Design and Simulation of a New Single Actuator Double Acting Electro-Mechanical Continuously Variable Transmission

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***Abstract*—This paper presents a new design of an electro-mechanical Continuously Variable Transmission (CVT) by using dual acting pulley at driver and driver sides with single actuator to vary the belt radius. Several conceptual designs on pulley geometry and its working mechanism were proposed and evaluated. The best evaluation design was selected and a prototype of the CVT system, namely single actuator double acting electro-mechanical (SADAEM) CVT system was built. All the mathematical equations will be derived in this paper and the modelling was developed using MATLAB Simulink software. The performance of the SADAEM CVT system was evaluated in term of belt radius and CVT ratio tracking by using proportional−integral−derivative (PID) controller. The results obtained by the simulation showed that the response trends were similar with an acceptable error.**

***Index Terms*—continuously variable transmission, single actuator, dual acting pulley, belt radius, CVT ratio**

I. Introduction

Recently, green technologies have been widely developed and used in automotive industry for minimizing hazardous gas emission and improving fuel consumption to reduce environment pollution. One of the technologies is developing an efficient transmission system. Generally, there are two types of transmission: transmission with step gears and infinite number of gears. The transmission with step gears has discrete number of individual gear ratios which can be set manually or automatically. Meanwhile, a continuously variable transmission (CVT) is a transmission with infinite number of gear ratios within the range.

A vehicle equipped with CVT offers smooth vehicle acceleration without gear shift shock and good fuel efficiency [1-6]. Commonly, CVT used in the market is an electro-hydraulically actuated type [7-14]. It needs continuous hydraulic power to supply clamping force to the pulleys for changing and maintaining the desired CVT ratio. Moreover, the drawback of this system includes heavy electro-hydraulic components and the possibility of hydraulic line leakage that could reduce the overall transmission efficiency [15].

An alternative solution is to use electro-mechanical type actuation system. Initially, this system consists of single acting pulleys that only operate during changing the CVT ratio. Once the desired CVT ratio has been achieved, the mechanical parts keep the CVT ratio in a fixed position without consuming any power [16-18]. However, the CVT system with a single acting pulley mechanism causes a belt misalignment and may reduce the belt lifespan and transmission efficiency.

Another alternative solution is to use a dual acting pulley system which moves simultaneously to keep the alignment of the belt in centre position, thus preventing the belt misalignment from occurring. This system namely electro-mechanical dual acting pulley (EMDAP) CVT consists of two DC motors, power screw mechanism and two set of movable pulleys in both driver and driven sides [19-24]. The drawbacks of this system are that it is complicated and precise control system needs to be implemented to control the two DC motors to gain the desired CVT ratio.

A current vehicle equipped with CVT has pulley ratio coverage from 0.38 to 2.64 [2]. Lower gear ratios are required to increase the vehicle acceleration and higher gear ratios are needed to achieve better fuel efficiency on the vehicle. The extension of ratio range depends on the running diameter of the belt at driver and driven sides. Thus, to obtain larger ratio range, it is necessary to develop smaller and bigger running diameter at pulley sides. Therefore, this study proposed a CVT system, namely single actuator double acting electro-mechanical

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(SADAEM) CVT system that consists of larger pulley ratio range.

This paper is organized as below. Section II describes the development and evaluation of several conceptual designs on pulley geometry. Then, the development of the mathematical model is elaborated in Section III. In Section IV, the simulation results that used conventional proportional−integral−derivative (PID) controller are discussed. Finally, the conclusion of the study is explained in Section V.

II. Conceptual Design

In this section, several electro-mechanical CVT concept designs especially on pulley geometry and working mechanism are discussed. Moreover, previously developed CVT designs have been referred to [25-29]. Then, all proposed concept designs had to fulfil the following requirements:

a) Target of pulley ratio range between 0.3 and 3.0.

b) The design must be functional, compact and easy to maintain.

c) The design only focuses on the CVT's pulley, relevant components and working mechanism to vary the belt radius.

The first design concept shown in Fig. 1 consists of several components, namely pulley with diameter of 340 mm, pulley slider and cone. Forward and reverse movement of the cone caused the pulley slider to move up and down which varies the belt radius.

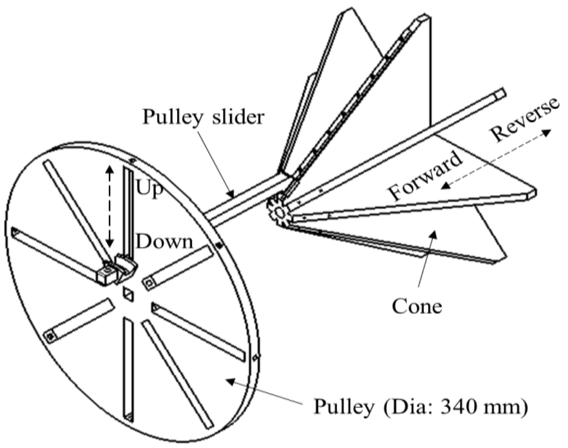

Figure 1. Conceptual design I

Next, Fig. 2 illustrates the conceptual design II which consists of same components as design concept I except the cone. It was replaced by a set of bevel gear and power screw. Rotation from DC motor in clockwise or counter clockwise will rotate the set of bevel gear and power screw. Therefore, the pulley slider will increase or decrease in term of belt radius. The disadvantage of conceptual design I and II was the possibility that the huge pulley diameter could affect overall transmission size.

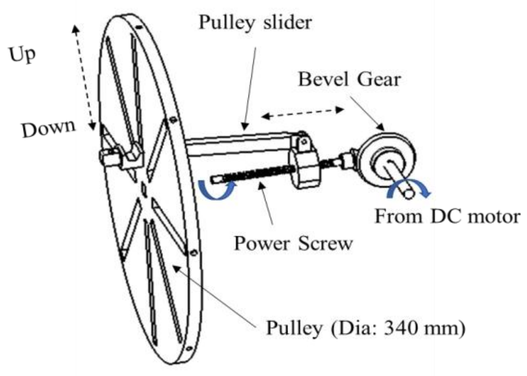

Figure 2. Conceptual design II

The third conceptual design was developed to overcome any weaknesses found in previous concept designs. Fig. 3 shows the conceptual design III with pulley size of 160 mm in diameter, sheave housing at both sides and shaft to support the dual pulleys and sheave housings. To maintain the transmission casing size, this concept was adopted because it approximately had the same size as the current pulley size that has been widely use in the market. The uniqueness of this concept was that the dual pulleys were able to move simultaneously to achieve the desired belt radius position.

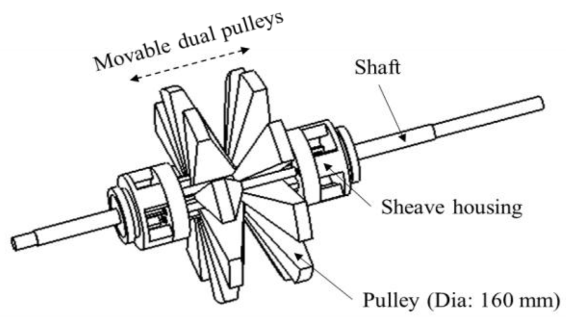

Figure 3. Conceptual design III

Next, all the conceptual designs need to be evaluated to determine which one of the conceptual designs was suitable to satisfy the requirements. Thus, weight objective factor and scale methods were used to evaluate the conceptual designs [30]. Table I shows the evaluation on every objective and determination of the weight factor. The scale was assigned to each objective using (0–10) points which indicates that the highest point represents a perfect solution, while the lowest point indicates a useless solution.

TABLE I. List of Weight Factor for Each Objective

Objective	Importance ranking	Scale	Weight percentage, %	Weight factor
Functional	1	8	26.7	0.267
Durability	2	7	23.3	0.233
Maintenance	3	6	20.0	0.200
Size	4	5	16.7	0.167
Cost	5	4	13.3	0.133
Total		30	100	1.0

The results of the conceptual design evaluation are shown in Table II, where the highest total point indicates the most suitable concept to be used in final design. Conceptual design III scores the highest point and was selected as the final conceptual design.

TABLE II. CONCEPTUAL DESIGN SELECTION BASED ON NUMERICAL EVALUATION

Objective	Weight factor	Conceptual design		
		I	II	III
Functional	0.267	5	7	8
		1.335	1.869	2.136
Durability	0.233	5	6	8
		1.165	1.398	1.864
Maintenance	0.200	5	8	7
		1.000	1.600	1.400
Size	0.167	5	5	8
		0.835	0.835	1.336
Cost	0.133	7	8	6
		0.931	1.064	0.798
Total		5.266	6.766	7.534

III. MODELLING OF SADAEM CVT

This section describes the mathematical model of the CVT prototype system after evaluation process of conceptual designs in the previous section. The prototype, namely the SADAEM CVT system consists of one DC motor (primary) as an actuator to vary the belt radius at driver and driven sides simultaneously, as shown in Fig. 4. The primary DC motor shaft was connected to the top linkage mechanism at driven side and driver side. The top linkage mechanism has power screw with different threads which were right threaded and left threaded at driven and driver side, respectively. This allowed an opposite direction of pulley axial movement at both sides. A variable speed rubber belt was placed between the pulley at driver and driven sides. This rubber belt acts as torque and speed transfer from driver side to driven side as a result of friction between rubber belt and pulley surfaces.

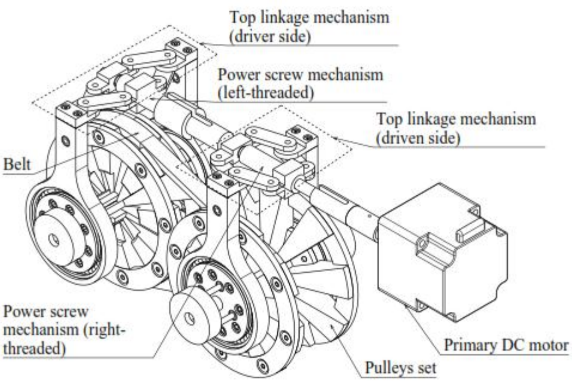

Figure 4. Prototype of SADAEM CVT system

This paper only covers the dynamic motion at only one side of SADAEM CVT since all components at both sides had same material properties and dimensions. The mathematical model in SADAEM CVT started with input voltage to DC motor and ended with belt radius output. There were several mechanisms involved in between the input to DC motor and belt radius output that will be elaborated in the next sub-sections.

A. Model of DC Motor

In this study, the brushless DC motor was modelled considering electrical and mechanical parts as described in [31]. The input voltage from DC motor, *Vm* produced current, *I* that converted into the required motor torque, *Tm*. Referring to [32] and using the trial and error method to fit the current DC motor model, Table III shows the simulation parameters of DC motor.

TABLE III. DC MOTOR MODEL PARAMETER LIST

Parameter	Symbol	Value	Unit
Motor damping coefficient	b	0.0070	Nms
Motor inertia	J	0.0012	kgm^2
Motor emf constant	Kv	0.2319	V/rpm
Motor torque constant	Kt	0.0260	Nm/A
Motor electrical inductance	L	0.0500	H
Motor electrical resistance	R	5	Ω

B. Model of Power Screw Mechanism

A power screw mechanism was used to axially move the top linkage mechanism either expand or shrink motions. It converts a rotation of 360 degree into 2 millimetres of horizontal movement. Force required by power screw to moves top linkage mechanism axially can be expressed as follows:

$$F_R = \frac{2T_m}{d_m}\left(\frac{\pi d_m - \mu t_l}{t_l + \pi\mu d_m}\right) \quad (1)$$

where, the motor torque is denoted as *Tm*, the mean diameter of power screw is presented as *dm*, the coefficient of friction is indicated as μ and power screw thread lead is denoted as t_l. Thus, the raising force, F_R will be input for the top linkage mechanism.

C. Model of Top Linkage Mechanism

Fig. 5 shows the top linkage mechanism components that consists of four links which equal in size, power screw nut, lock screw nut, power screw, and right and left hinges. If power screw rotates in clockwise direction, power screw nut will move in positive X-direction, hence the right hinge will translate in positive Y-direction and the left hinge will travel in negative Y-direction. The dynamic behavior of the top linkage mechanism can be mathematically derived by using Lagrange function, L_f that can be expressed as:

$$L_f = \sum_{i=1}^{n} T_i - \sum_{i=1}^{n} V_i \quad (2)$$

where T and V are the kinetic and potential energies, respectively at each components of top linkage mechanism.

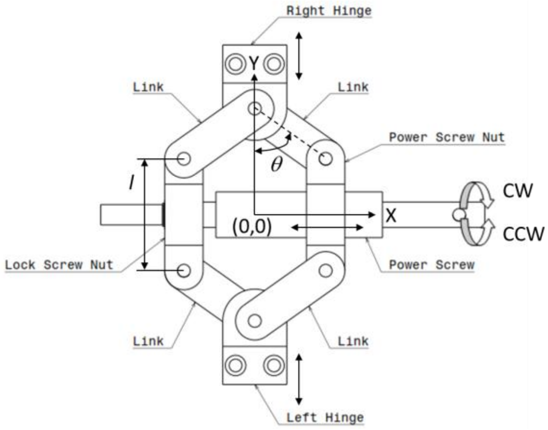

Figure 5. Top linkage mechanism components

Next, assuming the masses of links are same and denoted as *m*, and *M* are the masses of the right and left hinges, respectively, moments of inertia for links are equal and represented as *I*, length of all links, lock screw nut and power screw nut is same and represented as *l*, *F* is force generated from power screw mechanism, mass of power screw nut is denoted as *m1* and *m5* is lock screw nut mass, the nonlinear equation of angle, θ can be obtained.

$$\ddot{\theta} = F - \left\{ \begin{matrix} Ml^2(\sin 2\theta) - \frac{l^2}{2} m5(\sin 2\theta) \\ -\frac{l^2}{2} m1(\sin 2\theta) \end{matrix} \right\} \dot{\theta}^2 \Big/ \left\{ \begin{matrix} 4I + ml^2 + 2Ml^2(\sin\theta)^2 + \\ m5l^2(\cos\theta)^2 + m1l^2(\cos\theta)^2 \end{matrix} \right\} \quad (3)$$

Consequently, the displacement of the right and left hinges on the Y-axis is denoted as y_{rh} and y_{lh}, respectively, and can be expressed as:

$$y_{rh} = l(\cos\theta) + 0.022 \quad (4)$$

$$y_{lh} = -l(\cos\theta) - 0.022 \quad (5)$$

D. Model Belt Mechanism

The SADAEM CVT system consists of two set of pulleys at driver and driven sites which simultaneously move axially. The movement was directly related to right and left hinges displacement. Therefore, axial displacement on pulleys lead to the belt radius at driver and driven sides. Assuming the belt radius at driver side, *Rp* and belt radius at driven side, *Rs*, CVT ratio, r_{cvt} can be obtained.

$$r_{cvt} = R_s / R_p \quad (6)$$

IV. Simulation Results and Discussion

A model-based control design software, namely MATLAB Simulink was used to perform the simulation study. The proposed SADAEM CVT system was analysed with a fixed step of 0.01 second in time domain by using Runge-Kutta solver. This study used a simple, robust and stable controller, namely PID controller and the equation that governed a PID controller is presented as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (7)$$

where *u(t)* is control variable, *e(t)* is error value, K_p is proportional gain, K_i is integral gain and K_d is derivative gain.

Here, position control in term of belt radius and CVT ratio were performed to examine the behavior of the proposed SADAEM CVT system. Table IV displays the controller parameters obtained using the trial and error technique.

TABLE IV. Simulation Control Parameters

Parameter	DC motor controller	Belt radius controller
Proportional gain, *Kp*	53	250
Integral gain, *Ki*	25	0
Derivative gain, *Kd*	0	3

A. Control of Belt Radius Position

In the evaluation of the controller responses, several inputs, namely step, square, sine and triangle reference signals were fed into the SADAEM CVT system. The belt radius range was set between 0.022 and 0.064 m. Figs. 6 (a–d) shows the performance evaluation of the belt radius position tracking using step, square, sine and triangle inputs, respectively. The dashed line represents the desired input response, while the solid line indicates simulation results.

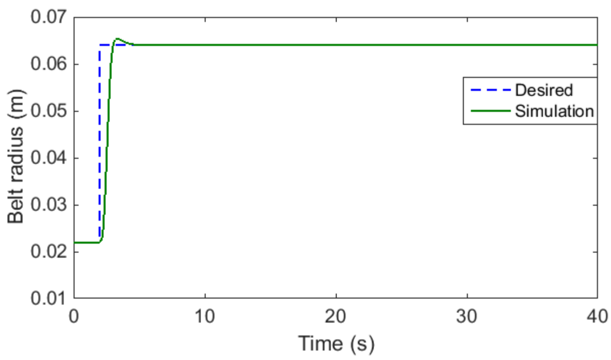

Figure 6. (a) Step input response

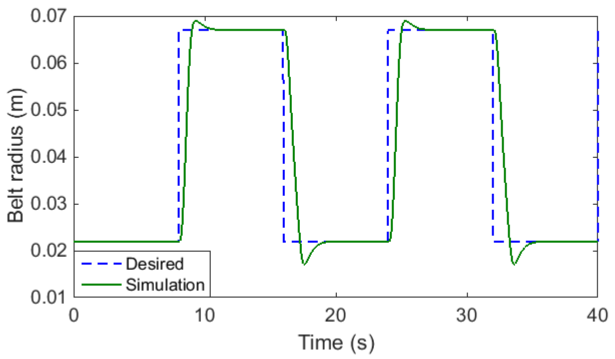

Figure 6. (b) Square input response

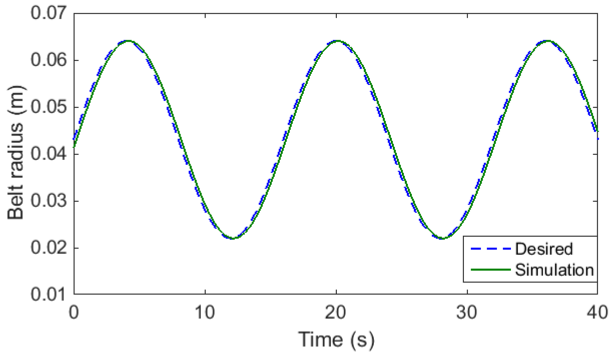

Figure 6. (c) Sine input response

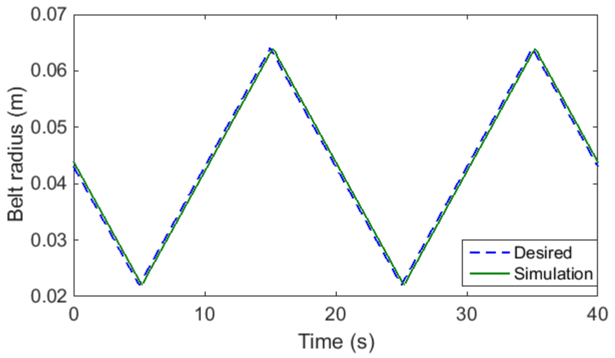

Figure 6. (d) Triangle input response

Based on the results of step input response, the simulation had a delay time of 0.07 s, rise time of 1.03 s, percentage overshoot of 2.03 % and settling time of 3.5 s. For square input response, the transient response results were nearly the same as step input results. The simulation results for square input were 0.05 s of delay time, 1.03 s of rise time, percentage overshoot of 2.03 % and settling time of 3.5 s (Fig. 6b).

Meanwhile, for sine and triangle input functions, both simulation results showed nearly 0.2 s phase lag along the desired response. Therefore, based on the simulation results of belt radius performance, the occurrence of delay time and phase lag were mostly contributed by a backlash and friction on the moving parts inside the SADAEM CVT system. However, the system still could provide adequate responses in following the desired radius position.

B. Control of CVT Ratio Position

Fig. 7 (a) to (d) displays the transient response of CVT ratio against time with different inputs. From these figures, the dashed line represents the desired CVT ratio and solid line denotes the simulation results of CVT ratio.

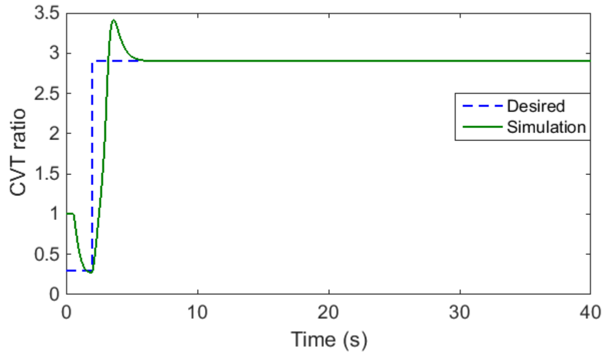

Figure 7. (a) CVT ratio position control by step input

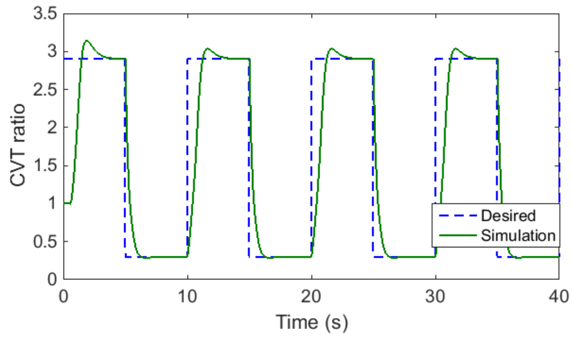

Figure 7. (b) CVT ratio position control by square input

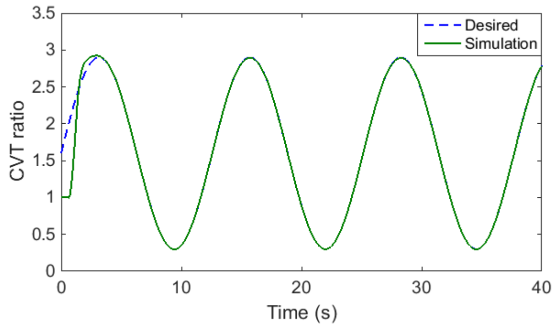

Figure 7. (c) CVT ratio position control by sine input

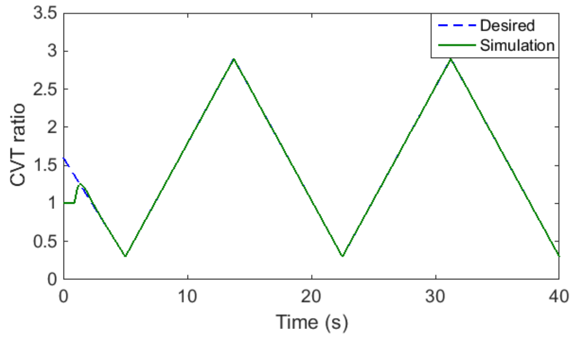

Figure 7. (d) CVT ratio position control by triangle input

The observation of the CVT ratio transient response results are listed in Table V in term of root mean square (RMS) values and percentage difference between simulation and desired results. Based on the tabulated results, the percentage of differences using RMS values between desired and simulation results are not more than 1 % for all inputs.

TABLE V. RMS RESULTS OF CVT RATIO RESPONSE

Input type	RMS value		RMS percentage difference (%)
	Desired	Simulation	
Step	2.909	2.902	0.241
Square	0.303	0.302	0.330
Sine	2.784	2.780	0.216
Triangle	0.303	0.302	0.330

V. CONCLUSION

In this study, several conceptual designs that meet the requirements have been proposed and evaluated. Next, the prototype of the SADAEM CVT system consisting of single DC motor actuator and dual acting pulleys has been designed. Then, from the proposed prototype design, the nonlinear mathematical model of the SADAEM CVT system has been derived and implemented in the MATLAB Simulink environment. To investigate the performance of the proposed system, the PID controller with four types of inputs has been employed in the system. The belt radius and CVT ratio results proved that with suitable controller parameters, the proposed SADAEM CVT system could produce good performance and closely followed the desired input responses. Although the simulation results had several deviations that contributed to minor errors due to backlash and mechanical parts friction, it was still acceptable. Therefore, future works would attempt to involve experimental works on the proposed SADAEM CVT system to investigate the belt radius and CVT ratio responses.

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