Electro-mechanical Transmission Ratio Shifter of Rubber Belt Continuously Variable Transmission for Motorcycle Applications

Bambang Supriyo¹, Sugeng Ariyono², Bambang Tjahjono² and Bambang Sumiyarso²

¹Master of Applied Telecommunications Engineering, Semarang State Polytechnic, Jl. Prof. H. Soedarto, S.H., Tembalang, Semarang, Indonesia.
²Mechanical Engineering, Semarang State Polytechnic, Jl. Prof. H. Soedarto, S.H., Tembalang, Semarang, Indonesia

E-mail: bsupriyo2015@polines.ac.id

Abstract. This paper introduces an electro-mechanical transmission ratio shifter of rubber belt continuously variable transmission (CVT). The CVT basic system consists of primary pulley (input), secondary pulley (output) and a rubber belt. This belt connects the primary pulley to the secondary pulley and transfers the speed and torque from the input to output by means of belt-pulley contact friction. Each pulley set has one fixed and one sliding pulley sheaves. The axial movement of primary sliding pulley sheave is actuated by an electro-mechanical system consisting of the DC servomotor, actuator gears and cam mechanism, while the secondary sliding pulley sheave is constantly pushed by contra spring to maintain the overall belt tension and to prevent belt slip. By controlling the DC motor revolution, the axial position of the primary sliding pulley sheave can be adjusted to vary the primary belt-pulley contact radius, which in turn mechanically changing the secondary belt-pulley contact radius and finally changing the transmission ratio. The relationship between motor revolution, primary belt-pulley contact radius, secondary belt-pulley contact radius and transmission ratio can be determined based on mathematical equations of variator geometry, the total gear ratio of the actuator gears and cam mechanism

1. Introduction
Nowadays, rubber belt Continuously Variable Transmission (CVT) is becoming very popular transmission for motorcycle applications. More people, especially in Indonesia, use CVT motorcycle, called matic, due to its easy driving and smooth driving comfort without experiencing torque interruption during shifting. Conventional transmission systems, frequently called manual gearbox, consist of several number of fixed gearsets, while CVT systems has a wider range of continuous transmission ratios between its minimum and maximum transmission ratios. Transmission ratio changing mechanisms in today’s motorcycle equipped with CVT highly depend on centrifugal forces developed from its engine speed. This engine speed causes the sliding metal rollers placed on the back of the primary sliding pulley sheave to produce centrifugal forces. These centrifugal forces axially exert the primary sliding pulley sheave to push the rubber belt on the primary pulley sheaves upward which in turn changing the primary belt-pulley contact radius. When the primary belt-pulley contact
radius changes, then based on variator geometry, the secondary pulley-belt contact radius will also change smoothly due to its flexible spring based clamping force exerted on the back of the secondary sliding pulley sheave. Compare to the conventional transmission, this kind of CVT needs higher engine revolution to generate centrifugal forces for initiating its transmission ratio changes, hence its power is still less efficient. Several studies concerning with solving the rubber belt CVT inefficiency has been done in [1], [2], [3] and power loss has been studied in [4],[5],[6],[7].

To improve the power inefficiency of the centrifugal based CVT, a viable CVT system based on electro-mechanical arrangement is proposed for motorcycle applications, in which its transmission ratio changes do not rely on centrifugal forces developed from engine speed, but based on controllable DC motor revolutions. The concept of the electro-mechanical rubber belt CVT have been introduced in [8],[9],[10]. This electro-mechanical system mainly consists of DC motor as an actuator combined with a gear train set (called actuator gears) to move a cam mechanism attached to the primary sliding pulley sheave. This system is called Electro-Mechanical Single Actuated Pulley Rubber Belt CVT (EMSAPRB-CVT). The use of cam mechanism is mainly to convert cam’s input rotation into its output axial movement to shift the primary sliding pulley sheave such that the position of the belt contact point on the surfaces of the pulley sheaves can move up or down, varying the belt-pulley contact radius, and finally changing its transmission ratio. In addition, the overall belt clamping force is mechanically maintained by the contra spring placed on the back of the secondary sliding pulley sheave, so that the belt is kept tight and able to transfer speed and torque from the input pulley shaft to the output pulley shaft with no slip.

2. Working Principle of Basic CVT

The working principle of a basic CVT system is analogous to a speed variator, as shown in Figure 1. The variator mainly consists of primary pulley, secondary pulley and rubber belt. The belt transfers speed and torque from the primary pulley to secondary pulley based on belt-pulley contact friction.

![Speed variator geometry](image)

**Figure 1.** Speed variator geometry

Based on Figure 1, the belt wraps some parts of the primary pulley segment and develops the primary belt-pulley contact radius of Rp. Similarly, the belt also wraps some parts of the secondary pulley segment and develops the secondary belt-pulley contact radius, Rs. If the belt has a constant length and it rotates smoothly on both pulley surfaces without slip, then the tangential velocity (νT) developed on the primary pulley, secondary pulley and belt are the same. Therefore, the relationship between tangential velocity and primary pulley speed and radius as well as secondary pulley speed and radius can be seen in (1) and (2).

\[
\nu_T = \omega_p R_p = \omega_s R_s
\] (1)
\[
\frac{\omega_p}{\omega_s} = \frac{R_s}{R_p}
\] (2)

Where \(\omega_p\) is primary pulley angular speed, \(\omega_s\) secondary pulley angular speed, \(R_p\) primary belt-pulley contact radius and \(R_s\) secondary belt-pulley contact radius. The transmission ratio (\(r_{cvt}\)) is determined based on primary radius and secondary pulley radius, as represented by (3). But the transmission ratio can also be represented as geometrical speed ratio (\(r_{gs}\)) which is determined based on primary and secondary pulley speeds, as given in (4).

\[
r_{cvt} = \frac{R_s}{R_p}
\] (3)

\[
r_{gs} = \frac{\omega_p}{\omega_s}
\] (4)

Based on Figure 1, the relationship between belt length (\(L\)) and primary belt-pulley radius (\(R_p\)) as well as secondary belt-pulley radius (\(R_s\)) can be expressed as follows:

\[
L = (\pi - 2\theta)R_p + (\pi + 2\theta)R_s + 2c \cos(\theta)
\] (5)

\[
R_s = R_p + c \sin(\theta)
\] (6)

Where \(c\) is the fixed center distance between the primary and secondary pulley shafts, and \(\theta\) is half additional angle in the secondary pulley’s half circle wrapped angle. By solving equations (5), (6) and (3), the relationship between transmission ratio and both primary and secondary belt-pulley contact radii can be determined and plotted in Figure 2.

![Figure 2](image-url)

**Figure 2.** The relationship between transmission ratio and primary and secondary contact radii

The relationship between the primary pulley shifting distance (\(X_p\)) and the primary belt-pulley contact radius is expressed in (7), while the relationship between the secondary pulley shifting distance (\(X_s\)) and the secondary belt-pulley contact radius is written as in (8).

\[
X_p = (R_p - R_{p0}) \tan(\alpha)
\] (7)

\[
X_s = (R_s - R_{s0}) \tan(\alpha)
\] (8)

where \(R_{p0}\) is the smallest primary belt-pulley contact radius, \(R_{s0}\) is the smallest secondary belt-pulley contact radius, \(\alpha\) is the pulley wedge angle (13°). By solving equations (5), (6), (7) and (3) for
$L=806.4\text{mm}$ and $c=285\text{mm}$, the relationship between the primary pulley shifting distance and transmission ratio can be plotted and presented in Figure 3. The regression equation least square method approximating the relationship between primary pulley shifting distance and transmission ratio is presented in (9) with the average % error of 1.35 %.

$$r_{cvt} = 0.017X_p^2 - 0.418X_p + 3.449 \quad (9)$$

Figure 3. The relationship between primary pulley shifting distance and transmission ratio

3. Electro-mechanical single actuated CVT

The Electro-mechanical Single Actuated Pulley Rubber Belt (EMSAPRB) CVT system for motorcycle applications utilizes one DC servomotor as an actuator for changing the transmission ratio, as shown in Figure 4. The system has a primary pulley set placed on input shaft and a secondary pulley set placed on the output shaft, and a rubber belt connecting the primary pulley to the secondary pulley to transmit the speed and torque from the input to the output shafts by means of friction between the belt and the pulley contact [11],[12]. Each pulley set has one fixed pulley sheave and one sliding pulley sheave that can be shifted axially along the shaft to vary the pulley gaps. The main components of the primary set consist of a dc servomotor, actuator gear sets with the total reduction (nag) of about 10.7:1, cam mechanism, one sliding and one fixed metal pulley sheaves for clamping and releasing the rubber belt and the primary shaft connected to the power source. The sequentially mechanical connection is as follows: shaft of the DC servomotor, actuator gears, cam mechanism and the primary sliding pulley sheave. Hence, the DC motor can control the axial shifting of the primary sliding pulley sheave. The components of the secondary set consist of one sliding pulley sheave, one fixed pulley sheave, a contra, and the secondary shaft which is connected to the drive wheel.

From Figure 3, the maximum displacement of the primary sliding pulley sheave ($X_{p\text{max}}$) is about 11.2mm. From Figure 6 and 7, the maximum tangential distance of the rotating cam ($X_{t\text{max}}$) of 60mm is required to achieve the maximum axial shifting ($X_{c\text{max}}$) of 15mm. Therefore, in order to satisfy $X_{c\text{max}}$, it will take tangential distance ($X_t$) as in (10).

$$X_t = (X_{p\text{max}} / X_{c\text{max}})X_{t\text{max}}$$
$$= (11.2 / 15) \times 60$$
$$= 44.8\text{mm}$$

The maximum revolution of the DC motor shaft ($Revm$) can be calculated using (11).

$$Revm = \frac{\text{nag} \times X_p}{(\pi \times D_c)}$$
$$= (10.71 \times 44.8 / (3.14 \times 100)$$
$$= 15.194$$
Figure 4. Electro-mechanical CVT

Figure 5. Cam movement

Figure 6. Initial cam axial displacement.

Figure 7. Cam axial displacement of Xp.
4. Conclusions
The mathematical model of the electro-mechanical system for transmission ratio shifter has been presented. The transmission ratio range is between 3.56 (under drive) to 0.88 (over drive). The equation related to primary pulley shifting distance and transmission ratio has been derived. This equation can be used to calculate the transmission ratio when the primary pulley shifting distance is known. By relating the primary pulley shifting distance and the DC motor revolutions, the desired transmission ratio can be achieved by setting the required numbers of the DC motor revolutions. The next study will focus on the controlling the DC motor revolutions using PID or Fuzzy methods to achieve the desired transmission ratio.

5. References
[1] B. Balta, F.O. Sonmez and A. Cengiz 2015 “Speed losses in V-ribbed belt drives” Mechanism and Machine Theory vol. 86, pp. 1–14
[2] B. Supriyo, K.B. Tawi and H. Jamaluddin 2013 “Experimental Study of an Electro-mechanical CVT Ratio Controller” International Journal of Automotive Technology vol. 14, no.2, pp. 313-323
[3] Balta, Berna&Sonmez, Fazil&Cengiz, Abdulkadir 2015Speed losses in V-ribbed belt drives Mechanism and Machine Theory 86. 10.1016/j.mechmachtheory.2014.11.016
[4] Bertini, Leonardo &Carmignani, L &Frendo, Francesco 2014Analytical model for the power losses in rubber V-belt continuously variable transmission (CVT) Mechanism and Machine Theory 78. 289–306. 10.1016/j.mechmachtheory.2014.03.016
[5] Cammalleri M 2005Anew Approach to the design of a speed torque controlled rubber V-belt variator” Journal of Automobile Engineering ProciMEchE Vol.219 Part D, 12, pp.1413-1428
[6] Grzegozek, W &Kot, A 2016The experimental analysis of the slip in the rubber belt CVT IOP Conference Series Materials Science and Engineering 148. 012006. 10.1088/1757-899X/148/1/012006
[7] N. Cholis, S. Aryono and G. Priyandoko 2013 “Design of single acting pulley actuator (SAPA) continuously variable transmission (CVT)” Energy Procedia vol. 68, pp.389 – 397
[8] S. Kanehara, T. Fujii and S. Oono 1996 “A Study of a Metal Pushing V-Belt Type CVT : Macroscopic Consideration for Coefficien of Friction between Belt and Pulley” SAE Paper No. 9636277
[9] T.F. Chen and C.K. Sung 2000 ”Design considerations for improving transmission efficiency of the rubber V-belt CVT” International Journal of Vehicle Design vol.24, no.4, pp. 320–333
[10] W.Grzegoek and M.Szczepka 2016 “Analysis of an employment of a gear ratio rate in CVT control system” Scientific Conference on Automotive Vehicles and Combustion Engines (KONMOT 2016) IOP Publishing IOP Conf. Series: Materials Science and Engineering vol. 148, pp. 1-10
[11] Y. Fushimi, T. Fujii and S. Kanehara 1996 “A Numerical Approach to Analyse the Power Transmitting Mechanisms of a Metal Pushing V-Belt Type CVT” SAE Technical Paper Series 960720
[12] Zhu, C & Liu, Huaiju& Tian, J & Xiao, Q & Du, X 2010 ”Experimental investigation on the efficiency of the pulley-drive CVT” International Journal of Automotive Technology Vol. 11, pp. 257-261