CONTINUOUSLY VARIABLE TRANSMISSIONS: PROGRESS AND CHALLENGES FROM THE LAST YEARS

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Abstract: *Interest in continuously variable transmissions (CVTs) has grown considerably in the context of increasingly stringent requirements for energy efficiency and emissions reduction. This article reviews recent research on conventional and unconventional CVTs, focusing on technological developments and current directions for development. It structures recent technical literature on the latest analytical models developed, control strategies implemented, and numerical methods used to simulate the behavior of these transmissions. The paper compares the reported performance and efficiency of CVT systems, including especially hybrid and electric vehicles, highlighting design solutions, design methods, and good experimental testing practices. The main contribution consists of the systematic organization of specialized literature and the highlighting of the technological trends that define the evolution of continuously variable transmissions.*

Keywords: *review, CVT, eCVT, AMT, transmission structure, FEM, efficiency*

1. Introduction

Continuously variable transmissions (CVTs) are increasingly used in modern vehicle construction, particularly due to their ability to continuously change the transmission ratio and allow the internal combustion engine to be maintained at its optimum operating range [1-2].

The works [1], [3-6] highlight the fact that CVTs contribute to reducing fuel consumption by up to 20% compared to automatic transmissions with step transmission of the transmission ratio.

1.1 Energy context, efficiency, and electrification

According to [2], [7-9], international pressure to reduce pollutant emissions has led to intensified research into high-efficiency transmissions. In these studies, CVTs are identified as promising solutions for optimizing energy performance in vehicles equipped with internal combustion engines, as well as in hybrid or fully electric powertrains. Although most production electric vehicles use single-ratio transmissions, studies such as [10-11] show that the use of an electromechanical continuously variable transmission (EM-CVT) can lead to a reduction in energy consumption of up to 22% over the entire WLTC cycle.

1.2 Structure of conventional and unconventional CVTs

CVT transmissions can be classified into two broad categories: conventional, equipped with a belt or metal chain, and unconventional, which can be compliant, toroidal, or hydrostatic.

CVTs with chains or metal belts are the most common in current applications due to their durability and high efficiency according to [1], [12].

Conventional CVT transmissions are based on the transmission of torque and rotational movement through friction between the pulley and the connecting element, or through contact pressure between the belt or chain elements. Both types use two conical pulleys, each consisting of two half-pulleys, one fixed and one movable, ensuring a progressive change in the wrap diameter and, with it, the transmission ratio [1], [12]. According to the information in [1], [4], [13], the chain CVT transmission offers superior efficiency due to reduced slippage between the contact elements, while the metal belt CVT ensures quieter operation but induces slightly higher mechanical losses. Figure 1 shows a comparison between the elements of these two types of transmissions, highlighting the structure of the connecting element between the pulleys.

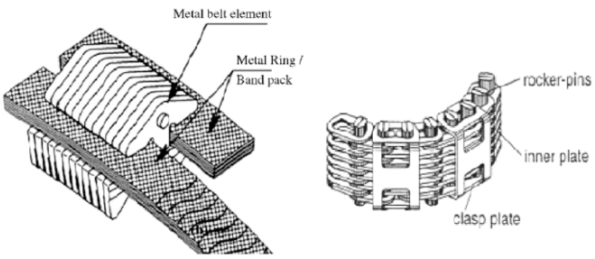

Figure 1 – *CVT* structure [14]

Although conventional systems seem to dominate the current market, the last decade has seen a significant increase in interest in unconventional CVT transmission solutions. Among the important areas of research in this direction are toroidal variators, whose basic structure is shown in Figure 2. In these, power transfer takes place through spherical, or disc-type contact elements arranged between two toroidal or semi-toroidal surfaces, and power transmission occurs through the shearing of the lubricant film at the interface.

Studies [3] and [13] highlight that this type of transmission can provide high power density but is limited by friction losses and high manufacturing costs.

Another type of unconventional transmission is one in which the transmission ratio variation is achieved by controlled elastic deformation of twisted beams, as shown in Figure 3.

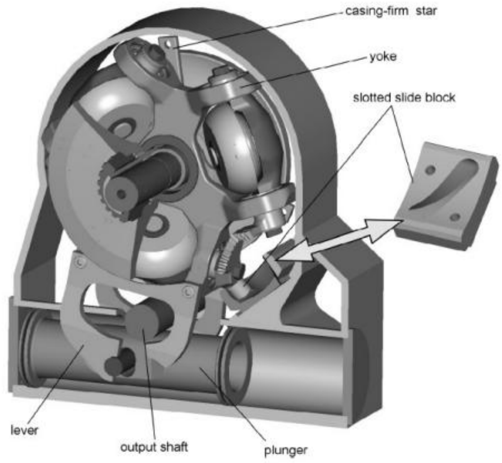

Figure 2 – *Toroidal transmissions structure* [15]

According to [8, 9], this solution promises an efficiency of over 90% and a much-simplified construction, representing an innovative direction in the field of continuously variable transmissions.

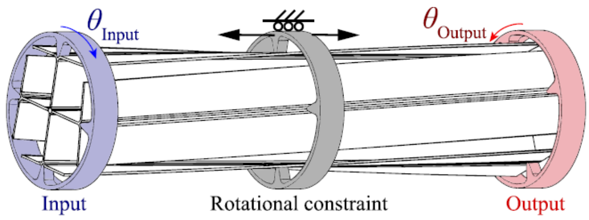

Figure 3 – *Compliant CVT structure [13]*

2. Analytical models and simulations for CVTs

Mathematical modeling of CVT transmissions is an essential tool for understanding the kinematic and dynamic behavior of the system, as well as for evaluating how design parameters influence overall efficiency.

According to studies [2], [11], [16-18], recent research has focused on developing advanced models that describe both the geometry and dynamics of the chain and the power flow distribution in power-split architectures. At the same time, more papers are addressing the elastic modeling of compliant transmissions, with the aim of highlighting the relationship between component deformability and system performance.

2.1 Analytical models

Analytical models are fundamental in continuously variable transmission (CVT) engineering to understand, predict, and optimize the kinematic, dynamic, and energetic behavior of these systems.

Thus, Giacomo Mantriota in [2] defines the kinematic performance of a Power-Split CVT architecture, which is a promising solution for hybrid electric vehicles (HEVs), using equation (1).

$$T_{gl} = \frac{\omega_0}{\omega_i} = \frac{\omega_2}{\omega_1} = \frac{T_{W1}T_{eCVT}(T_{W2}-1) - T_{W2}(T_{W1}-1)}{T_{eCVT}(T_{W2}-1) - (T_{W1}-1)} \quad (1)$$

Since power losses are predominantly located in the eCVT, Giacomo Mantriota proposes in [2] an equation (2) that quantifies the amount of power flowing through the CVT component (eCVT) of the system. This equation represents the ideal fraction of power passing through the eCVT (P_{eCVT}) relative to the total input power (P_i), ignoring losses.

$$\left\|\frac{P_{eCVT}}{P_i}\right\|_{ideal} = \frac{T_{eCVT}(T_{W2}-1)(T_{W1}-T_{W2})(1-T_{W1})}{(T_{eCVT}(T_{W2}-1)-(T_{W1}-1))} \cdot \frac{1}{(T_{W1}T_{eCVT}(T_{W2}-1)-T_{W2}(T_{W1}-1))} \quad (2)$$

Bing Fu, in [7], proposes an equation (3) that describes the dynamics of the slip rate (s) of a metal belt CVT transmission, which is fundamental for the development of control strategies aimed at optimizing efficiency by maintaining slip in the optimal region.

$$\frac{ds}{dt} = \frac{(1-s)n_{se}}{i_{se}^2}\left(\frac{T_L}{I_{se}} - \frac{2F_{se}R_{se\mu}}{I_{se}cos\alpha}\right) + \frac{1}{n_{se}i_0}\left(T_{em} - \frac{2F_{se}R_{se\mu}}{i_0 I_{pm}cos\alpha}\right) \quad (3)$$

For compliant CVTs, the torque ratio (4), according to Vlasov's theory [13], is:

$$\theta(x) = \frac{M_t}{GJ}x + \frac{M_t}{EI_\omega}\int_0^x \omega(x)dx \quad (4)$$

where M_t is the torsional moment, G is the shear modulus, J is the polar moment of inertia, and I_ω is the restricted torsion constant. This relationship describes the elastic behavior and local variation of the section's rotation angle.

2.2. Numerical Simulations CVT

The finite element method (FEM) is one of the most widely used approaches for analyzing the structural and vibrational behavior of CVT transmissions.

The papers [1-2], [16] use this method in programs such as ANSYS and LS-DYNA to evaluate stress distribution, pulley cone deformation, and chain dynamic behavior.

According to [16], the use of static simulations is less appropriate because they cannot capture the complex transient phenomena that occur during actual transmission operation.

In his article [19], Toshihiro Saito presents an FEA analysis (Figure 4) that highlights how stresses propagate through the main components of the CVT transmission, emphasizing the stress concentrations in the contact region of the metal belt with the drive pulley.

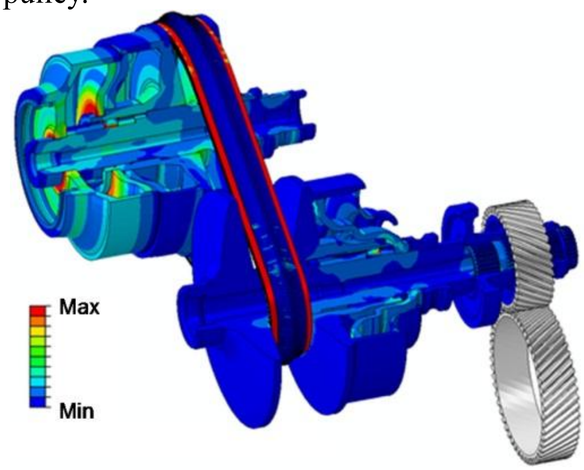

Figure 4 – *Stress distribution of Metal V-belt and pulleys [19]*

The results of the study [16] show that maximum deformation occurs in the outer edge of the pulley, increasing with the speed ratio. Also, the stress distribution varies significantly depending on the number of metal belt elements, influencing the stiffness and durability of the system.

For compliant CVTs, FEM simulations confirm a very good correlation with analytical models derived from Vlasov theory. The papers [12-13] used the ANSYS Parametric Design Language (APDL) to define 3D models that combine beam and shell elements, achieving a match of over 90% between the numerical and theoretical solutions. Multibody models applied to chain CVT transmissions provide an accurate representation of the geometry and interactions between connecting elements and pulleys. According to studies [1], [11], [17], these models are a valuable tool for investigating vibrations and noise generated during operation, but they require a high level of resources. To optimize computation time, in [17] is recommend continuum body models, which treat the chain as a continuous body, reducing the degree of freedom but with limitations in capturing the polygon effect.

Matlab/Simulink programs are also widely used to simulate CVT transmissions integrated into hybrid and electric powertrains. In studies [4] and [7], the authors developed longitudinal vehicle dynamics models in which they integrated both the dynamics of the electric motor and the behavior of the CVT transmission to analyze the interaction between traction control and the energy performance of the system. In the study conducted by Marcos R. C. Coimbra [4], a prototype CVT transmission with a 3D-printed conical friction wheel was developed and tested, experimentally demonstrating that the use of this type of CVT can reduce vehicle energy consumption by 10.46% compared to a fixed-ratio transmission.

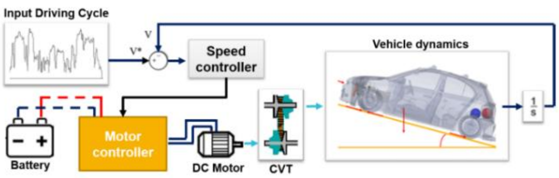

Figure 5 – *Matlab/Simulink simulation model of an EV system equipped with CVT [4]*

Figure 5 shows the computational simulation model of the electric vehicle (EV) prototype, implemented in the Matlab/Simulink environment, which is considered a longitudinal dynamic model and a continuously variable transmission (CVT).

Another study [7] proposes a fuzzy control strategy for adjusting the tension force of the secondary pulley, validated by integrated simulation (vehicle + engine + CVT). The results showed a 6.67% reduction in energy consumption over the NEDC cycle, confirming the efficiency of slip rate-based control.

3. Efficiency, Control, and Undesirable Phenomena in Modern CVTs

Controlling the clamping force and limiting slippage and vibration are key factors in transmission efficiency.
Studies like [7] and [20] show that the main losses in CVTs come from hydraulic pump consumption and excessive friction in contact areas.

3.1. Clamping Force Control Strategies

The papers [7], [11] and [20] show that the traditional approach, based on applying a fixed safety factor, leads to excessive clamping force and, implicitly, to a decrease in overall efficiency. Bing Fu, in his article, highlights that adaptive fuzzy control, dependent on the slip rate, can dynamically adjust the contact pressure, improving the performance of CVT systems. Simulation results from [7] and [21-22] indicate a reduction in clamping force between 12.8% and 21.6% and an increase in average mechanical efficiency of 3.7%.

Figure 6 illustrates how the efficiency of a CVT varies depending on the slip rate for different torque values, as used in the conceptual modeling of a fuzzy control of the clamping force, according to the study by Bing Fu (2022).

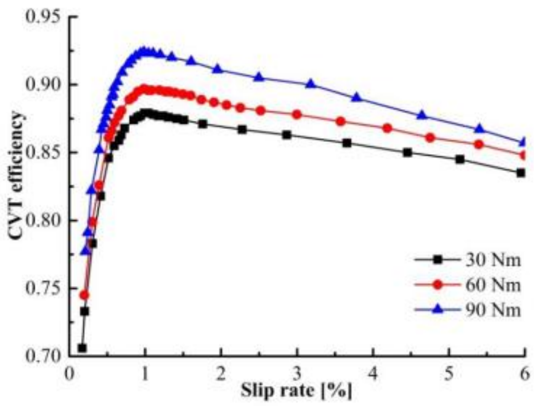

Figure 6 - *Conceptual diagram of fuzzy control of clamping force in CVT [7]*

3.2. Energy Comparisons between CVT and AMT

CVT and AMT (Automated Manual Transmission) transmissions are different design solutions, each with specific advantages.

In [10-11], comparative simulations were performed on FCHEV (Fuel Cell Hybrid Electric Vehicle) hybrid vehicles, showing a 2.5–4% reduction in fuel consumption and a 3.6–5% improvement in energy efficiency for CVT transmissions, especially in urban driving conditions. However, AMT transmissions have slightly higher mechanical efficiency due to lower friction losses.

Study [10] showed that CVT is 11.6% slower at 0–30 km/h acceleration and consumes 19.4% more energy at low speeds due to slippage and hydraulic system inertia. In the case of the electro-mechanical CVT (EMCVT), the paper [11] indicates the elimination of losses due to the hydraulic pump and an increase in overall efficiency of up to 10%. On the WLTC cycle, energy consumption decreases by 22.4% compared to a single transmission ratio, demonstrating the advantage of using CVT in modern electric vehicles.

3.3. Vibration and Noise in Chain CVTs

For CVT-type electro-mechanical transmissions (EMCVT), studies [11] and [23-24] highlight the elimination of losses associated with the hydraulic pump, leading to an efficiency increase of approximately 10%. Simulations performed on the WLTC cycle show a reduction in energy consumption of up to 22.4% compared to a conventional single-speed transmission, highlighting the potential of CVT systems to improve the energy performance of modern vehicles.

Figure 7 is a schematic diagram showing the action of the chain when it enters a sprocket. A phenomenon called the polygonal effect occurs because the chain has a finite pitch l_p. As a result, chain vibration occurs. The vibration value is defined as the displacement z.

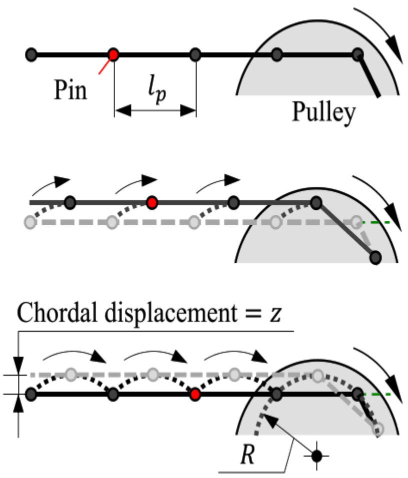

Figure 7 - *Polygonal effect of chain movement in a CVT transmission [1]*

According to studies [1] and [10], the geometry of fasteners directly influences the amplitude of vibrations in chain CVT transmissions. Analyses based on multibody and geometric models have shown that optimized bolt profiles, compared to involute ones, contribute to reducing chain noise and vibrations, especially at extreme transmission ratios (below 0.5 and above 2.0). These studies highlight the importance of optimizing chain geometry and contact pressure to improve acoustic comfort and transmission efficiency.

4. Implementation, Test Benches, and Development Directions

4.1. Design and Use of Test Benches

Test benches are essential tools for validating analytical and numerical models. The papers [12] and [25-26] present various test bench configurations for CVT transmissions, designed to measure pulley pressure, clamping force, and mechanical efficiency.

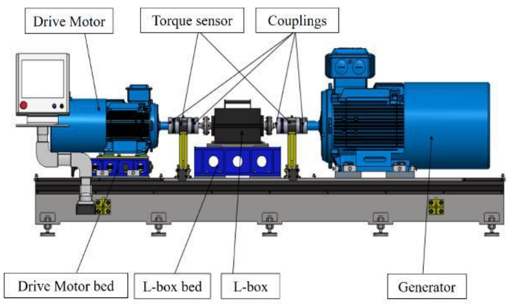

Figure 8 – *Mechanical design of the CVT test bench [12]*

The modern benches can reproduce variable loads ranging from 2 to 6 kW, allowing for accurate assessment of transmission efficiency and slip rate as a function of speed and torque variation. This configuration provided a detailed characterization of transmission performance under controlled conditions. Advanced devices include sensors for simultaneous measurement of the pitch and yaw angles of metal elements, according to [26], highlighting their correlation with contact pressure and torque transmission.

4.2. CVT manufacturing

Recent advances in additive manufacturing (AM) have accelerated the development of unconventional transmissions. Papers [4], [27-29] demonstrates the manufacture of a conical polymer pulley using 3D printing, which resulted in a 12% reduction in mass without compromising mechanical strength. This approach allows for the optimization of the vehicle's total mass and, implicitly, a reduction in energy consumption. Papers [11], [30-31] describes an electro-mechanical transmission (EMCVT) in which the transmission ratio is varied by means of a screw mechanism: an electric motor drives a screw that acts as an actuator, and the axial displacement of the nut causes the mobile flanges of the pulley to move closer together or further apart. In this way, the effective running diameter of the belt is changed without the use of a hydraulic system. The tension force is maintained by disc springs, which provide the necessary pressure and allow precise control of operation in dynamic modes, contributing to high efficiency of the assembly.

4.3. Development Directions for CVT Transmissions

Continuously variable transmissions (CVTs) are an area of research undergoing continuous development, supported by recent advances in the fields of automatic control, additive manufacturing, and numerical simulation. Analysis of the literature reveals a clear trend towards optimizing energy efficiency, reducing mechanical losses and improving clamping force control strategies. The implementation of fuzzy algorithms, the integration of electric oil pumps (EOP), and the use of advanced numerical methods (FEM, multibody, Matlab/Simulink) have contributed significantly to increasing the performance and predictability of modern transmissions.

Compliant and electro-mechanical CVTs (EMCVTs) emerge as promising solutions, offering an optimal balance between efficiency, compactness, and reliability. However, current challenges remain related to reducing chain noise and vibration, optimizing dynamic clamping force control, and extending the service life of components subject to cyclic stresses.

5. Conclusions

This paper aims to investigate recent advances in continuously variable transmissions, with a focus on applications dedicated to internal combustion engine vehicles. The results of research aimed at improving energy efficiency, reducing mechanical losses, and refining control strategies to increase the performance and reliability of these systems are presented and discussed. By correlating theoretical and experimental data, the article provides an integrated view of the evolution of CVT technologies and current development trends aimed at optimizing continuously variable transmissions. The main contribution consists of bringing together and interpreting these results in a unified framework that supports both the understanding of operating mechanisms and the identification of innovative solutions for future applications.

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