Industrial Research Workshop and National Seminar 2012
ISBN 978-979-3541-25-9

Development of Electro-Mechanical Actuation System for Continuously Variable Transmissions in Automotive Applications

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Abstract

Developing and eventually producing an efficient and environmentally friendly transmission technology for passenger cars has always been a major challenge for transmission manufacturers and carmakers, with many different ideas to be considered, studied and tested comprehensively. Continuously variable transmission (CVT) with electro-mechanical actuation system is an innovative idea that has been studied in recent years by many researchers from renowned research institutions with collaboration from relevant companies as a possible solution for an efficient, practical and environmentally friendly automotive transmission. In this paper, a new concept of electro-mechanical actuation system for CVTs is introduced. Firstly, the basic idea of electro-hydro-mechanical actuation system, which is normally used in existing CVTs, is reviewed briefly. Consequently, the working principle together with the fundamental design of the proposed new concept of electro-mechanical actuation system for CVTs is also described. Lastly, potential benefits that can be gained through this new concept are discussed.

Key words: *electro-mechanical, actuation system, continuously variable transmission, automotive application*

1. INTRODUCTION

In recent years, engineers and researchers from many institutions worldwide have studied the possibility to produce an efficient continuously variable transmission (CVT) that can be used for automotive applications. Pulley-based CVT with metal pushing V-belt is one of the most common CVT used for existing passenger cars; it uses electro-hydro-mechanical (EHM) system as its actuation system. However, this type of actuation system still possesses some major issues such as high power consumption (Klaassen, 2007), power loss (Klaassen, 2007 and Kirchner, 2007) and belt misalignment (Tawi, 1997 and Faye, 2009). These are the key sources that decrease the efficiency of EHM CVT used in automotive applications.

The first occurs during the event of constant CVT ratio, where EHM actuation system will have to provide sufficient hydraulic pressure to maintain the desired CVT ratio. For this to take place, the engine has to continuously provide additional power to the hydraulic pump so that the position of the primary and secondary pulleys can be retained accordingly.

The second (i.e., power loss) happens when insufficient clamping force is provided to maintain the desired CVT ratio, where slipping of metal belt can occur. In contrary, excessive clamping force would cause the metal belt to overstress. Both conditions lead to power loss between primary and secondary pulleys. Therefore, maintaining sufficient clamping force on the metal belt is very important to minimize the power loss suffered in the EHM CVT. It is important to note that the process to provide sufficient clamping force on metal belt is quite complicated due to the requirement of additional hydraulic control system.

Belt misalignment (i.e., third issue) is inevitable during operation of the present EHM CVT since it uses single acting pulley actuation mechanism. This, according to Tawi (1997), introduces internal sinusoidal couple that could lead to shorter lifespan of the metal belt due to wear, tear and vibration. Furthermore, the efficiency of the CVT will decrease.

In order to avoid the aforementioned issues, engineers and researchers have recently introduced an improved concept, namely the electro-mechanical (EM) actuation system, to replace the existing EHM actuation system used widely in current metal pushing V-belt CVTs. To the best of the authors' knowledge, only two research institutions, namely Technische Universiteit Eindhoven (TU/e) and Universiti Teknologi Malaysia (UTM), are working independently to develop working prototypes of CVT with EM actuation system to overcome the high power consumption and the power loss issues. Between these two institutions, only UTM is working on developing dual acting pulley mechanism to overcome the belt misalignment issue. In this paper, improved design of EM actuation system for CVT is introduced.

2. EXISTING PROTOTYPES OF CVT WITH EM ACTUATION SYSTEM

Pulley-based CVT with metal belt, unlike normal transmission with discrete gears, does not have gears. In this type of CVT, the transmission ratio is changed by varying the radius of metal belt on primary pulley and secondary pulley simultaneously. This process is done by moving axially the movable sheaves of both primary and secondary pulleys, conventionally through EHM actuation system (Akehurst, 2001, Klaassen, 2007 and Kirchner, 2007). Equation (1) shows the relationship between CVT ratio, r_{CVT}, the radius of primary pulley, R_p and the radius of secondary pulley, R_s. Subsequently, the relationship between the changes in axial position of the pulleys (X_p and X_s) and their radius (R_p and R_s) is shown in the following Equation (2) and Equation (3). Other important parameters in these equations are α (angle of the pulley), R_{p0} (minimum radius of primary pulley) and R_{s0} (minimum radius of secondary pulley). All parameters for Equations (1), (2) and (3) are shown in Figure 1 (example used in this figure is the primary pulley). Figure 2, on the other hand, shows the example of CVT with metal belt under the conditions of low ratio (A), medium ratio (B) and overdrive ratio (C), with light-grey pulley as the primary pulley and dark-grey pulley as the secondary pulley.

$$r_{CVT} = \frac{R_s}{R_p} \quad (1)$$

$$X_p = (R_p - R_{p0}) \tan \alpha \quad (2)$$

$$X_s = (R_s - R_{s0}) \tan \alpha \quad (3)$$

r_{CVT}: CVT ratio [-]
R_s: radius of secondary pulley [mm]
R_p: radius of primary pulley [mm]
R_{s0}: min. radius of secondary pulley [mm]
R_{p0}: min. radius of primary pulley [mm]
X_s: axial position of secondary pulley [mm]
X_p: axial position of primary pulley [mm]
á: angle of the pulleys [°]

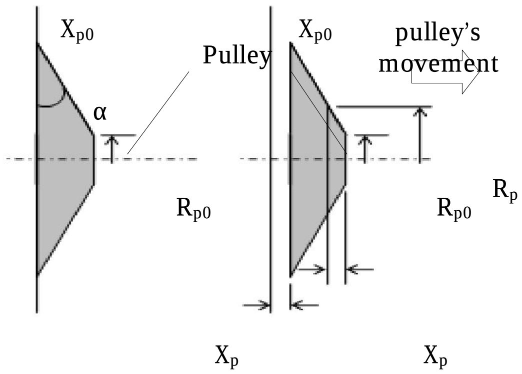


Figure 1. Important parameters of the CVT's pulley for Equations (1), (2) and (3)

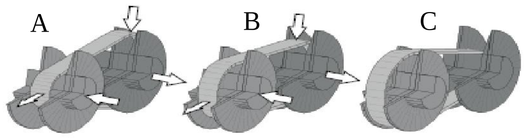


Figure 2. Low ratio (A), medium ratio (B) and overdrive ratio (C) in CVT with metal belt (Klaassen, 2007)

The researchers from TU/e and UTM have been working extensively in the recent years to

develop the prototypes of CVT with EM actuation system. From these efforts, two working prototypes were produced, namely EMPACT CVT and EMDAP CVT. EMPACT CVT stands for Electro-Mechanical Pulley Actuation CVT and it was developed in TU/e. EMDAP CVT, meanwhile, was developed in UTM and the acronym stands for Electro-Mechanical Dual Acting Pulley CVT.
The schematic sketch of EMPACT CVT's prototype can be viewed in Figure 3. According to Klaassen (2007), the EM actuation system of this prototype applies double planetary gears with adjustment ring gears at both input and output shafts of the CVT. These components are responsible to axially move the movable sheaves (3-01) of the primary pulley (3-02) and the secondary pulley (3-06) during the event of shifting CVT ratio. The adjustment ring gear of the primary pulley, called ratio adjustment ring gear (3-03), is meshed with the double planetary gear of the primary pulley (3-04) and it is actuated by the primary servomotor (3-05). This ratio adjustment ring gear is also meshed directly (3-12) with the double planetary gear of the secondary pulley (3-10). In the secondary pulley, the double planetary gear of the secondary pulley is meshed with the clamping force adjustment ring gear (3-07). This adjustment ring gear, in addition, is also connected to its actuator, which is the secondary servomotor (3-09), through chain gear (3-08). Lastly, the thrust bearing (3-11) is used to support the clamping force on both primary and secondary pulleys.

In this prototype, there is a transfer of energy between the movable sheaves of the primary pulley and the secondary pulley during the event of changing CVT ratio. This is achieved through the direct meshing (3-12) between the ratio adjustment ring gear in the primary pulley and the double planetary gear of the secondary pulley. This feature reduces the required power from primary servomotor and secondary servomotor for the process to change CVT ratios, thus improves the efficiency of the CVT (Klaassen, 2007 and Veenhuizen et al., 2004). However, the EM actuation system in EMPACT CVT still uses single acting pulley actuation mechanism, hence makes the issue of belt misalignment unavoidable. This leads to a limited lifespan of metal belt and it also decreases the efficiency of the CVT.

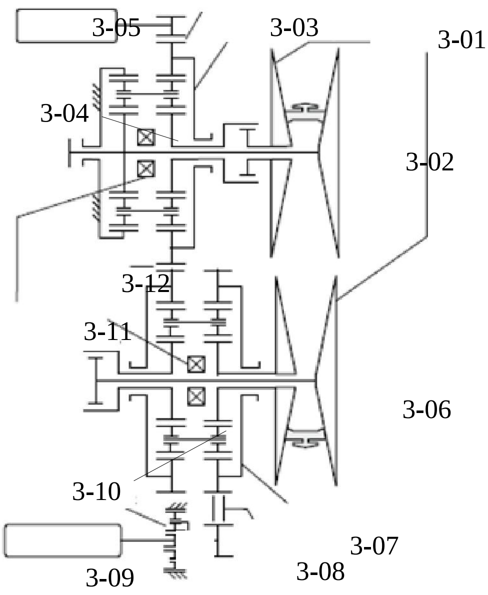
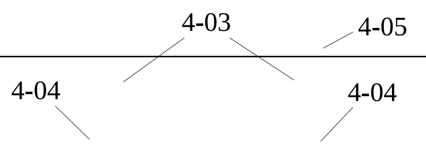


Figure 3. EM actuation system of EMPACT CVT from TU/e (Klaassen, 2007)

On the other hand, the schematic sketch of EMDAP CVT, which was developed by the researchers from UTM, is shown in Figure 4 on the following page. However, unlike EMPACT CVT, the EM actuation system of this prototype uses dual acting pulley actuation mechanism and power screw mechanism for actuating the movement of pulleys during changing CVT ratio. The former allows both sheaves of primary pulleys (4-02) and secondary pulleys (4-07) to be moved axially during the process of shifting CVT ratio and this minimizes the effect of belt misalignment in the CVT. The latter, meanwhile, is a mechanism to actuate the axial movement of the movable sheaves of primary pulley and secondary pulley. This mechanism mainly consists of fix gears, power screws and power screw holders.

For the primary pulley, torque is provided by the primary electrical DC motor (4-06) to the primary fix gears (4-03) through the primary pinion gear (4-05). Then, the primary power screws (4-04) will convert the rotation of the primary fix gears into an axial movement. This will trigger the movement of the movable sheaves of primary pulley (4-02) axially, hence varying the radius of metal V-belt (4-01) on the primary pulley. The same principle is also applied in the secondary pulley with secondary fix gears (4-08), secondary power screws (4-09), secondary electrical DC motor (4-11) and secondary pinion gear (4-10).



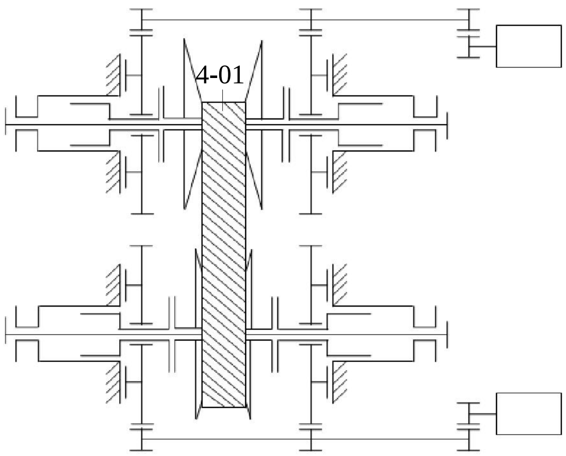


Figure 4. EM actuation system of EMDAP CVT from UTM

However, compared to EMPACT CVT, the EM actuation system in EMDAP CVT lacks direct meshing between primary fix gears and secondary fix gears. The absence of this feature leads to no transfer of energy between both primary and secondary pulleys during changing CVT ratio. This results in high power consumption in both primary electrical DC motor and secondary electrical DC motor. In addition, the lack of this feature also makes the process to control the EM actuation system of EMDAP CVT very complicated. Therefore, an improved design of EM actuation system for CVT that combines the strength from both prototypes and eliminates their major weaknesses is very much desired.

3. THE PROPOSED IMPROVED DESIGN OF EM ACTUATION SYSTEM FOR CVT

The improved design of EM actuation system for CVT proposed in this paper will apply dual acting pulley actuation mechanism for both primary and secondary pulleys, similar to the one in EMDAP CVT, as well as the modified power screw mechanism. The schematic sketch of this design is shown in Figure 5.

The dual acting pulley actuation mechanism in this improved design is identical to the mechanism used in EMDAP CVT. It allows both sheaves of the primary (5-02) and secondary pulleys (5-07) to be moved axially to vary the radius of metal belt (5-01) during changing CVT ratio. However, in this improved design, while the power screw mechanism of the primary pulley remains like the one in EMDAP CVT, there are 3 significant modifications done to the power screw mechanism of the secondary pulley. These modifications are the introduction of the secondary clamping fix gears (5-09), the new design of secondary pulley’s power screw (5-10) and the direct meshing of the primary pinion gear (5-05) with both primary fix gears (5-03) and secondary ratio fix gears (5-08).

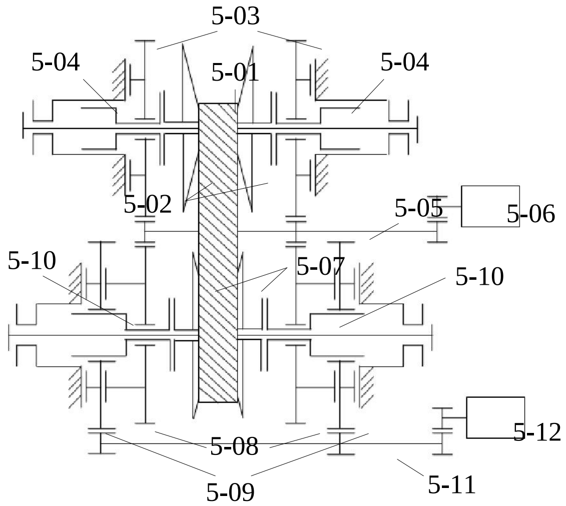


Figure 5. The proposed new design of EM actuation system for CVT

The first modification, which is the addition of the secondary clamping fix gears (5-09), is very important for controlling sufficient clamping force on the secondary pulley (5-07). By providing sufficient clamping force, the slipping and the overstress of the metal belt can be avoided. The secondary clamping fix gears are actuated by the secondary electrical DC motor (5-12) through the secondary pinion gear (5-11).

The second modification (i.e., the new design of the secondary pulley’s power screw), is essential to accommodate the inclusion of secondary clamping fix gears in the secondary pulley’s power screw mechanism. The task of this power screw is to convert the rotational motion of the secondary ratio fix gears (5-08) and the secondary clamping fix gears (5-09) into axial motion.

The final significant modification on the secondary pulley’s power screw mechanism is the direct meshing of the primary pinion gear (5-05) with primary fix gears (5-03) and secondary ratio gears (5-08). With this modification, the torque from the primary electrical DC motor (5-06) can be transferred to both primary fix gears and secondary ratio fix gears. This feature allows both primary power screw (5-04) and secondary power screw (5-10) to be moved axially simultaneously during the process to shift CVT ratio.

4. WORKING PRINCIPLE OF THE PROPOSED IMPROVED DESIGN

Basically, the change of CVT ratio is achieved by varying the radius of metal belt on primary pulley and secondary pulley simultaneously. The radius of metal belt on primary and secondary pulleys is changed by moving axially both pulleys in opposite direction at the same time.

In the proposed new design of EM actuation system, during changing CVT ratio, the axial movements of the sheaves of both primary and secondary pulleys are actuated by the primary electrical DC motor. These movements will vary the radius of metal belt on primary and secondary pulleys simultaneously, thus change the CVT ratio accordingly. This is possible in the new design since there are direct meshes between primary pinion gear to both primary fix gears and secondary ratio fix gears.

Then, the sufficient amount of clamping force will be provided on the metal belt by the secondary pulley. This is done by adjusting the position of the secondary pulley accordingly. This process is actuated by the secondary electrical DC motor, which provides torque to the secondary clamping fix gears through the secondary pinion gear, hence moves the secondary pulley's power screw together with the secondary pulley's sheaves axially.

Figure 6 shows the simplified working principle of the proposed new design of EM actuation system for CVT in block diagram. This figure includes some important components for the process, namely primary pulley (6-01), secondary pulley (6-02), metal belt (6-03), primary electrical DC motor (6-04), primary pinion gear (6-05), primary fix gear (6-06), primary pulley's power screw (6-07), secondary electrical DC motor (6-08), secondary pinion gear (6-09), secondary ratio fix gear (6-10), secondary clamping fix gear (6-11) and secondary pulley's power screw (6-12).

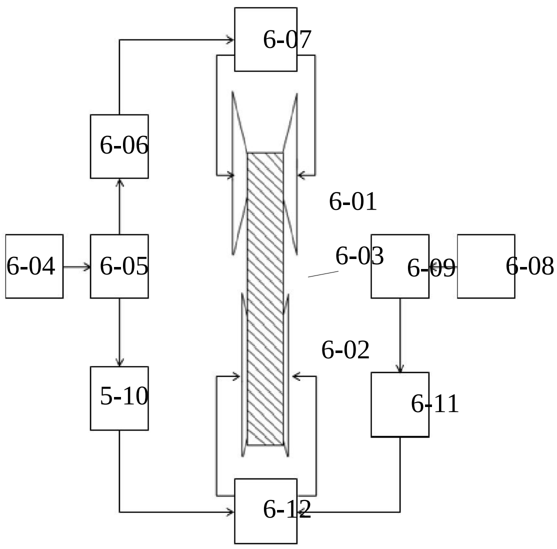


Figure 6. The simplified working principle of the proposed new design of EM actuation system for CVT

5. POTENTIAL BENEFITS OF THE PROPOSED IMPROVED DESIGN

There are 3 major benefits that can be potentially gained from this proposed improved design of EM actuation system for CVT. These potential benefits are the efficient power consumption on the electrical DC motors, minimum effect of belt misalignment and improved controllability of the actuation system.

The first benefit, which is the efficient power consumption in the CVT, is achieved because of the application of EM actuation system to replace EHM actuation system in CVT. EM actuation system requires no continuous hydraulic pressure to maintain the desired CVT ratio since it uses thread to hold the position of the pulleys. Furthermore, the direct meshes between the primary pinion gear, primary fix gears and secondary ratio fix gears also allow the exchange of energy between the sheaves of primary and secondary pulleys. As a result, the total power required from the primary and secondary electrical DC motors for the actuation process can be reduced significantly.
The second potential benefit (i.e., minimum effect of belt misalignment) is realized through the dual acting pulley actuation mechanism used in this new design. This mechanism allows both sheaves of the primary pulley and the secondary pulley to be moved axially, hence reduces the effect of belt misalignment. Through this mechanism, the total lifespan of the belt can be improved significantly. Besides,

the efficiency of the CVT can also be increased.
Next, the modification on the secondary pulley's power screw mechanism makes the job of the primary electrical DC motor only for changing ratio, while the secondary electrical DC motor will only be responsible for providing sufficient clamping force on the secondary pulley. As a result, it will be possible for engineers to regulate the primary electrical DC motor and the secondary electrical DC motor separately, hence improves the controllability of the actuation system, which is the third potential benefit of the proposed improved design. As a comparison, in the EM actuation system of EMDAP CVT, it is not possible to regulate both primary and secondary electrical DC motors independently, since both electrical DC motors are responsible for changing ratio. This issue reduces the controllability of the actuation system in EMDAP CVT.

Consequently, because of the improved controllability too, it will be easier to provide and maintain the sufficient clamping force on the V-belt. This ultimately reduces the power loss because of insufficient clamping force suffered in the conventional CVT with EHM actuation system.

6. CONCLUSION

It can be concluded here that, the EM actuation system in general has tremendous potentials to further improve the efficiency of the CVT for applications in automotive fields. Through this technology, the issue of high power consumption and power loss in conventional CVTs with EHM actuation system can be reduced. With the improved design of EM actuation system proposed in this paper, not only these mentioned issues can be overcome, but the effect of belt misalignment in CVT can also be minimized. This prolongs the total lifespan of the CVT's belt while at the same time also increases its efficiency even further. Additionally, the improved controllability of the actuation system makes the proposed design an even more attractive option for applications. Given sufficient efforts and supports, this new design has the potentials to contribute positively and meaningfully for automotive industry.

7. ACKNOWLEDGEMENT

The authors would like to thank all persons from Drivetrain Research Group (DRG) of Universiti Teknologi Malaysia (UTM) who have involved in providing comments and suggestion for improving and completing this paper as well as Malaysia's Ministry of Science and Technology (MOSTI) for providing Technofund to fund this project.

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