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PID Control of an Electro-Mechanical Friction Clutch System

M. S. Che Kob, B. Supriyo, K. B. Tawi, M. Hussein, Y. Zainal Abidin

***Abstract*—**The main contribution of control technology in automotive powertrain system is that, it enables the whole powertrain system to be precisely controlled; thereby, improving the overall vehicle powertrain performance and sustainability. This paper describes a proportional-integral-derivative (PID) controller development for an electro-mechanical friction clutch (EMFC) system for automotive applications especially, those using continuously variable transmission (CVT). Initially, a simulation study was carried out to determine the PID preliminary parameters values derived using the Astrom and Hagglund tuning method with Ziegler-Nichols formula; then, they are manually being fine- tuned experimentally to improve the clutch engagement and disengagement control performance until satisfying engagement and disengagement process are achieved. The results of this work show that the application of Astrom-Hagglund method and Ziegler-Nichols formula is capable of providing a practical solution for obtaining initial parameters of the PD controllers of engagement and disengagement control of the EMFC system. Through optimizing of P and D parameters, the system indicated excellent performances with improvement in terms of percentage overshoot, settling time and a very small steady state error for clutch engagement and disengagement processes.

***Keywords*—**Electro-mechanical Friction Clutch, Clutch Engagement Control, PID Controller.

I. Introduction

Advances control technology in internal combustion engine (ICE) normally reduces the toxicity of exhaust gasses leaving the ICE, but this alone have generally been proved insufficient to meet emissions goals. Thus, the trend towards more highly automated transmissions will play important role in future automotive systems. With the current theorised threat of global warming where fossil fuel powered vehicles are one of the major contributors – it becomes a paramount important for all car manufactures to produce fossil fuel powered vehicles that are environmentally friendly and if possible with zero CO_2 emissions. Unfortunately, to the best of the authors' knowledge until today the later is still far from possible.

However, different approaches, such as dual clutch transmission (DCT), automatic transmission (AT), automated manual transmission (AMT) and continuously variable transmission (CVT) that utilize the drive-by-wire technologies, to a certain extent has manage to minimise fuel consumption and exhaust emissions; and also improve vehicle safety, comfort, reliability and driving performance [1]. For example, vehicle with AMT is generally constituted by a dry friction clutch-by-wire system as means of easing the driver's task and thus, enhancing driving satisfaction [2]. Clutch-by-wire basically, replaces the clutch pedal with a mechanically or hydro-mechanically actuated dry friction clutch that operates based on appropriate control algorithm. With regards to manual transmission, the AMT relatively, improve driving comfort and shifting quality by controlling the dry clutch engagement process. This clutch engagement process plays an important role in reducing clutch wear and improves the overall powertrain performance [3-5, 17].

Currently, most of the clutches used in CVT applications are based on electro-hydraulic and electro-magnetic actuations. These actuation systems are selected because they can be controlled electronically [5]. Relating to this technology, a novel EMFC system for a novel electro-mechanical dual acting pulley (EMDAP) CVT applications have been developed by Drivetrain Research Group (DRG) of Universiti Teknologi Malaysia (UTM) as one the future generation transmission [20]. This novel EMFC enables the clutch to be operated electronically so that a suitable closed loop control strategy can be applied in order to satisfy clutch engagement control objectives such as smooth engagement process with minimum engagement time [4].

However, since there are quite a number of available potential methods that can be used to come out with an appropriate control strategy, the authors choose Astrom and Hagglund tuning method with Ziegler-Nichols formula to continuously and variably control the newly developed EMFC engagement process. Thus, this paper intend to determine the possibility of using Astrom and Hagglund tuning method with Ziegler-Nichols formula to continuously and variably control a newly developed EMFC engagement process.

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II. Problem Description

Nowadays, most clutch systems used in metal V-belt CVT applications are either electro-hydraulically or electro-magnetically actuated [6-8]. The designs of these clutches cause energy losses due to continuous power consumption for continuous clutch engagement. The current CVT vehicle models, such as Insight and Prius use integrated torque converter which provides comfort and convenience, but in return increases its cost and fuel consumption [9]. This hydraulically actuated torque converter needs continuous energy from the hydraulic pump to supply force to maintain the clutch engagement. The continuous energy consumption becomes one of the major disadvantages of the hydraulic CVT clutch system as it reduces the transmission efficiency [10]. Electro-magnetic clutches, as used in Nissan Micra, also consume continuous power in terms of electricity to create continuous magnetic field to maintain the clutch engagement. In both cases, certain amounts of energy are lost in terms of heat.

This research introduces EMFC system as another alternative to this problem. In the EMFC system, engagement and disengagement of the dry friction clutch operates only during starting and stopping of vehicles. A power screw mechanism lock is used to provide continuous clamping force to maintain axial position of the clutch spring, once it is engaged. Hence, no power is consumed for continuous clutch engagement.

However, the engagement and disengagement processes of the EMFC system require appropriate controllers. These controllers must be able to satisfy the requirement of both smooth engagement process with minimum error and sufficient engagement time to provide good powertrain performance and driving comfort. However powertrain performance and driving comfort requirements are different and conflicting to each other. The designed controller should also be able to overcome the fundamental constraint of the clutch engagement process during standing start specifically which is known as no-kill conditions [4, 11].

III. EMFC System

Basically, the main sub-systems of the EMFC system consist of mechanical actuator, a standard dry friction clutch, clutch linkages, a series of gear reducers and a direct current (DC) motor, as shown in Fig. 1. Output shaft of the DC motor is directly connected to the series of gear reducers and a power screw mechanism. The DC motor system is acts as an actuator to the power screw mechanism inside the mechanical actuator. Clutch linkages are used to connect a release bearing to the mechanical actuator. The standard dry friction clutch is used to engage and disengage power from an internal combustion engine (ICE) through the EMDAP CVT gearbox.

Engagement and disengagement of the EMFC system for this EMDAP CVT are being operated by the movement of an inner and outer power screw mechanism inside the EMFC's actuator. The outer power screw is converted into 2 millimetres of linear movement of the inner power screw after every 360^0 of rotation. The linear movement is then transmitted to actuate the shift fork either to engage or disengage the clutch system. The inner power screw is connected to the shift fork by the clutch linkages and the outer power screw is coupled with an output of a gear reducer. The gear reducer serves as a speed reducer and torque multiplier to the DC motor so that the DC motor can supply sufficient power during engagement and disengagement of the EMFC system.

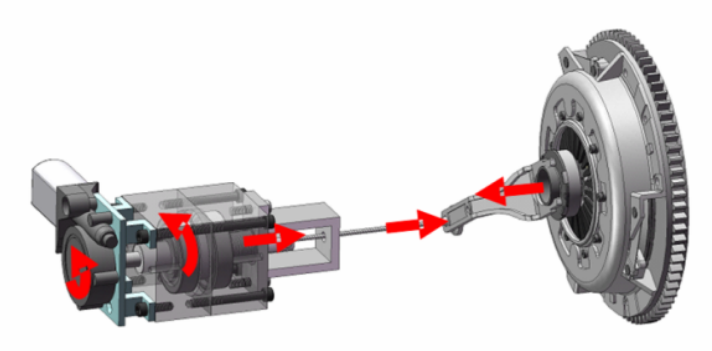

Fig. 1 EMFC System

IV. Proposed Controller

Various efforts were made to control the dry friction clutch engagement process during standing start by proposing a variety of controllers. The main objective of those design controllers is to ensure that two fundamental conditions; no-kill conditions and no-lurch conditions have to be satisfied [11-12]. The no-kill condition states that the engine stall must be avoided, whereas the no-lurch condition assumes that the unwanted oscillations induced in the powertrain should be reduced in order to allow the driving comfort. However these requirements were in conflict with the minimum duration of the engagement time, such as oscillations induced in the powertrain system due to the sudden change of torque within limited time during the clutch engagement process. Furthermore, an engine could be stalled if an excessively fast engagement process occurs.

In order to satisfy the different requirements and desired engagement time, this study proposes a PD controller for the EMFC engagement and disengagement process. The PD controller is relatively easy to be achieved and provides the system an excellent performance through optimizing the P and D parameters [13]. A method for automatically tuning of simple regulators was introduced in Astrom and Hagglund [14]. The idea was to determine the critical period of waveform oscillation (T_c) and the critical gain (K_c) from a simple relay feedback experiment and also to use the Ziegler-Nichols formula to determine the suitable value of three parameters, namely K_p, K_i, and K_d to satisfy certain control specifications. The block diagram of the proposed controller scheme is given in Fig. 2.

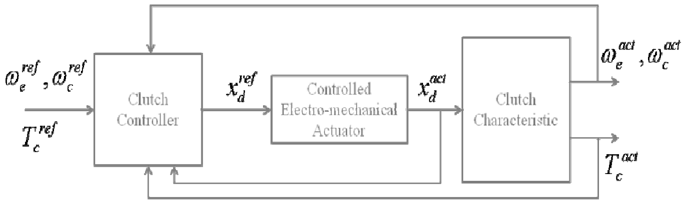

Fig. 2 General closed-loop schemes of EMFC system

A. PD Parameter Tuning Using Astrom-Hagglund Method

Simulation studies of the proposed PD controller were carried out in order to investigate its effectiveness in position control. The values of critical period of waveform oscillation (T_c) and critical gain (K_c) are determined using the Astrom-Hagglund method which is used in Table 1 to obtain the initial parameters of PID controller. Relay feedback is utilized as a controller to the closed loop control system of the DC motor as shown in Fig. 3. The period of sustain oscillation attained from relay feedback is approximated as the critical period. Based on this critical period (Fig. 4, Fig. 5 and Fig. 6), the critical gain can be defined as follows [15], [16], [18] and [19]:

$$K_c = \frac{4d}{\pi a} \tag{1}$$

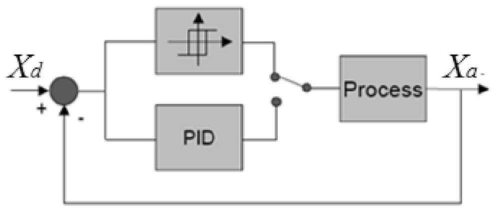

Fig. 3 Block diagram of the relay feedback controller

Once T_c and K_c values are found, the PID parameters (K_p, T_i, and T_d) can be specified using Ziegler-Nichols formula (Table 1).

Table 1 Ziegler Nichols parameter tuning

	K_p	T_i	T_d
P	0.50 K_c		
PI	0.45 K_c	0.85 T_c	
PID	0.60 K_c	0.50 T_c	0.125 T_c

B. Initial Parameter of PD Controller

Fig. 4 shows the results of relay feedback experiment of the DC motor to actuate the inner power screw for full clutch engagement and disengagement processes. The T_c, a, d and K_c values are shown in Table 2. The K_p, K_i, and K_d of the clutch engagement and disengagement PID controller variations are shown in the Table 3.

Table 2 Parameters Tuning

Process	T_c (s)	a (V)	d (V)	K_c
Engagement	0.35	0.93	10	13.69
Disengagement	0.33	0.70	10	18.19

Table 3 PID controller variations

Process	Controller Type	K_p	K_i	K_d
Engagement	P	6.85	0.00	0.00
	PI	6.16	20.65	0.00
	PID	8.21	46.80	0.36
	PD	8.21	0.00	0.36
Disengagement	P	9.10	0.00	0.00
	PI	8.19	29.63	0.00
	PID	10.91	67.16	0.44
	PD	10.91	0.00	0.44

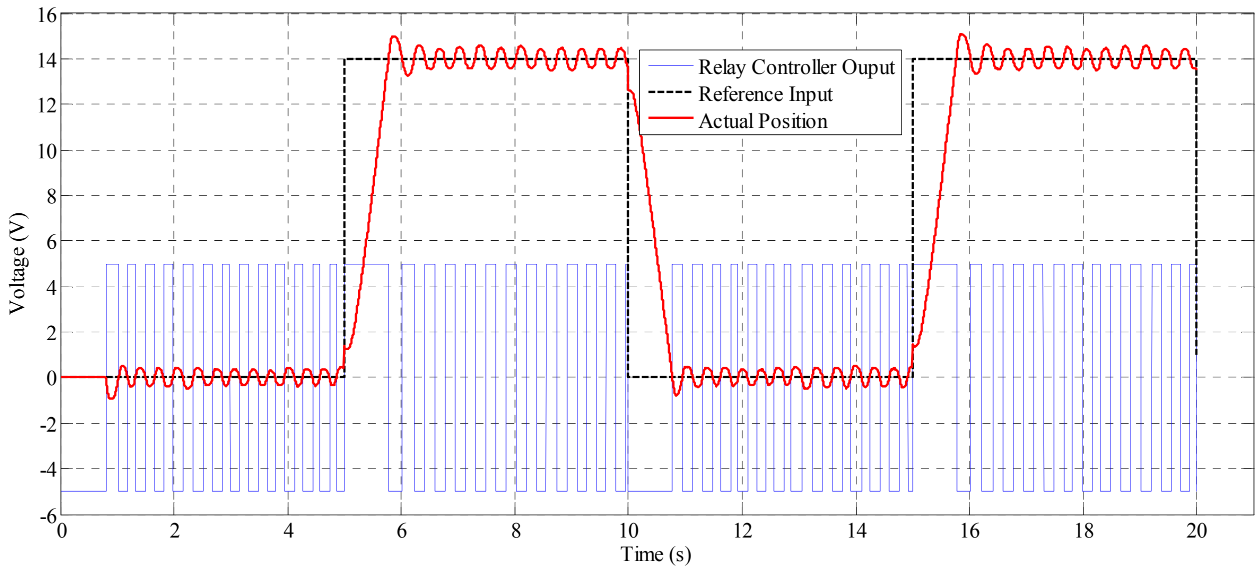

Fig. 4 Relay feedback controller for the DC motor system

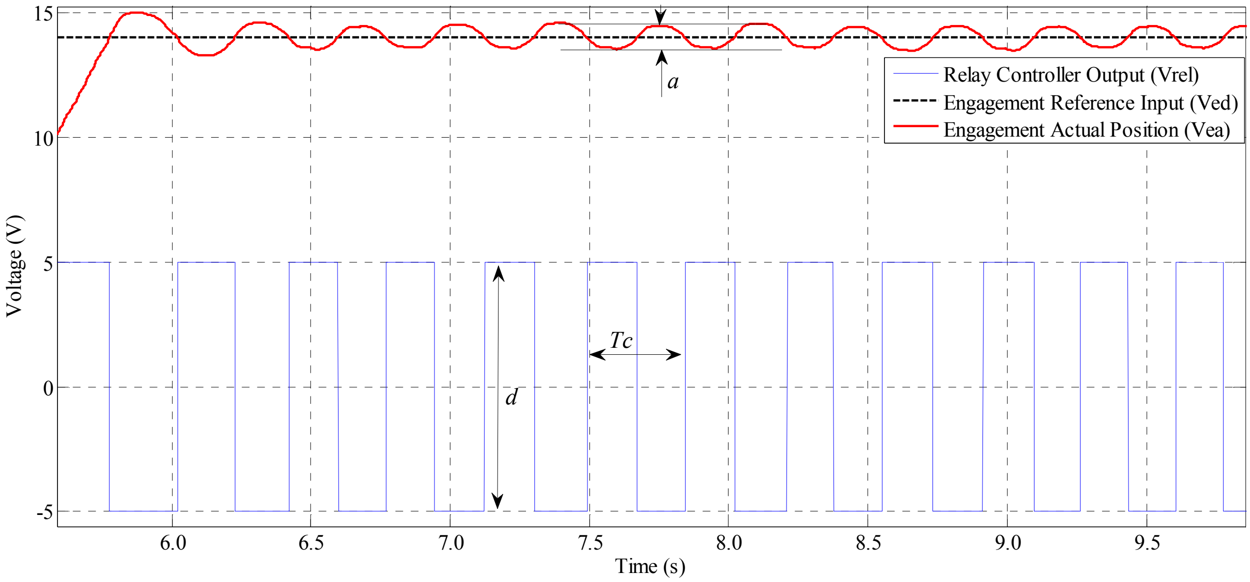

Fig. 5 Relay feedback controller for the DC motor system during full clutch engagement process

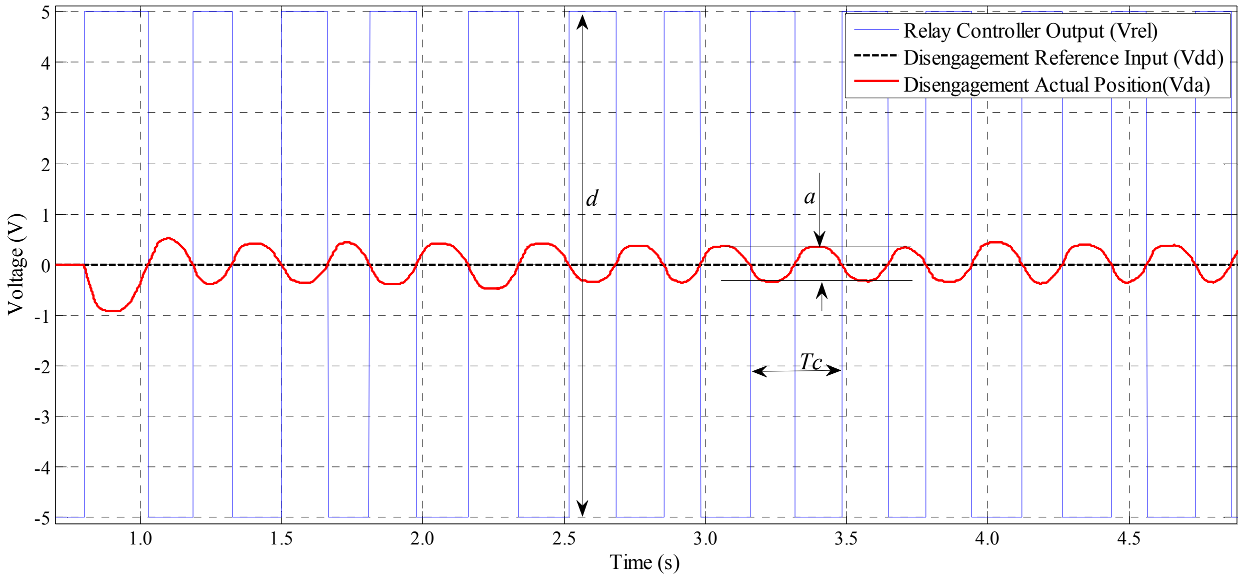

Fig. 6 Relay feedback controller for the DC motor system during full clutch disengagement process

From Table 3, it can be seen the initial (K_i) parameter values obtained from relay feedback experiment for both engagement and disengagement of the EMFC system were bigger than K_p and K_d values for both PID controllers.

This means that the tuning algorithm proposed in experimental studies only tuned the proportional gain (K_p) and derivative gain (K_d) of the PID controller. Based on the system behaviour performed during the relay feedback experiment, a small tolerable steady state error has occurred; therefore the integral gain is not used for controlling this kind of system because the use of big integral gain makes the system unstable as shown in Fig. 7 for PI and PID controller. The P controller makes the system oscillates around the set point in a decaying sinusoid. It can be observed that the PD controller can be considered has a good performance in terms of percent overshoot, settling time and steady state error. Thus, the PD controller gives better result with minimum error and less overshoot.

C. Fine Tuning of PD Controller

In order to increase the capabilities of the PD controller in improving its performance, a manually fine-tuned PD parameters has been used. However, the authors believe that this is just a first start, with further works on PD auto tune controller; better results can be obtained. The initial parameter values obtained from relay feedback experiment needs to be fine-tuned for the clutch engagement and disengagement process. The tuning process is conducted by examining the output responses of engagement and disengagement by inner power screw position sensor when the position reference is shifted up from 0 mm to 14 mm (Engaged) and 14mm to 0 mm (Disengaged). The tuning process will only fine tune the differential part of PD controller manually and leave the proportional part unchanged.

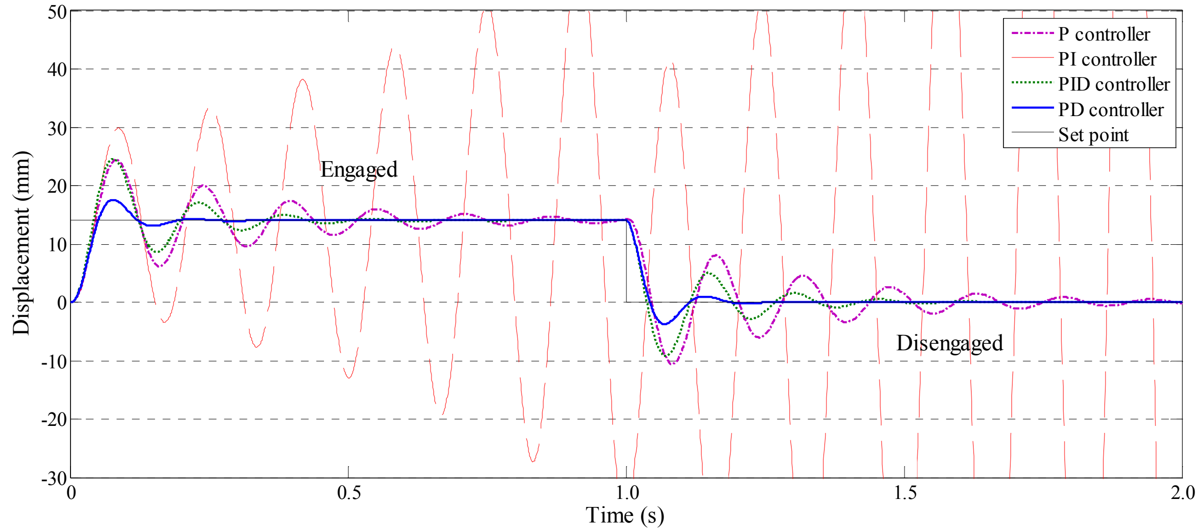

Fig. 7 Response curve for PID controller variations of Ziegler Nichols parameter tuning

However, the proportional part also needs to be fine-tuned if the tuning process of the differential part does not satisfy the control performance for the PD controller in terms of percent overshoot (POS), settling time T_s and steady state error E_{ss} as shown in Fig. 8.

The output responses of the system during fine tuning process for the engagement and disengagement PD controller based on Ziegler Nichols tuning method are shown in Fig. 9 and Fig. 10.

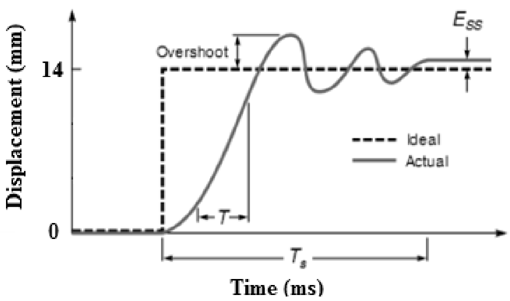

Fig. 8 Transient response

The fine-tuned values of proportional and differential parts of PD controllers and their control performances from Fig. 9 and Fig. 10 are given in Table 4 and 5. From both tables, it can be seen that the shaded cells in the tables gave better results with good minimum (tolerable) error for the PD controllers with manual tuning.

Through optimizing of P and D parameters, the system indicated excellent performances with 5.93% improvement in terms of percentage overshoot, 86.41% improvement of settling time and a very small 0.07% steady state error for clutch engagement process; while for clutch disengagement, the improvement values are 3.11% overshoot and 58.49% settling time with 0.01% steady state error. However, PD controller with Ziegler-Nichols tuning gives a guidance to attain the initial parameters of PID controller as implemented in simulation studies.

The performances of these PD controllers were tested using square wave excitations (Fig. 11) in order to engage and disengage the clutch automatically during experiment. These results are shown in Fig. 13 and Fig. 14.

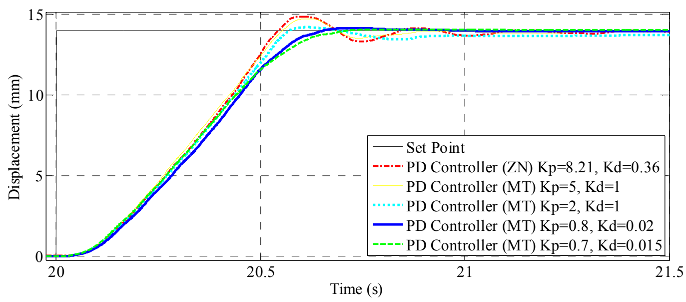

Fig. 9 Response curves of the different PD controller parameter tuning (engagement)

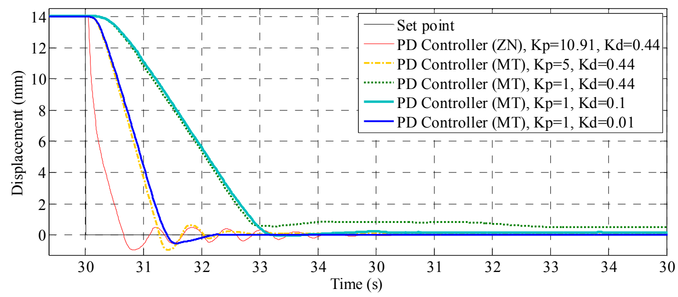

Fig. 10 Response curves of the different PD controller parameters tuning for the clutch disengagement

Table 4 Fine-tuned PD controller for clutch engagement

Tuning Method	PD Controller		Percent Overshoot, (POS) (%)	Settling Time, T_s (s)	Steady State Error, E_{ss}
	K_p	K_d			
Ziegler Nichols	8.21	0.360	6.14	5.74	0.01
Manual Tuning	5.00	1.000	5.00	5.32	0.07
	2.00	1.000	1.43	5.50	0.07
	0.80	0.020	0.93	0.78	0.29
	0.70	0.015	0.21	0.78	0.07

Table 5 Fine-tuned PD controller for clutch disengagement

Tuning Method	PD Controller K_p	PD Controller K_d	Percent Overshoot, (*POS*) (%)	Settling Time, T_s (s)	Steady State Error, E_{ss}
Ziegler Nichols	10.91	0.44	6.84	1.06	0.03
Manual Tuning	5.00	0.44	6.94	0.57	0.05
	1.00	0.44	0.00	3.47	0.21
	1.00	0.10	0.01	7.61	0.07
	1.00	0.01	3.73	0.44	0.01

Fig. 11 shows the output response curves of the inner power screw during application of a square wave excitation to engage and disengage the EMFC system with the PD controllers. The inner power screw movements were consistent for all clutch engagement and disengagement processes since it is only influenced by the clutch spring stiffness.

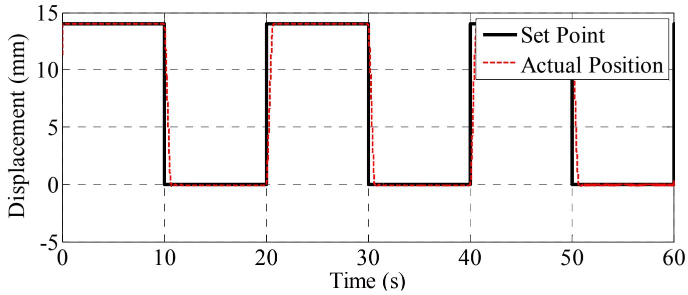

Fig. 11 Response curves during engagement and disengagement of the inner power screw for the proposed PD controller using square wave excitations

D. Experimental Setup

The laboratory test-bench consists of dry friction clutch and electro-mechanical clutch actuator, engine as power source, water-brake dynamometer as a variable load, torque-speed sensors for measuring engine and output speeds and torques, and data logger systems for recording the data during experiments as shown in Fig. 12.

The engine output is connected to the input shaft of the EMFC. The engine is capable of supplying 62 kW at 6000 rpm and maximum torque of about 109 Nm at 4000 rpm. The engine power, which is transferred to the output shaft of the EMFC is then absorbed by hydraulic dynamometer capable of absorbing 15 kW to 1500 kW at angular velocities of up to 8000 rpm.

Input torque and speed of the EMFC are measured by a torque meter mounted between the engine and the EMFC input shaft, while the output torque and speed are measured by another torque meter mounted between the EMFC output shaft and the hydraulic.

A laser displacement sensor measures the position of the inner power screw during engagement and disengagement processes. The laser sensor has resolution of about 4µm and sampling frequency of about 1 kHz.

All experimental measurements, such as engine speed, engine torque, clutch speed, clutch torque and the inner power screw displacement are measured with the aid of data acquisition system, computer and engineering software (Matlab/Simulink).

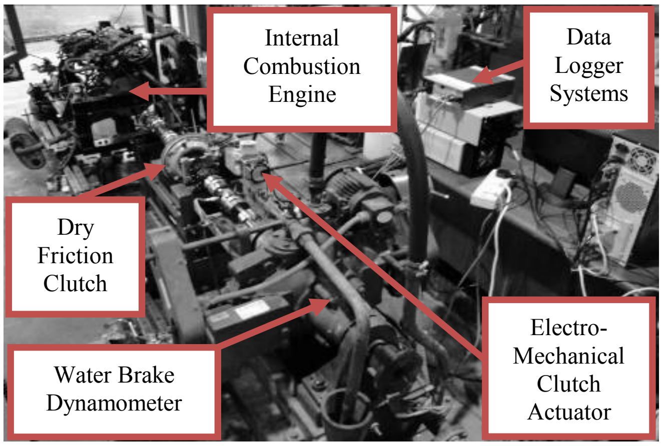

Fig. 12 Schematic diagram of the EMFC experimental test rig

E. Performance Evaluation

The performances of fine-tuned PD controllers were tested to EMFC engagement and disengagement processes. With an initial engine speed of 1000 rpm, the dynamic behaviour of the clutch was initiated by applying loads of 11 Nm, 16 Nm and 21 Nm. The clutch was controlled such that it initially fully engaged, slipped, fully disengaged, slipped again and finally fully engaged again. During this process, the data was taken by data logger system and recorded by computer for 60 seconds. From Fig. 13, it can be seen that when the load increases, the clutch input and output speed during full engagement decreases as given below:

i. from 1000 rpm decreases to 800 rpm with applied torque of 11 Nm,
ii. from 1000 rpm decreases to 700 rpm with applied torque of 16 Nm and
iii. from 1000 rpm decreases to 600 rpm with applied torque of 21 Nm.

During the transition from slip to full engagement process, no overshoot occurs for clutch output speed response as shown in Fig. 13 but small overshoots occur for the clutch torques as shown in Fig. 14. These clutch torque overshoots decrease as the respective torques increase. For torque of 11 Nm, 16 Nm and 21 Nm, the percentage overshoots are 3.6%, 1.5% and 0.9%, respectively. During transition from full engagement to slip going to full disengagement, no overshoots occur.

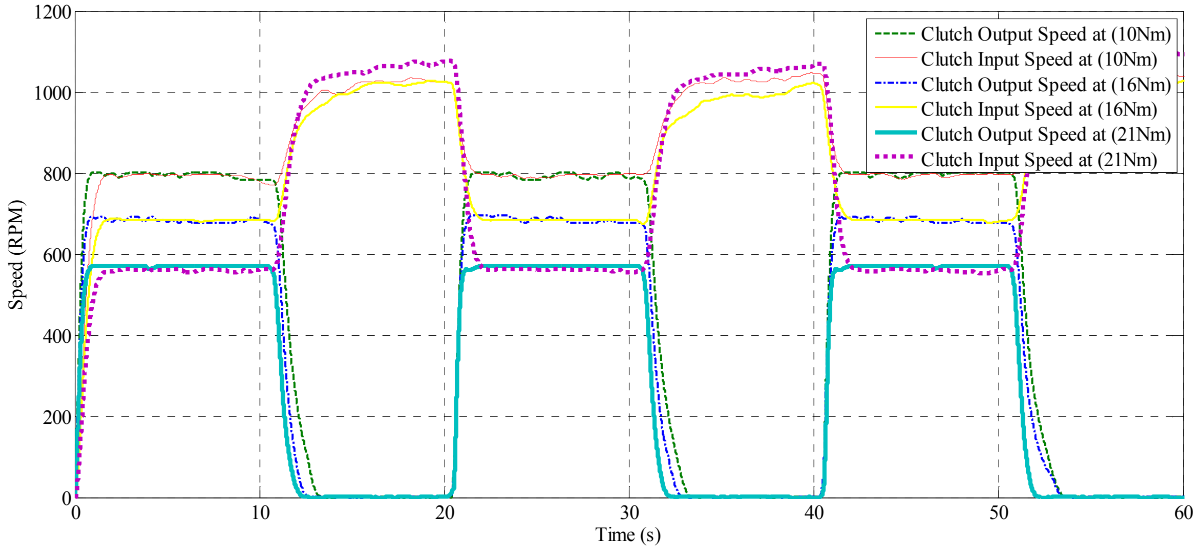

Fig. 13 Speed curves behaviour of the input and output of the EMFC at constant initial engine speed of 1000 rpm with variable applied loads

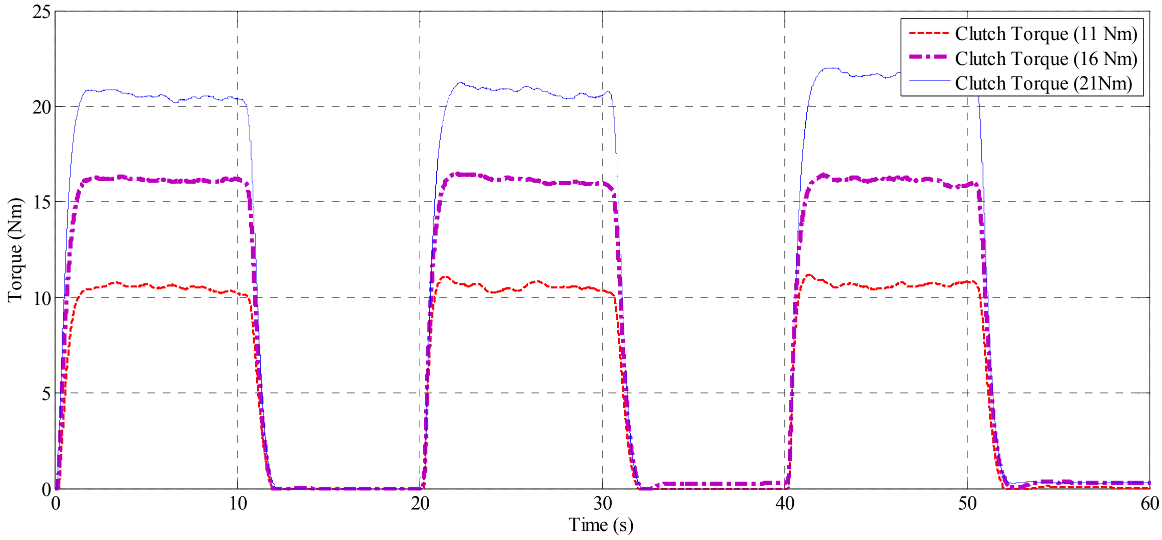

Fig. 14 Clutch torque curves behaviour of the EMFC at constant engine speeds of 1000 rpm

V. Conclusion

An investigation of EMFC engagement and disengagement behaviours with the proposed PD controllers from experimental study for both processes has been carried out. The results of this work show that the application of Astrom-Hagglund method and Ziegler-Nichols formula are capable of providing a practical solution for obtaining initial parameters of the PD controllers for the EMFC engagement and disengagement processes.

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