Ratio Calibration of Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission System

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Abstract: - This paper introduces an electro-mechanical dual acting pulley (EMDAP) continuously variable transmission (CVT) and presents ratio calibration of EMDAP CVT system. The desired speed ratio is set manually by adjusting the primary and secondary axial pulley positions accordingly by controlling both primary and secondary DC motors. The real speed ratio is calculated based on input and output shaft speed measurements, while the geometrical ratio is indirectly determined from primary and secondary axial pulley positions obtained from pulley gap measurements. The geometrical ratio is validated using speed ratio. Based on this validation, all corresponding values of primary and secondary pulley positions, output voltages of pulley position sensors as well as output voltages of shaft speed sensors are recorded and used as reference data for future calibration and ratio control applications.

Key-Words: - geometrical ratio, speed ratio, CVT ratio, calibration, electro-mechanical CVT

1 Introduction

Nowadays, continuously Variable Transmission (CVT), especially for metal pushing V-belt type CVT [1], is gaining its popularity as a promising transmission for future automotive applications [2]. Conventional transmission systems use a fixed number of gearsets, while CVT provides a wider range of transmission ratios between engine and wheel. An engine equipped with CVT operates more efficiently, since the selected CVT ratios ensure the engine to mostly run within its efficient operating points [3], hence improving fuel economy [4]. Also, CVT offers a smooth driving comfort due to continuous shift and no torque interruption during shifting.

The majority of belt type CVTs equipped in cars uses hydraulic actuation system. The drawbacks of this CVT are mostly related to high pump and high oil pressure of hydraulic system as well as belt loss [3],[5],[6]. Continuous power consumption of hydraulic actuator in the CVT, especially when driving using a constant transmission ratio, introduces power loss which contributes a big part of the overall CVT losses.

An electro-mechanical pulley actuating CVT adopting power screw mechanism has potential benefit of improving CVT efficiency by eliminating power loss experienced by hydraulic type of CVT. DC motor actuation systems actuate power screw mechanisms to axially shift the primary and secondary pulley sheaves for changing CVT ratio. When no electrical power is supplied to the DC motor, axial positions of primary and secondary pulley sheaves are locked by screw mechanism to produce constant CVT ratio. Current researches in electro-mechanical CVTs, such as electro-mechanically actuated metal V-belt type Continuously Variable Transmission- EMPAct CVT [7], dry hybrid belt electro-mechanical CVT [8], [9]. and electro-mechanically actuated pulley (EMDAP) CVT [10], [11], have been carried out to mature their concepts and technologies.

Most of electro-mechanical CVTs uses single movable pulley sheave on each of its pulley shaft, hence introducing belt misalignment. Application of belt misalignment for long period of time may damage the belt and pulley which worsening CVT's performance, efficiency, reliability and safety [12]. Therefore, various control strategies have applied to minimize belt misalignment effects [13], [14].

Unlike other electro-mechanical CVT systems, EMDAP CVT adopts two movable pulley sheaves on each of its primary and secondary pulley shafts to mechanically eliminate belt misalignment . These primary and secondary movable pulley sheaves always clamp the metal pushing V-belt in alignment condition.

This paper focuses on experimental calibration of EMDAP CVT ratio by validating the geometrical ratio determined from pulley gap measurements with the speed ratio calculated from input and output shaft speed measurements based on measurements of primary and secondary axial pulley positions and primary and secondary shaft speeds. Based on this validation, all corresponding values of primary and secondary pulley positions, output voltages of pulley position sensors as well as output voltages of shaft speed sensors are recorded and used as reference data for future calibration and ratio control applications.

2 Basic CVT Ratio

The basic CVT ratio adjuster is shown in Fig. 1. It has primary and secondary pulleys and belt connecting the two pulleys. If an inextensible belt runs on both pulleys without slip, then both pulleys and belt have the same tangential velocities (v_T).

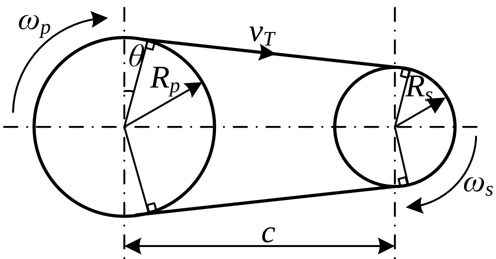

Fig. 1 Basic CVT ratio adjuster

The equations related to speed, running radii and ratios are given as follows:

$$\omega_s R_s = \omega_p R_p \quad (1)$$
$$r_g = R_s / R_p \quad (2)$$
$$r_s = \omega_s / \omega_p \quad (3)$$

where R_p and R_s are primary and secondary pulley running radii, respectively, ω_p and ω_s are primary and secondary angular speeds, respectively, r_g is geometrical ratio and r_s is speed ratio. The terms of CVT ratio in this study refers to the general terms for transmission ratio where there is no belt slip, hence actually the same as geometrical and speed ratio. The equations involving belt length, running radii and axial pulley positions are presented as follows:

$$L = (\pi+2\theta)R_p + (\pi-2\theta)R_s+2c\cos(\theta) \quad (4)$$
$$R_p = R_s + c\sin(\theta) \quad (5)$$
$$X_p = (R_p-R_{p0})\tan(\alpha) \quad (6)$$
$$X_s = (R_s-R_{s0})\tan(\alpha) \quad (7)$$

where, L is belt length (645.68 mm), c is pulley center distance (165 mm), θ is half the increase in the wrapped angle on the primary pulley, R_{p0} and R_{s0} are minimum primary and secondary running radii, X_p and X_s are primary and secondary pulley positions and α is pulley wedge angle (11º).

By using equations (4) and substituting R_p with the R_p in equation (5) and setting various values of angle θ, it is possible to obtain the values of running radii R_p and R_s. Then, by using equation (2), the CVT ratio can be determined and the values of angle θ can be limited to the range that satisfies CVT ratio from 0.7 to 2.0, and the relationship between running radii and CVT ratio can be established. Next, by using equations (6) and (7), the relationship between axial pulley positions X_p and X_s can also be established. Based on this relationship, the desired CVT ratio can be achieved by setting primary and secondary axial pulley positions, and conversely, the current CVT ratio can be determined using equations (2), (6) and (7) if the primary and secondary axial pulley positions are known. In real time application, axial pulley positions are sensed using linear position sensors and shaft speeds are detected using incremental encoder speed sensors. The CVT ratio, represented by speed ratio, is then determined using equation (3).

3 EMDAP CVT System

The EMDAP CVT, as shown in Fig. 2, consists of primary (input) pulley set, secondary (output) pulley set and a Van Doorne's metal pushing V-belt connecting the two pulleys. Each pulley set consists of two movable pulley sheaves facing to each other which can be axially shifted along the primary shaft. The movement can be either narrowing the pulley gap to clamp the belt or widening the pulley gap to loosen the belt. By using these two movable pulley sheaves, the belt is always clamped in alignment condition, hence eliminating belt misalignment. The belt transmits power and torque from primary to secondary shaft by means of friction [15], [16].

Electro-mechanical actuation system of EMDAP CVT mainly consists of DC motor system, gear

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reducer, two sets of helical gear reducers, two sets of power screw mechanisms and two movable pulley sheaves. The DC motor acts as a power source for the actuator, while the gearing system acts as speed reducer and torque multiplier for the DC motor to encounter power screw friction and belt clamping force. The input of the gearing system is driven by the DC motor, while its output actuates power screw mechanisms to shift the two movable pulley sheaves on each pulley shaft in opposite direction to each other such that the pulley gap can be either narrowed or widened. Thus, the DC motor system directly controls axial position of pulley sheaves and indirectly adjusts the belt-pulley running radius. The narrower the pulley gap, the bigger the running radius will be. Both primary and secondary axial pulley positions are directly measured using two position sensors. By knowing these two pulley positions, the running radii, R_p and R_s, can be calculated using equations (6) and (7), and geometrical ratio of CVT can be determined using equation (2).

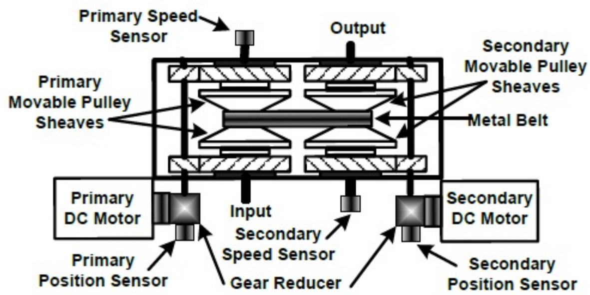

Fig. 2 EMDAP CVT system

Electro-mechanical actuation system of EMDAP CVT mainly consists of DC motor system, gear reducer, two sets of helical gear reducers, two sets of power screw mechanisms and two movable pulley sheaves. The DC motor acts as a power source for the actuator, while the gearing system acts as speed reducer and torque multiplier for the DC motor to encounter power screw friction and belt clamping force. The input of the gearing system is driven by the DC motor, while its output actuates power screw mechanisms to shift the two movable pulley sheaves on each pulley shaft in opposite direction to each other such that the pulley gap can be either narrowed or widened. Thus, the DC motor system directly controls axial position of pulley sheaves and indirectly adjusts the belt-pulley running radius. The narrower the pulley gap, the bigger the running radius will be. Both primary and secondary axial pulley positions are directly measured using two position sensors. By knowing these two pulley positions, the running radii, R_p and R_s, can be calculated using equations (6) and (7), and geometrical ratio of CVT can be determined using equation (2).

Insertion of a spring disc at the back of each secondary pulley sheave keeps the belt tight. Each disc spring can be flatted using about 10 kN compression force. Two spring discs are applied to push movable pulley sheaves to clamp the belt, therefore the a total of about 20 kN force is developed for belt-pulley clamping force [17]. The secondary DC motor provides adequate belt-pulley clamping force by controlling the flatness of the spring discs when preventing belt slip. During ratio calibration process, when the desired ratio is achieved, the spring discs are fully flattened by the secondary DC motor, then the primary and secondary axial pulley positions as well as primary and secondary shaft speeds are recorded.

4 Experimental Test Rig

Experimental test rig was set up for carrying out experimental works concerning with CVT ratio calibration. Block diagram of the test rig is shown in Fig. 3, while the photograph is shown in Fig. 4. The test rig of EMDAP CVT system consist of position sensors, speed sensors, DC motor drivers, DC motors, The DC motors are supplied using car battery of 24 V /70 Ah. An additional battery charger can be provided to back up the battery during experiment. Data Acquisition Card, desktop computer, Matlab/Simulink software, power supply unit and AC motor. The desktop computer, together with data acquisition card and Matlab/Simulink software is used to actuate the DC motors, read, calculate and record pulley positions, shaft speeds and CVT ratio from the respective sensors.

This research uses a three-phase alternative Current (AC) motor of 0.5 kW, shown in Fig. 4, as a power source to rotate the input shaft of the EMDAP CVT. Output shaft of the AC motor is connected to the input of the speed reducer gearbox having ratio 1:30 to increase the output torque of the speed reducer gearbox by 30 times and decrease the speed of the reducer gearbox also by 30 times. The output of the speed reducer gearbox is connected to the input shaft of the EMDAP CVT. The speed of the AC motor is constantly set to 1700 rpm, hence

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the speed of the primary shaft on the EMDAP CVT is 56.66 rpm.

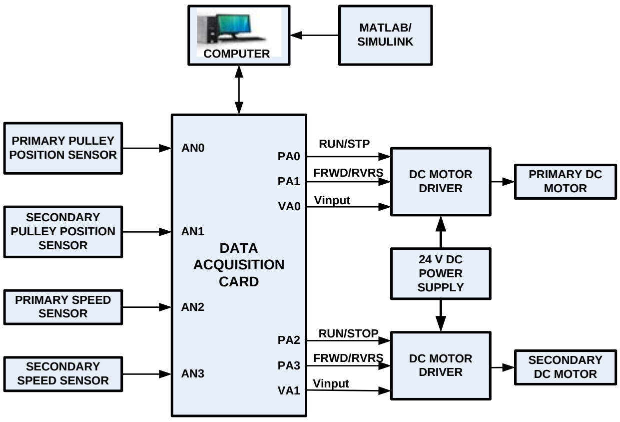

Fig. 3 Block diagram of experimental test rig

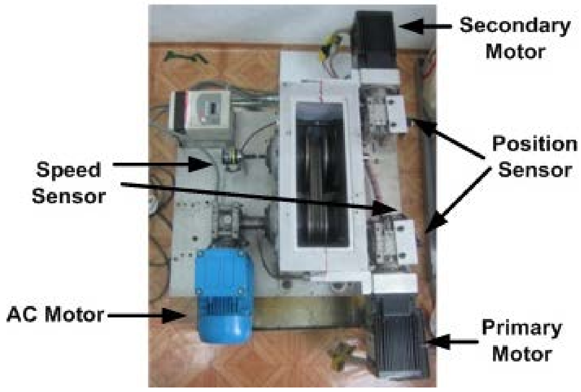

Fig. 4. Photograph of the test rig

The calibration procedure can be carried on as follows. Firstly, the AC motor is turned on to rotate the primary shaft at about 57 rpm. Then, the desired speed ratio is set manually by adjusting the primary and secondary axial pulley positions accordingly. The real speed ratio is calculated by dividing the input shaft speed with the output shaft speed resulted from speed measurements, and displayed on the computer screen. When the desired speed ratio is achieved, the AC motor is stopped, then the pulley widths are measured using digital Vernier Caliper as shown in Fig. 5. By performing some calculations, the axial pulley positions, pulley radii, and geometrical ratio can be determined. Finally the geometrical ratio is validated using the speed ratio.

This experiment was carried out for CVT ratio from 0.7 to 2.0 with the step increment of 0.05. The corresponding values of primary and secondary pulley positions, output voltages of pulley position sensors as well as output voltages of shaft speed sensors are recorded and used as reference data for future EMDAP CVT calibration process before it is used for real control implementation.

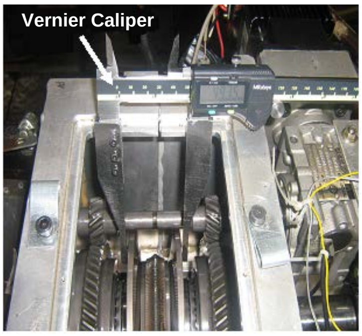

Fig. 5 Pulley gap measurement

6 Results and Discussion

The results presented are based on the data obtained from several experiments performed using data acquisition system and MATLAB/Simulink software. The software reads and saves the output voltages of axial primary and secondary pulley position sensors as well as the output voltages of primary and secondary speed sensors. Based on these voltage data, calculations were performed to determine the actual measurement values of axial pulley positions, pulley radii, shaft speeds and CVT ratios.

When the CVT ratio value increases from 0.7 to 2.0, the secondary shaft speed decreases from approximately 80 to 28 rpm. The same speed is achieved when the CVT ratio is one which is 1:1 ratio. If the CVT ratio is less than one, then the secondary speed is bigger than the primary speed. The fastest secondary speed occurs when the CVT ratio is 0.7 which is called as an over-drive ratio. But, if the CVT ratio is bigger than one, then the secondary speed is less than the primary speed. The slowest speed occurs when the CVT ratio is 2.0 which is an under-drive ratio. For all CVT ratios (0.7 to 2.0), the average values of primary and secondary speeds are shown in Fig. 6, while the output voltages of primary and secondary pulley position sensors are displayed in Fig. 7.

The effective working ranges of the primary and secondary pulley position sensors are approximately 0.9 to 3.8 and 0.49 to 2.9 Volts respectively. Maximum voltages of primary and secondary pulley position sensors are about 3.8 and 2.9 Volts respectively, which are less than 5 Volt. It means that both position sensors are working in the safe

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region, since their working ranges never exceeds 5 Volt.

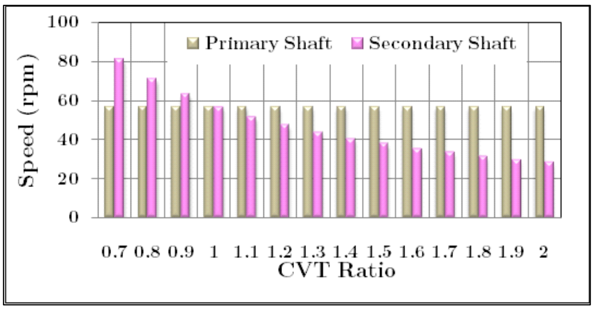

Fig. 6 Speeds vs. CVT ratio

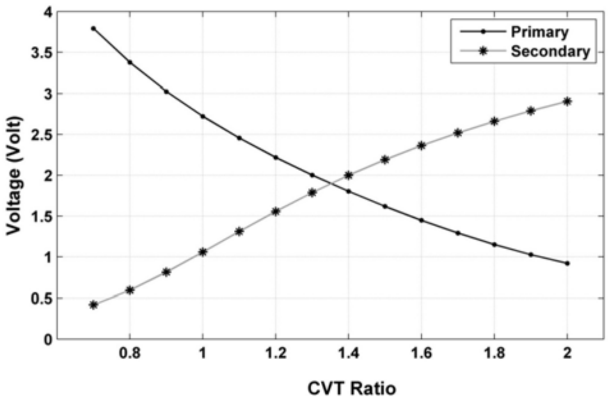

Fig. 7 Voltages of position sensors vs. CVT ratio

7 Conclusion

The experimental rig has been set up and validation of CVT ratio based on speed and geometrical ratio has been performed successfully. The proper geometrical ratios for all CVT ratios of (0.7 to 2.0) were obtained by controlling the primary and secondary DC motor systems manually to adjust the primary and secondary pulley positions such that the secondary (output) shaft speeds gives matching values between the geometrical ratio and speed ratio. This validation also results in output voltages of primary and secondary pulley position sensors which correspond to their respective CVT ratios. These voltages will later be used as references to control the actual CVT ratio.

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