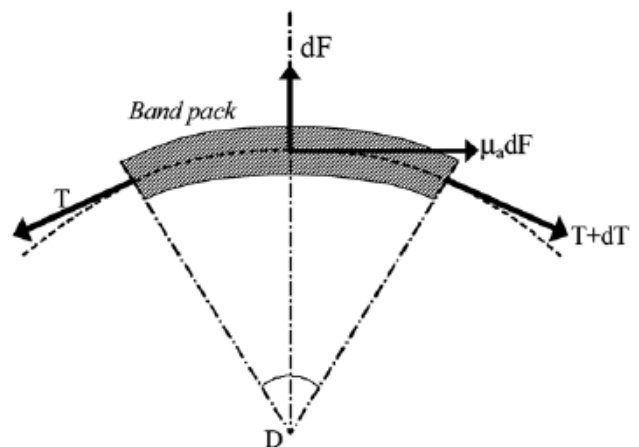


Figure 5 – FBD of driver band pack [9]