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Research paper

Study on the transmission efficiency of electro-mechanical continuously variable transmission with adjustable clamping force

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ABSTRACT

The purpose of this study is to analyze the EMCVT transmission efficiency. Power loss of a continuously variable transmission (CVT) consists of the energy consumed by an actuator and frictional energy loss in a CVT variator. The objective of studying electro-mechanical continuously variable transmission (EMCVT) is reducing the energy consumed by a CVT actuator. However, power loss resulting from frictional loss may increase owing to increases in the driven pulley clamping force. And then a simplified transmission efficiency model of an EMCVT was established to analyze the energy consumed by an electro-mechanical actuator and frictional energy loss. Under ECE (Economic Commission for Europe) and EUDC (Extra Urban Driving Cycle) driving cycles, the energy consumed by an EMCVT is compared with that consumed by an electro-hydraulic CVT (EHCVT). Comparison results indicate that the EMCVT transmission efficiency is lower than that of an EHCVT. Thus, an EMCVT with two actuator motors is proposed to reduce the frictional energy loss in the variator. Simulation results indicate that the transmission efficiency of the proposed EMCVT exceeds that of an EHCVT. The frictional energy loss is reduced by controlling the driven pulley clamping force, and this improves the EMCVT transmission efficiency.

1. Introduction

Transmission efficiency is one of the most important performance indicators that is used to describe the quality of vehicle transmission. Continuously variable transmissions (CVTs) are widely used in modern vehicles. However, the transmission efficiency of an electro-hydraulic CVT (EHCVT) is unable to reach an ideal value owing to the energy consumed by the hydraulic actuator and the frictional losses in the variator [1]. An electro-mechanical continuously variable transmission (EMCVT), replacing the hydraulic actuator with an electro-mechanical actuator, is proposed to improve the transmission efficiency of an EHCVT. Although the actuator of an EMCVT operates at lower power relative to that of a hydraulic actuator and reduces the energy consumed by a CVT actuator, the frictional loss could increase because the driven pulley clamping force cannot be occasionally adjusted based on the input torque [2]. Thus, it is important to investigate the transmission efficiency of an EMCVT.

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In traditional EHCVT, it is necessary for a hydraulic actuator to provide sufficiently high pressure and flow quality to ensure the power transfer and control of the speed ratio [3]. Additionally, this will require a hydraulic pump that is driven by the engine to operate at high power, and this will result in significant energy consumption. A modified CVT ratio map was proposed to realize the highest engine-CVT overall transmission efficiency [4]. However, it is not possible to optimize the transmission efficiency of a CVT itself under certain conditions. The modified CVT ratio map only attempts to operate the CVT at its higher efficiency point, and the CVT system loss continues to occupy most of the drive train loss. An EMCVT was subsequently proposed to eliminate the energy consumed by the hydraulic actuator and improve the transmission efficiency of the CVT itself.

Several mathematical models related to the transmission loss of a CVT were developed [5–8]. In the model developed in [5], the power losses are depicted as the hydraulic power required to generate the clamping forces and power resulting from shearing of the oil film between the pulleys and belt. It was concluded that a CVT with a sufficiently small pump displays higher transmission efficiency. The loss mechanisms in a pushing metal V-belt CVT were systematically investigated in three aspects, namely, the torque loss due to band friction [6], pulley deflection losses [7], and belt slip losses [8]. Additionally, the efficiency of the torque loss model was experimentally proven. Furthermore, several dynamic models of a belt CVT were described in a review paper [9] in which most were also experimentally validated. These proposed models aid in obtaining higher transmission efficiency in a CVT. However, these models are relatively complex, and thus a simplified dynamic model based on the above models is proposed in the present study.

Several types of EMCVTs were proposed and examined to date [2,10–13]. The modeling and ratio control of an EMCVT was investigated in [10]. The EMCVT was also equipped in a vehicle to validate the effectiveness of the ratio control strategy. In [11], an electromechanical CVT pulley actuator was designed to control the ratio and clamping force and includes spindles, epicyclic gearings, and electric motors. Additionally, the ratio and clamping force are independently adjusted using this actuator. Two types of EMCVTs are described in [2] in which an EMCVT is suitable for a small torque CVT, and the other is applied to the currently prevalent CVT. An EMCVT with a dual acting pulley is introduced in [12], and the development of a ratio controller by using a proportional-derivative-plus-conditional-integral controller is described. An EMCVT with a single motor actuation system is introduced in [13], and a ratio controller based on a fuzzy-PID is proposed. In [14], an EMCVT with double motors actuation system is proposed to make the driven pulley clamping adjustable, and a driven pulley clamping force controller is developed. Most of the above studies focused on the structure and ratio control, and a few studies examined the energy loss of an EMCVT and specifically the energy consumed by an electro-mechanical actuator. Hence, the present study focuses on the energy losses of an EMCVT actuator and attempts to improve its transmission efficiency.

This study is organized as follows. In Section 2, the construction and working principle of an EMCVT with a single actuation motor are introduced. In Section 3, the factors influencing the transmission efficiency of the EMCVT are analyzed from the following two aspects: energy losses from friction within the components of the variator and energy consumed by the electro-mechanical actuator. In Section 4, the construction of a transmission efficiency simulation model is described based on the equations given in Section 3, and the energy losses of the EMCVT are compared with those of an electro-hydraulic CVT under standard driving cycles. Additionally, another EMCVT with two actuator motors is introduced to reduce the energy loss. Finally, a few concluding remarks are given in Section 5.

2. EMCVT with single actuator motor and EHCVT

In a traditional EHCVT, a hydraulic actuator is used to control the CVT clamping force and ratio, and it consumes high amounts of energy. The objective of studying an EMCVT is to reduce the energy consumed by the CVT actuator. Fig. 1(a) shows a particular type of EMCVT in which the hydraulic actuator is replaced by an electro-mechanical actuator [2]. The ratio and clamping force of this EMCVT are adjusted using an electro-mechanical actuator, which consists of a direct current (DC) motor, gear pair, screw-nut pair, and Belleville springs. In this electro-mechanical actuator, the DC motor is the power source, the gear pair reduces the rotation speed and enlarges the torque of the DC motor, the screw-nut pair converts the rotation motion into linear motion and then adjusts the displacement of driving pulley moveable sheave, and the clamping forces of the driving pulley and driven pulley are mainly obtained using Belleville springs.

The ratio is controlled using the DC motor on the driving pulley side, and a set of Belleville springs assist the DC motor in adjusting the displacement of the movable sheave of the driving pulley. The driven pulley clamping force is solely applied by a set of Belleville springs, and thus, the clamping force is only related to the ratio and cannot be actively adjusted. In order to guarantee torque transfer, the electro-mechanical actuator must provide a sufficiently high driven pulley clamping force. Thus, the driven pulley clamping force of an EMCVT significantly exceeds that of an EHCVT. However, a high driven pulley clamping force results in a higher frictional energy loss [15]. Therefore, the frictional energy loss increases although an electro-mechanical actuator may consume less energy than an electro-hydraulic actuator. Hence, it is clear that the energy loss of an EMCVT differs from that of an EHCVT, and thus it is necessary to analyze the energy losses of an electro-mechanical actuation system and the variator of an EMCVT.

Fig. 1(b) shows the hydraulic system of an EHCVT. An engine-driven pump supplies hydraulic oil to control CVT driven pulley clamping force and ratio [3]. The driven pulley clamping force of the EHCVT is adjusted by an electro-hydraulic proportional overflow valve, and the EHCVT ratio is controlled by a ratio control valve.