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Comparison Between Adaptive Fuzzy and PID Fuzzy Automotive Engine Controllers in Idle Speed Mode

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Abstract

Automatic control of automotive engines provides benefits in the engines performance like emission reduction, fuel economy and drivability. To ensure better achievement of these requirements the engine is equipped with an electronic control unit (ECU) that is a microprocessor based system. This control unit continually monitors the engine state using several sensors and selects better control actions to achieve what is demanded from an engine under different defined operating modes. One of the most important modes in automotive engines is the idle speed mode. Due to high dropping in the rotational speed in the presence of load torque and disturbance, which may lead to engine stalling, the ECU has to keep the engine speed at the reference idling speed.

In this paper, The problem of maintaining the engine idle speed at a reference value with minimum overshoot, minimum undershoot, minimum settling time and minimum steady state error with the presence of load is studied. A Self Tuning adaptive Fuzzy Logic Controller (ST-FLC) is designed to solve this problem. Comparisons between fuzzy controller and adaptive fuzzy controller are made. Simulation results of this adaptive fuzzy controller show good improvement over the PID fuzzy controller in the idle speed response.

All simulations are carried out using MATLAB software. Simulink is used in the simulation, which comprises system model, controllers design and implementation.

Keywords: Fuzzy Logic, PID, Automotive engine, Idle Speed

مقارنه بين مسيطر المنطق المضبب المتكيف ومتحكم المنطق المضبب نوع PID في المحركات الذاتية الحركه خلال نمط سرعة العطاله

الخلاصة

إن السيطرة الالية على المحركات الذاتية الحركة تحقق فوائد عديدة في خصائص هذه المحركات مثل خفض الإنبعاثات واقتصاديه الوقود وأداء المحرك. ولضمان أحسن انجاز لهذه الخصائص فقد جهزت هذه المحركات بوحدة تحكم اليكترونيه ، وهي عبارة عن نظام يعمل بمعالج دقيق. وحدة السيطرة هذه تراقب بإستمرار حالة المحرك من خلال بعض المتحسسات و تختار افضل إجراءات لإنجاز ما مطلوب من المحرك ضمن بعض أشكال عمل معرفة ضمن هذه الوحدة . احد أشكال العمل الأكثر أهميه في المحركات الذاتية الحركة هي بقاء العمل ضمن سرعة العطالة والتي تنخفض بسبب الانخفاض الكبير في السرعة الدورانية للمحرك بوجود عزم الحمل والضوضاء المسلطين على المحرك , والذي يمكن أن يؤدي إلى توقف المحرك . إن وحدة التحكم الالكترونية مسؤولة عن الحفاظ على سرعة التوقف ثابتة على قيمة معينة بوجود عزم الحمل و الضوضاء .

وفي هذا البحث تمت دراسة مشكلة تثبيت سرعة المحرك على قيمة محددة مع اقل قيمه لتجاوز الهدف وأقل قيمه لأسفل الهدف واقل زمن للاستقرار و اقل خطأ في حالة الاستقرار بوجود ضوضاء

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عزم الحمل . و تم تصميم مسيطر متكيف متغير ذاتيا يعمل على اساس المنطق المضبب لحل هذه المشكلة . وقد أجريت مقارنات بينه وبين مسيطر المنطق المضبب نوع PID وقد أظهرت نتائج محاكاة المسيطر المتكيف تحسن جيد لهذا المسيطر مقارنة مسيطر المنطق المضبب نوع PID في تصرف استجابة السرعة .

أن كل المحاكاة نفذت باستخدام برمجيات Matlab حيث استخدمت رزمة Simulink في محاكات النظام و الذي شمل نموذج النظام و تصميم المسيطرات و تنفيذها.

Introduction

Most automotive machines that are used in every day's life are equipped with gasoline Port Fuel Injection (PFI) engines. Typically these engines are of four stroke type, Spark Ignited (SI), and Otto cycle based convert chemical energy of the fuel into mechanical work [1]. At idle operating mode, which is characterized by low engine speed typically between (800-1500) RPM [1], the throttle valve is closed. This increases vacuum in the intake manifold. High vacuum and low engine speed results in increasing exhaust residual gases due to valve overlap which creates poor combustion and leads to low produced torque. Poor combustion must be compensated by supplying rich mixture to the engine which contributes to high exhaust emissions and high fuel consumption [2]. According to low produced torque, the operation of any ancillary device, like air conditioning system which is powered by the engine, will lead to drop in the engine speed. Moreover, if all ancillaries are switched on simultaneously the engine speed dropping will be very high and may cause engine stalling [3]. Furthermore, Idle Speed Control (ISC) represents one of the generic and challenging problems in automotive engines, due to complexity, nonlinearity and time delays exhibited by the system. And such a typical challenge is confronted by automotive control researchers and practitioners. From this point of view, a controller that compensates for error in speed in the presence of disturbance load torque is needed. The controller has to provide fast and precise reach of target speed with improved fuel economy and reduced emissions as well as guaranteed combustion stability. Several control methodologies for idle speed problem have been proposed through the last decades. Kmap and Puskorius [4] described in1993 a simulation based training of fuzzy controller using neural based procedure. They found that training process proceeded more slowly than similarly executed training simpler plants. And a purely intuitive approach to fuzzy control would have much success in dealing with such model. Moreover, a control structure based on the analogy between a nonlinear control technique, which is chosen to be sliding mode, and the fuzzy control technique was introduced by Boverie et al. in 1994 [5]. This structure takes into account large dynamic variations in the processes. The designed controller controls the air valve only, while the developed algorithm had been implemented on a real time electronic controller and successfully tested on a car engine (Renault19, 16 valves).

Furthermore, Kruse et al., 1994 [6] developed a well founded generalized fuzzy controller for idle speed regulation of a car engine. The proposed fuzzy controller realizes a charge control only, the ignition adjustment is retained. The developed controller possesses a quite smooth control characteristic. In addition, fast and precise reach of the target rotation speed is achieved with great stability on slowly increasing load. Balluchi et al. [7], proposed in 2000 a hybrid controller where continuous and discrete variables retain their distinctive nature. The problem of maintaining the crankshaft speed within a given range has been formalized as safety specification for the closed loop system modeled as hybrid automation. Albertoni et al. [8] presented in 2003 a hybrid model of gasoline direct injection engine operating in stratified mode. The idle speed control problem is formulated as constrained optimal control problem where fuel consumption has to be minimized. Panse [1], developed in 2005 a dynamic control oriented MVEM of a PFI engine. Then a PID controller for idle mode is also developed that uses the throttle to adjust the speed. The developed PID controller successfully maintains the steady state idling speed in simulated environment. Santis et al., [9] formulated in 2005 the idle speed control as the problem of computing a maximal safe set for a hybrid system modeling of an SI engine. Finally, Gibson et al., [10] presented in 2006 the analysis of lead compensation, feed-forward and disturbance observer design techniques for ISC system with minimal spark reserves levels. Simulation results show that a 30 percent reduction in the maximum drop of the engine speed was obtained compared with an ISC with no lead disturbance observer compensation.

Design of Idle Speed Controller

The design of intelligent idle speed controllers for automotive engine is considered. The idle speed control is formalized as a control problem, where the engine stalling has to be prevented in spite of load acting and varying. So, the engine with the controller designed should get the idle rotational speed with minimum overshoot, minimum undershoot minimum steady state error and reach the target rotational speed as fast as possible. One successful control technique is fuzzy control which originates from the human experiences. The objective of the Fuzzy Logic Control (FLC) systems is to control complex process by experience of human being. The designer uses rules to link the input variables with control variables by linguistic variables [11]. The focus in this paper is on the application of fuzzy and adaptive fuzzy control techniques to the engine. The idle speed controller designed in this paper uses the throttle angle only to compensate the drop in the rotational speed of the engine, by enlarging the area available for the air flow at the throttle valve. It is assumed that the air fuel ratio is held at the stoichiometric value and the spark timing is maintained to give Maximum Break Torque (MBT).

Design of Fuzzy Logic Controller (FLC)

In this section, a PID like Fuzzy Controller (PIDFC) is developed. This controller uses the discrete form of the conventional PID controller equation as follows:

$$u(k+1) = Kpe(k) + Kd\Delta e(k) + Ki\sum e(k) \qquad (1)$$

where e(k) is the error signal and the index (k) represents the present sampling instant. It is clear from the equation that the controller has three inputs. If seven fuzzy sets are used for each input, then a (7*7*7=343) rules will be needed for the controller. Also, each rule will have three conditions in its antecedent part, which is very difficult to design such controller. In the case of more than two inputs, projection on the three dimensional space, is used to generate multiple three dimensional diagrams to represent the control action of the controller. These representations usually have limited usefulness [11]. To avoid such problems, the PIDFC is constructed as a parallel structure of PD-like Fuzzy Controller (PDFC) and PI-like Fuzzy Controller (PIFC). As a result, the equation of the PIDFC will be:

PIDFC=PDFC+PIFC (2)

Where:

$$PDFC = \frac{Kp}{2}e(k) + Kd\Delta e(k) \qquad (3)$$

And

$$PIFC = \frac{Kp}{2}e(k) + Ki\sum_{0}^{k} e(k) \qquad (4)$$

It is clear that each controller will need two inputs only, with seven fuzzy sets for each input. This results in 49 rules which will be needed for each controller. So, the PIDFC will need (49 + 49 = 98) rules only. Reducing the number of rules in a fuzzy controller makes the implementation of the fuzzy controller possible with limited processor throughput [12]. It is clear from equation (4) that there is a need for the summation of error in the PIFC, and it is known that there is a difficulty in formulating rules depending on summation of error because it may have very wide range of universe of discourse. To avoid such a problem the summation is moved from the input to the output as in the following equations using the continuous form of the PI controller [11]:

$$u(t) = Kpe(t) + Ki\int e(t)dt$$

$$\frac{d}{dt}u(t) = Kp\frac{d}{dt}e(t) + Kie(t) \qquad (5)$$

And in discrete form:

$$\Delta u(k) = Kp\Delta e(k) + Kie(k) \qquad (6)$$

With this simplification, the PIFC will need error e(k) and change of error Δe(k) as inputs and to get the control action of PIFC, it is only needed to make summation for the output of the controller as follows:

$$u(k) = \Delta u(k) + u(k-1) \qquad (7)$$

The indices (k) and (k-1) represent the present sample and the previous sample instants respectively.

Moreover, the PIDFC is designed using Mamdani type [11]. It has two inputs e(k) and Δe(k) and one output. The inputs are defined as follows:

$$e(k) = r(k) - y(k) \qquad (8)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (9)$$

Figure (1) shows the block diagram of the closed loop structure with PIDFC. All the membership functions of the FLC inputs and outputs are defined on the common normalized domain [-1, 1] as shown in Figure (2) and Figure (3). The characters NB, NM, NS, Z, PS, PM, PB are the linguistic variables of the inputs and output fuzzy sets. The letters N, P, Z, B, S, M, represent Negative, Positive, zero, Big, Small and Medium respectively. μ is the certainty of the membership. The rule base for computing the output u(k) (Δu(k)) is shown in Table (1). The selection of rules shown is based on the knowledge of the behavior of the error equation. The successful design of a FLC depends on the right selection of the input and output scaling factors, and in many cases this task is done through trial and error or based on some training data [13]. In this paper, the FLC scaling factors are tuned manually and a set of gains are obtained. The error allowed using these scaling factors is around 30 RPM and shown in Table (2) below. The closed loop structure simulated in Matlab/Simulink environment is shown in Figure (4) below: The closed loop system with PIDFC is simulated with applying a variable value of a uniform load torque is applied to the closed loop system, as shown in Figure (5).

Design of Self-Tuning Adaptive Fuzzy Logic Controller

In the procedure of fuzzy controller design, an appropriate selection of input and output scaling factors is very important because of their significant effect on the controller stability and response performance. So, the scaling factors determined manualy can be further fine tuned to obtain better system response especially with respect to the steady state error. There exists two methods for developing a self tuning fuzzy controller exits: the first is based on neural networks and the second method uses fuzzy logic[12][13]. A Self-Tuning Adaptive fuzzy system is used to tune the output scaling factor for the fuzzy controller developed before, in order to achieve a better speed response specicially in reducing oscillation and steady state error. According to this tuning mechanism, the output scaling factor of the PIDFC controller is updated using the following equation[12]:

$$G_u{}' = G_u \cdot e \qquad (10)$$

where $G_u{}'$ is the updated scaling factor and G_u is the output scaling factor of the PIDFC and e is the updating factor, which is obtained online based on fuzzy reasoning. The FLC designed uses the error and change of error as inputs, and the updating factor as output. The closed loop structure of the Self-Tuning Fuzzy Logic Controller ST-FLC is shown in Figure (6) . The inputs and output membership functions are defined on the common normalized domain [-1,1]. The inputs have five fuzzy sets of trapizoidal type except (Z) input fuzzy set which is defined to be of traingular type, while all the output fuzzy sets are defined as triangular type. The characters N, P, Z, B, S and M, which appear with the inputs fuzzy sets, have the same representation defined before, while the new charcters V and U represent Very and Unity respectively as shown in Figure (7) and Figure (8) respectivelly. The normalized domain requires scaling factors for both inputs and output, and after several trials a set of gains are obtained and shown in Table (3). The computation of the updating factor (e) is made by using the rule base shown in Table (4). According to the fact that if the state is far away from the set point, then, the updating factor should be large enough to increase system speed to reach the set point. Conversely, if the the speed is near the set point by a small value then the updating factor should take a nearly unit value to leave the response without any change. Otherwise, the updating factor will be small value. The closed loop structure of the ST-FLC is achived using Matlab/Simulink and shown in Figure (9). However, the closed loop system with ST-FLC is simulated with applying a variable value of a uniform load torque is applied to the closed loop system, as shown in Figure (10).

Comparison between PIDFC and ST-FLC

The main goal of designing the ST-FLC is to achieve better system response especially with respect to the steady state error. The performance of the proposed ST-FLC is compared with the corresponding PIDFC in terms of several performances defined before, these are: Peak Overshoot (P.O), Peak Undershoot (P.U), Settling Time (Ts), steady state error (ess) and Fuel Consumption (F.C). The comparison is made to a step change in the load torque from 0 to 20 N.m at 20 seconds. A comparison between the obtained results is shown in Table (5). It is clear from comparing the results obtained from both ST-FLC and PIDFC that the drop in engine speed at the moment of applying load torque is reduced by (7%) with ST-FLC, and the peak overshoot of speed response at the moment of removing load torque is reduced by (7%) with ST-FLC. The steady state error of the speed response with ST-FLC is reduced by (89%) compared with the PIDFC within the same settling time. This is the main goal of the adaptive controller within the same consumed fuel during a comparison period of operation which is equal to (45 sec). Fuel Consumption (F.C) which is the consumed fuel by the engine during the period of operation is calculated by summing the injected fuel (mfi) at each sample time [8]. Figure (11) shows the speed response comparison between ST-FLC and PIDFC with applying a step change in the load torque.

Conclusions

This work has focused on studying the problems associated with the operation of automotive engine during idle mode, especially the compensation of the effect of load torque and disturbance on the engine speed, and designing a suitable intelligent controller to improve engine performance during idling. The following points outline the most important conclusions that have been obtained in this work:

1. To achieve an improvement on the speed response, a PIDFC was designed and good improvement has been obtained.
2. The only problem in using the PIDFC is that the steady state error. This problem is avoided using a ST-FLC. It is used to achieve fine tuning to the output scaling factor for proposed PIDFC, thereby, improving the steady state error. Good improvement on the speed response is achieved with the ST-FLC. The simulation results with ST-FLC show that the dropping in the engine speed is reduced by (7%) and the peak overshoot is reduced by (7%) compared with PIDFC controller. The steady state error, which is the main reason for proposing the self tuning controller, was reduced by

(89%) with ST-FLC within the same settling time compared with the PIDFC.

3. Finally, it can be concluded that the ST-FLC can be used to control the idle speed mode in the four stroke PFI, SI engines by controlling the throttle valve and, thereby, the mass of air loaded to the engine and using the speed error and change of error as inputs.

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Table (1): Rule base of the PIDFC

		Δe(k)						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e(k)	**NB**	PB	PB	PB	PB	PM	PS	Z
	NM	PB	PB	PB	PM	PS	Z	NS
	NS	PB	PB	PM	PS	Z	NS	NM
	Z	PB	PM	PS	Z	NS	NM	NB
	PS	PM	PS	Z	NS	NM	NB	NB
	PM	PS	Z	NS	NM	NB	NB	NB
	PB	Z	NS	NM	NB	NB	NB	NB

Table (2): PIDFC scaling factors values

Scaling factor	Value
G_e	0.03
$G_{\Delta e}$	0.007
G_u	0.16

Table (3): ST-FLC scaling factors values

Scaling factor	Value
G_e	0.004
$G_{\Delta e}$	0.0003
G_ε	1.7

Table (4): Rule base of FLC.

Δe(k)

e(k)	**NB**	**NS**	**Z**	**PS**	**PB**
NB	VS	VS	VS	S	U
NS	VS	VS	S	U	B
Z	VS	S	U	B	VB
PS	S	U	B	VB	VB
PB	U	B	VB	VB	VB

Table (5) : PIDFC and ST-FLC comparison results.

Parameters	**ST-FLC**	**PIDFC**
P.O	184.5 RPM	199 RPM
P.U	164 RPM	176 RPM
Ts	4 sec	4 sec
Ess	4 RPM	35 RPM
F.C	0.000644	0.000643 Kg

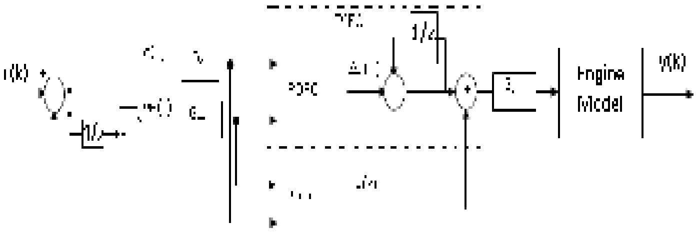


Figure (1): Closed loop structure with PIDFC.

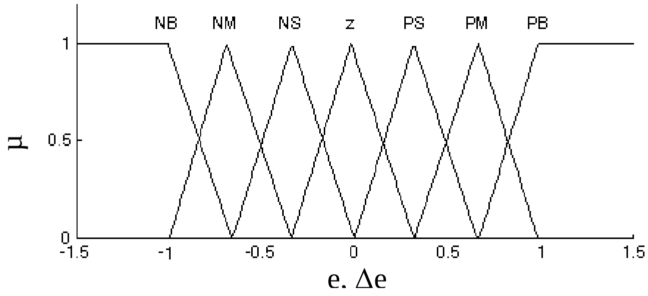


Figure (2): Membership functions for input variables.

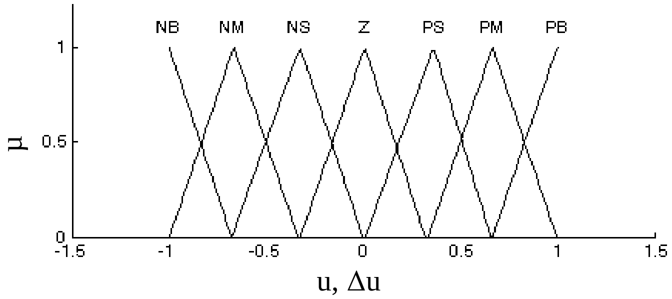


Figure (3): Membership functions for output variables.

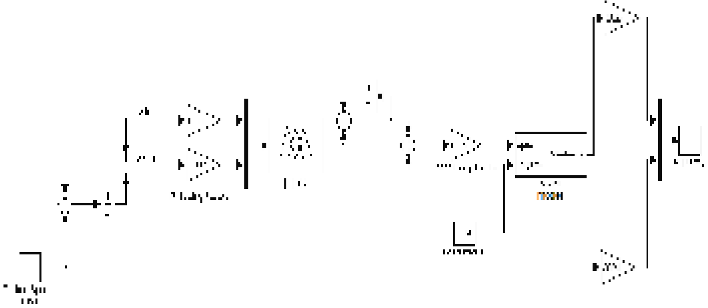
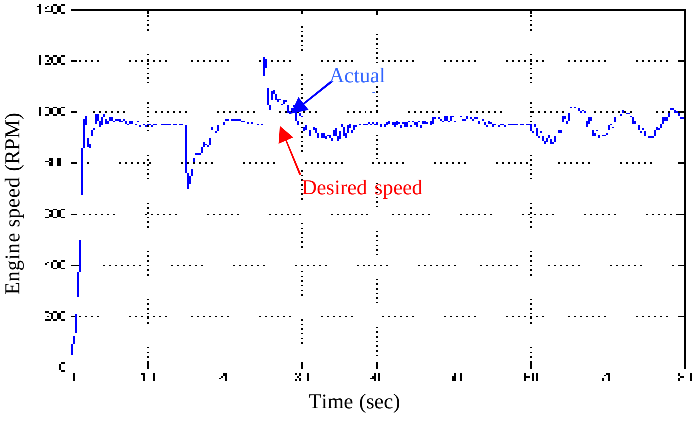
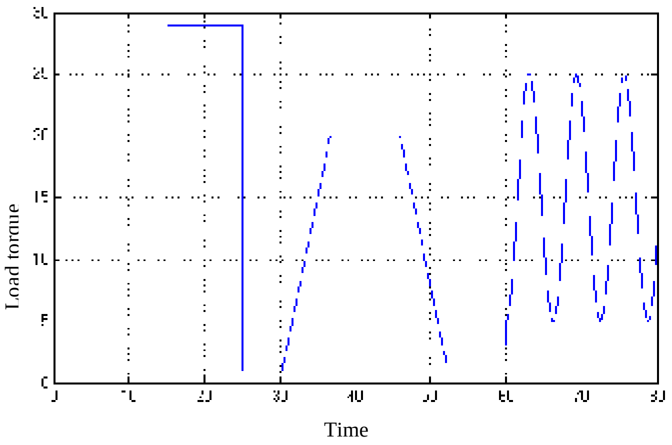


Figure (4): Closed loop PIDFC controlled system model.



(a)



(b)

Figure (5): Simulation results of the closed loop system model with PIDFC:
(a): Engine speed with applying load torque.
(b): Variable value of a load torque.

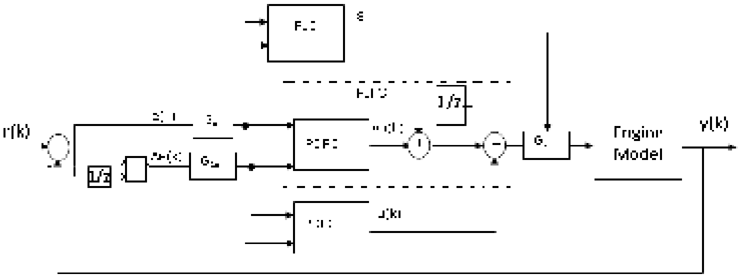


Figure (6): Closed loop system with ST-FLC Controller.

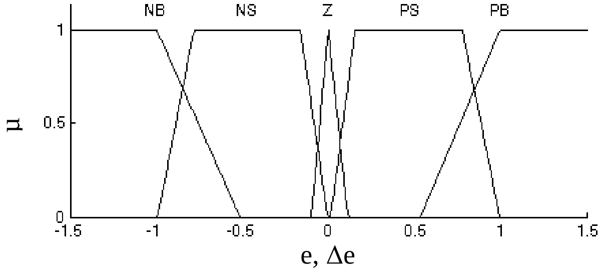


Figure (7): Membership functions for input variables.

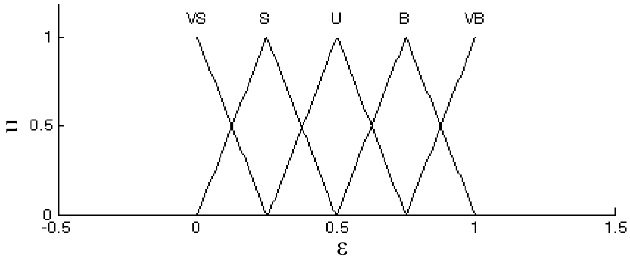


Figure (8): Membership functions for output variables.

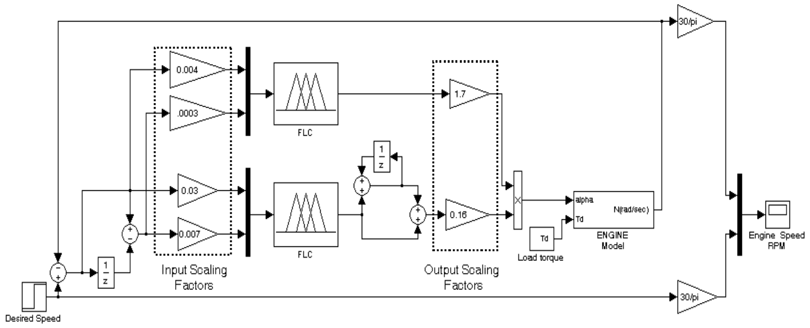


Figure (9): Closed loop system of the engine model with ST-FLC simulated in Matlab/Simulink environment.

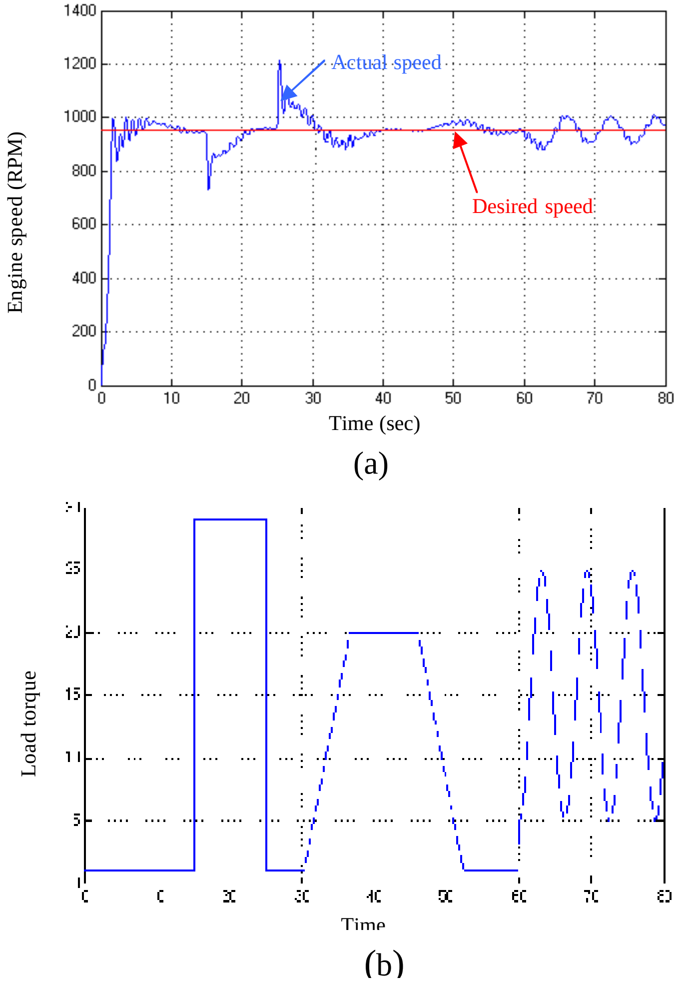
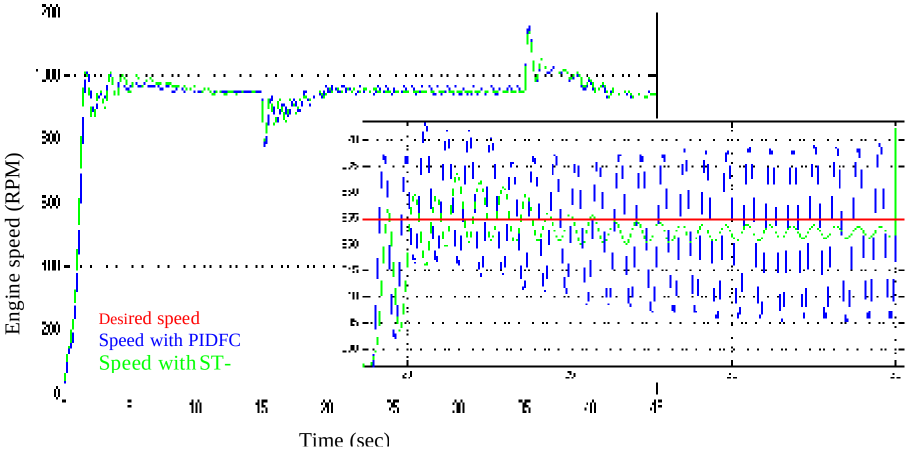
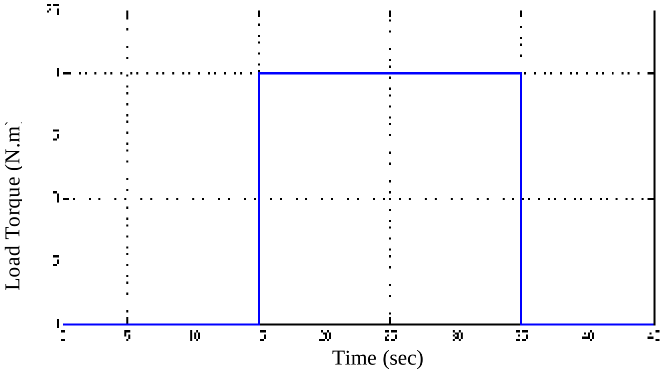


Figure (10): Simulation results of the closed loop system with ST-FLC
(a): Engine speed with applying load torque
(b): Variable value of a load torque



(a)



(b)

Figure (11): Comparison between speed responces for bothPIDFC and ST-FLC:
(a): Speed response for both PIDFC and ST-FLC.
(b): Step change in the load torque.