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SECONDARY PULLEY CLAMPING FORCE CONTROLLER FOR ELECTRO-MECHANICAL DUAL ACTING PULLEY CONTINUOUSLY VARIABLE TRANSMISSION SYSTEM

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ABSTRACT

This paper introduces an electro-mechanical dual acting pulley continuously variable transmission (EMDAP CVT) system and presents a method of measuring belt-pulley clamping force indirectly using a DC motor current sensor. The EMDAP CVT mainly consists of two movable primary (input) and secondary (output) pulley sheaves connected by metal pushing V-belt. Two DC motor's actuation systems adjust the CVT ratio. Additionally, the secondary actuation system controls belt-pulley clamping force by adjusting the flatness of the spring discs placed at the back of each secondary pulley sheave to keep the belt tight and prevent belt slip. Ideally, a force sensor is used to measure the belt-pulley clamping force however the use of force sensor inside transmission gearbox is not feasible due to high temperature and oily environment. A viable solution for indirectly measuring the clamping force using current sensor for DC motor is proposed. Since the DC motor actuates the movable pulleys to clamp the belt, the relationship between the DC motor current and belt-pulley clamping force can then be investigated experimentally. The results will give positive impact on precisely controlling belt-pulley clamping force of EMDAP CVT using current sensor which is relatively simpler and less expensive than force sensor.

Keywords: continuously variable transmission (CVT), pulley clamping force, PID, electro-mechanical.

INTRODUCTION

A Metal Pushing V-Belt (MPVB) Continuously Variable Transmission (CVT) is a kind of transmission mainly consisting of metal belt, primary and secondary pulley system. The belt connects the two pulleys and moves on their surfaces to transfer both torque and speed from the primary to secondary pulleys. This system allows the CVT to have infinite number of transmission ratios between its lowest to highest limits; hence providing stepless ratio changes and delivering smooth driving experience. In CVT application, transferring both torque and speed from the primary to secondary shaft is done based on friction developed between belt and pulley sheaves' contacts [1-4]. Sufficient amount of clamping force is required to ensure the belt will not slip. Since an excessive belt slip can severely damage the belt [5,6]. Most todays CVT application uses higher clamping force safety factor to prevent belt slip. However, this excessive safety factor application may reduce CVT's fuel efficiency performance [7,8]. For hydraulic CVT, the clamping force can be obtained from pressure sensor measurement, while for an electro-mechanical CVT, clamping force should be ideally measured using force sensor. But, the use of force sensor inside the CVT gearbox for real application might not be feasible because of high temperature and oily environment [9]. However, the use of force sensor is still required in the EMDAP CVT experimental test rig for studying the behavior of pulley clamping force before the force sensor is replaced by other feasibly alternative sensor. Data acquisition system used in this experiment is Arduino Uno, as shown in Figure-1, which is inexpensive microcontroller board based on ATMega328 system with 6 analog to digital converter (ADC) pins and 14 configurable digital input/output pins, in which 6 of them can be configured as pulse width modulation (PWM) based analog outputs [10]. The Arduino Uno should be pre-programmed first before it is used to communicate with Matlab/Simulink via USB port. Recently, there have been quite numbers of control applications involving Arduino microcontroller system and Matlab/Simulink such as robot prototyping [11], water level control [12], autopilot rapid prototyping [13], DC-to-DC boost converter [14] and solar tracker control [15]. In this research, Arduino Uno is used as a data acquisition system which reads force sensor and drives the brushless DC (BLDC) motor which actuates the clamping force system.

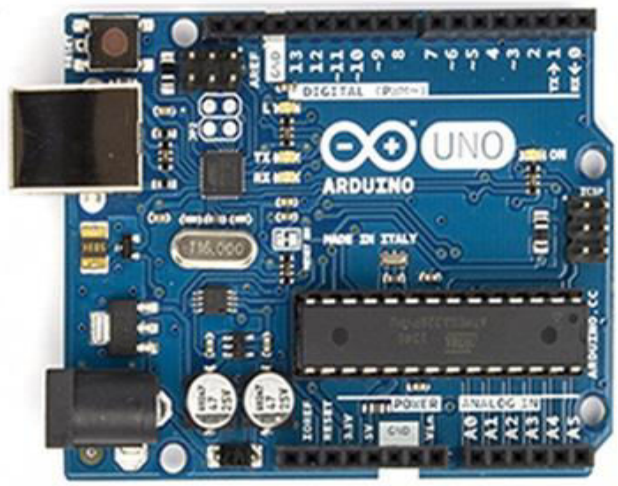

Figure-1. Arduino uno.

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The objective of this research is to implement real time Proportional-Integral-Derivative (PID) based secondary pulley clamping force controllers using an inexpensive Arduino Uno data acquisition system and Matlab/Simulink® software. The combination of relay feedback method and Ziegler Nicholl formula is utilized to determine initial PID parameters experimentally. By applying PID based controllers to the DC motor, the pulley clamping force can be adjusted to achieve the desired force. The performance of the clamping force controller is assessed in terms of percent overshoot, settling time and steady state error.

SYSTEM DESCRIPTIONS

The pulley clamping force test rig, as shown in Figure-2, consists of computer with Matlab/Simulink, Arduino Uno based data acquisition system, force sensor, power supply and electro-mechanical actuated clamping force system (EMACFS). The EMACFS mainly consists of pulley clamping force system, as shown in Figure-3, which is actuated by a brushless DC motor. The pulley clamping force system has two sets of pinion and helical gears, power screw mechanisms, spring discs, and movable pulley sheaves. The spring discs transfer spring axial force to the pulley sheave. The pulley sheaves are facing to each other to clamp the belt placed between them. In this case, the belt has been replaced by a force sensor for clamping force measurement. The DC motor acts as a power source for the actuator. Two sets of gear reducers are used as speed reducer and torque multiplier for the DC motor to ensure a sufficient amount of belt clamping force can be delivered to the pulley sheaves to clamp the belt. The first gear reducer of this system has the ratio of 40:1, while the other, which consists of pinion and helical gear set, has the ratio of 68:14. The screw mechanism converts every one rotational movement of the helical gear into 2 mm axial movement. When the DC motor activates the gearing system, the helical gear outputs rotate and actuate the power screw mechanisms to axially move the two sets of disc spring and movable pulley sheave in opposite direction to each other to clamp the belt. In this test rig, the belt has been replaced by a force sensor which is used to measure the clamping force developed by the spring discs on the movable pulley sheaves. The clamping force acting on the force sensor can be varied by regulating the spring deflections. The minimum clamping force occurs when the springs are fully uncompressed, while the maximum force occurs when the springs are fully compressed at their flat positions.

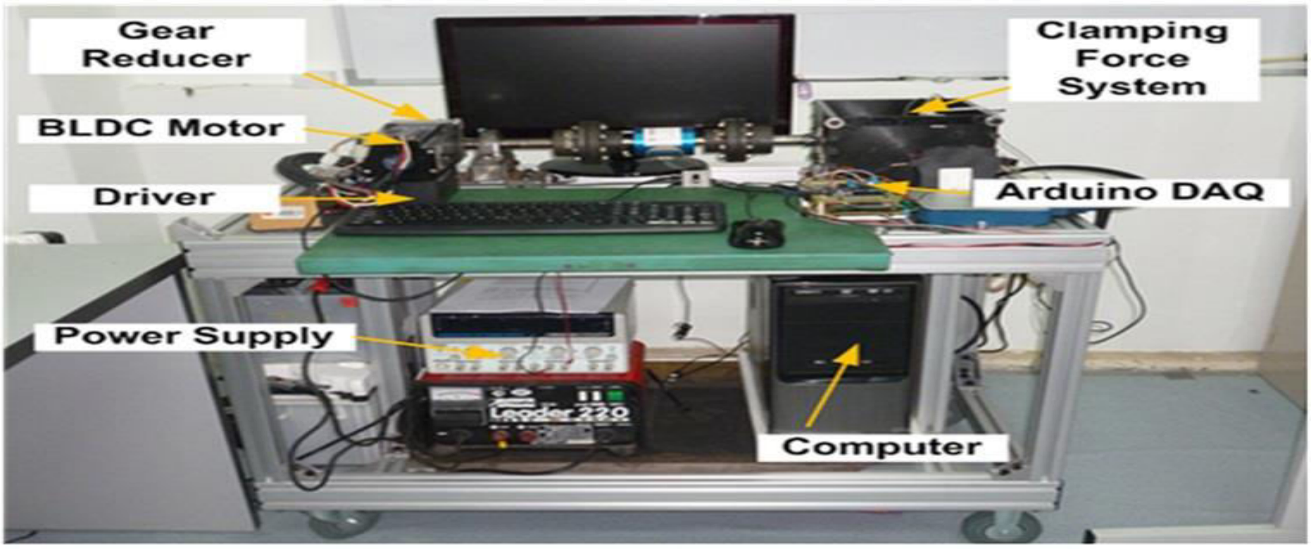

Figure-2. SEM image for peanut shells powder.

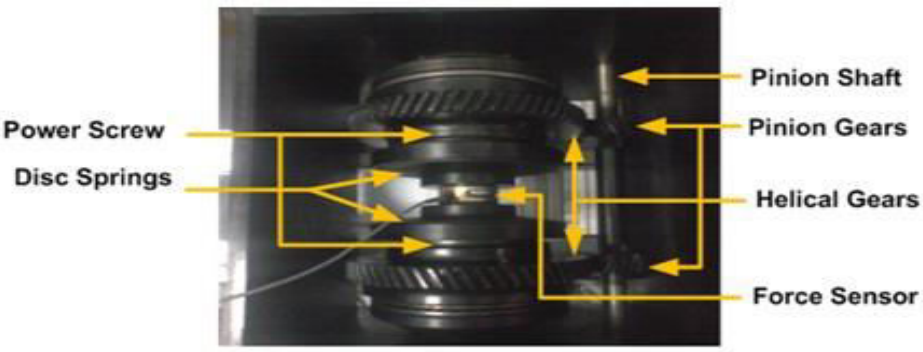

Figure-3. Pulley clamping force system.

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INITIAL PID PARAMETERS

In order to satisfy the objectives of the clamping force controller system, the PID based clamping force controller requires suitable PID parameters consisting of proportional (K_p), integral (K_i) and derivative (K_d) gains. These parameters can be obtained using relay feedback tuning method (RFTM) [16]. The RFTM is used due to easier to implement, less time consuming and safer than Ziegler-Nichols (ZN) sustained oscillation, limited cycle oscillation amplitude and no need of system's mathematical model. By applying relay feedback in the clamping force closed loop system, the clamping force oscillations output and relay output voltage can be produced. The critical gain (K_c) is determined using Eqn. (1), while the critical period (T_c) is determined from periodical time of relay output. Next, by using Ziegler-Nichols formulas as listed in Table-1, proportional gain (K_p), integral time (T_i) and derivative time (T_d) are calculated. Finally, the K_i and K_d can be computed using Eqns. (2) and (3), respectively. Some equations related to PID parameters are given as follows:

$$K_C = \frac{4h}{\pi a} \qquad (1)$$

$$K_i = \frac{Kp}{Ti} \qquad (2)$$

$$K_p = K_p T_d \qquad (3)$$

where, h is output relay voltage and a is output oscillation amplitude.

Table-1. Ziegler-Nichols formula for oscillatory response method.

Controller	K_p	T_i	T_d
PID	0.60 Kc	0.50 Tc	0.125 Tc

PROPORTIONAL DERIVATIVE PLUS CONDITIONAL INTEGRAL (PDPCI) CONTROLLER

PDPCI controller is combination of PD controller and integral controller, in which the integral action will be activated later when the steady error is approaching to zero to eliminate steady state error [17]. PID controller with a big integral gain (K_i) may cause the system unstable due to integral windup [18]. For this case, PDPCI can be an alternative controller which separates the PID into PD and conditional integral controller to improve the PD controller performance. PDPCI compares the absolute value of the system error with the predetermined conditional value to activate the integral action. If the system error is bigger than the conditional value, then PDPCI acts as a standard PD controller. But if the system error is less than or equal to the conditional value, then PDPCI acts as a standard PID controller in which the integral part gradually eliminates the steady state error.

RESULTS AND DISCUSSIONS

The results of relay feedback experiment are shown in Figure-4 and Figure-5. Based on the average values of amplitudes in Figure-4 and relay voltage in Figure-5, the critical gain (K_c) can be calculated using Eqn. (1). By taking the average values of period in Figure-3, the critical period (T_c) can be obtained. The initial PID parameters are computed using Ziegler-Nichols formula in Table-1, Eqn. (2) and Eqn. (3). The resulted initial PID parameters are presented in Table-2, while the controller performance for 10 kN set point is shown in Figure-6. From Figure-6 all controllers do not show any overshoot. The fastest respond is produced by PDPCI controller with settling time of about 5 seconds, then PD controller with about 7 seconds and finally P controller with the longest settling time. In terms of steady state error, PDPCI controller has the lowest of about 0.01 kN (0.1%), then PD controller with about 0.04 kN (0.4%) and P controller with about 0.92 kN (9.2%).

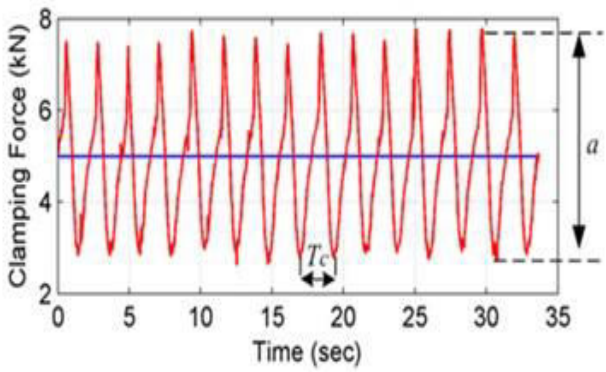

Figure-4. Pulley clamping force system.

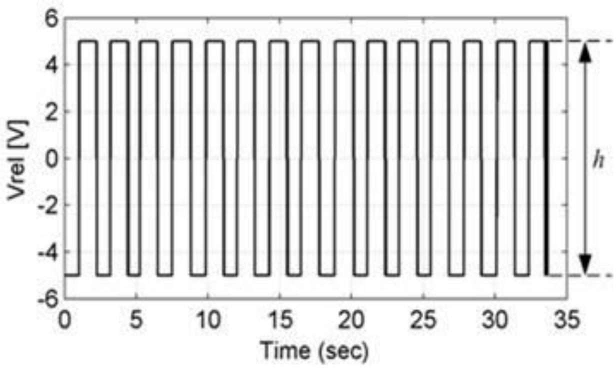

Figure-5. Relay output voltage.

Table-2. PID parameters.

K_p	K_i	K_d
16.98	14.84	0.29

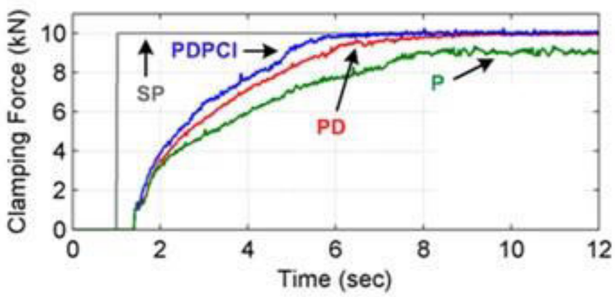

Figure-6. Clamping force controller respons.

CONCLUSIONS

By using initial PID parameters resulted from relay feedback tuning method (RFTM), the clamping force PID based controllers have shown good performance. It proves that the RFTM can be an acceptable and effective method of providing initial PID parameters for PID based control algorithms used in this electro-mechanical clamping force controller system. The system response performance tests of P, PD and PDPCI controllers were carried out using step input of 10 kN clamping force. In this case, the PDPCI controller has adequately improved the P, and PD performance in terms of settling time and steady state error.

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