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Hybrid Fuzzy Logic Controller in Matlab/Simulink for Controlling AFR of SI Engine

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ABSTRACT

The Kyoto Protocol (1997) has been a turning point for the future economical and environmental policies for both industrialized and developing countries. The vehicle engine manufacturers are continuously working towards reducing fuel consumption and emissions while maintaining optimum performance by keeping the Air to fuel ratio (AFR) as close to the stoichiometric value of 14.7. In the present paper, new simulation model using Matlab Simulink for a SI (Spark-Ignition) engine has been developed that included all engine dynamic models such as dynamic model of the throttle body, a lambda dynamic model, a model of the intake manifold dynamic, and models of engine torque and fuel injection dynamic. Then, to control the AFR in SI engines, new controllers were proposed to maximize fuel economy and minimize exhaust emissions. A hybrid fuzzy logic controller (HFLC) was created by combining a PID control and fuzzy control. However, this model was validated using the results from engine for various operation tests such as 40, 50 and 60 N.m but this paper only presented operation at 60 N.m. The simulation results founded that the maximum and minimum AFR for convectional look-up and HFLC methods were (16.80, 12.4) and (15.02, 14.4), respectively. Simulation results from HFLC was also compared to other control methods such as, sliding mode control (SMC), neural network (NN), Proportional–integral controller (PI) and model-based predictive control (MPC).

KEY WORDS: *Hybrid Fuzzy Logic Controller, Air to Fuel Ratio, Matlab/Simulink, SI Engine.*

NOMENCLATURE

AFR	Air to Fuel Ratio
HFLC	Hybrid Fuzzy Logic Controller
TWC	Three Way Catalytic

1.0 INTRODUCTION

Environment in forms of air pollution emitted by land, ocean and air transportation systems such as hydrocarbons (HC), compounds of hydrogen nitrogen (NO_x), carbon dioxide (CO_2), particulate matter (PM) and sulfur oxides (SO_x) became an essential issue on societies' point of view. The Kyoto Protocol (1997) has been a turning point for the future economical and environmental policies for both industrialized and developing countries (Koto and Ikeda, 2002).

According to the Ward's research, the number of vehicles jumped from 980 million units in 2009 to 1.015 billion in 2010 (Sousanis, 2011). The governments and vehicle manufactures in industrialized and developing countries consider not only economical issue, but also environmental issue. In order to do that, the vehicle engine manufacturers are continuously working towards reducing fuel consumption and emissions while maintaining optimum performance as they try to meet the growing demands of governmental automotive standards based on the Kyoto Protocol (1997).

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To reach this goal, many different variables must be controlled such as engine torque, engine speed, timing of fuel injection, timing of spark ignition, air intake, and air to fuel ratio (AFR) which is related to each other. Furthermore, several different operating modes are defined for spark-ignition (SI) engines such as startup, idle, running and braking. Consequently, the engine dynamics very nonlinear and multivariable due to those factors (Balluchi et al., 1998).

To decrease effectively the emission of harmful gases subsequent to engine combustion, three way catalytic (TWC) converter can be installed at the exhaust system. TWC is very important element of the car's exhaust system due to capable of making some harmful gases such as unburned hydrocarbons (HC), carbon monoxide (CO), and hydrogen nitrogen (NO_x), in the exhaust gas to less toxic pollutants by catalyzes the redox reaction as shown in Figure 1 (Berkeley). A catalyst is a chemical compound that helps the reaction to occur faster by reducing the activation energy barrier of the reaction (Berkeley). Conversion efficiency depends on the air to fuel ratio during combustion. The effect of emission controls can be also influenced by AFR due to its stoichiometric value that guarantees the highest TWC efficiency.

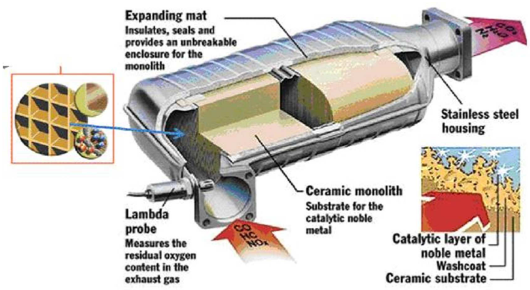

Figure 1: Catalytic Converter – Deconstructed (Berkeley).

According to Benninger and Plapp (1991) variations in the AFR should be within ± 0.2%. More than a 1% variation below 14.7 may significantly increase emissions of unburned hydrocarbons (HC) and carbon monoxide (CO). As shown in Figure 2, the production of hydrogen nitrogen (NO_x), up to 50% can be the result of deviations greater than 1% (Kilagiz et al., 2005).

To control the AFR in most of SI engines, proportional and integral (PI) controls together with a look-up table were used. This was not a robust system due to the effect of uncertainty and time variations. A neural network (NN) and a Proportional-integral (PI) control for the AFR was established by Zhai et al. (2010).There was a control performance but still the deviation between the AFR and stoichiometric AFR is too great .The maximum and minimum AFR with PI and NN methods based on the (Zhai et a,. 2010) was (22.5, 12.8) and (17.7, 13.25), respectively. Wang 2006 studied the air–fuel ratio control using the MPC controller (16.2, 14.05)

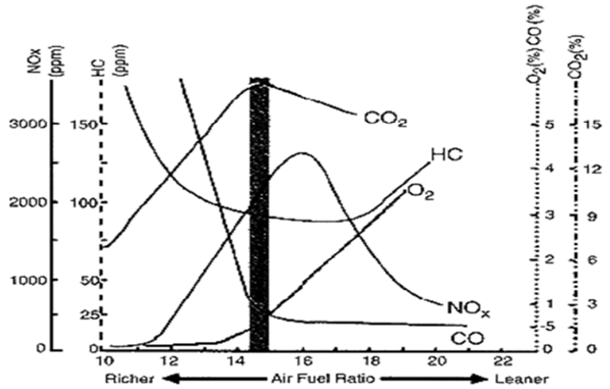

Figure 2: The most suitable values of CO, HC, NO_x, CO_2 and air to fuel ratio for an Internal Combustion engine (Kilagiz et al., 2005).

In this study, the AFR in SI engines was controlled using new control methods to maximize fuel economy while minimizing exhaust emissions. In this way, a hybrid fuzzy logic control (HFLC) was created by combining two control models, PID control and fuzzy control.

2.0 SOFTWARES SIMULATION

2.1 Commercial Software Simulation

Currently, engineering simulation software can be found abundantly in market. To simulate the engine model, appropriate software should be selected. In the automotive engineering field, simulation software is provided mainly in two different groups: commercial software and custom in-house software, which are explained in detail in the following subsections

Nowadays, four commercial packages of engine simulation are principally applied to automotive industry, namely Lotus Engine Simulation (LESoft), Ricardo Wave (RW), GT Power, mathematica and AVL CRUISE as shown in Figure 3; functionality of all is the same (Chan et al., 2013). Note that detailed input parameters should be provided for them to simulate the engine operation in an integrated manner rather than using a variety of subsystems.

Figure 3: Commercial packages of engine simulation

The commercial engine simulation software has a number of advantages; the most important ones include as follows:

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1. The commercial software is use friendly, hand on and click button software. They can handle a wide range of technical applications in regard to vehicle and engine due to contain many modules and libraries.
2. Innovative graphical user interface and methods of model construction help a user perform the simulation by means of drag-and-drop element library, easy-to-use, modular, extendable.
3. The application software can provide an accurate engine performance block, engine component blocks, and dynamic control blocks in order to apply to a real-time simulation. The application is also fast and reliable fuel economy and performance predictions from early concept phase. In addition, vehicle dynamics blocks are included in some of the software, which help to analyze the engine combustion and emissions; simulated items are fast, and the obtained results have a high accuracy.
4. Strong teams are ready to update modules and provide solution to the problems faced by customs. In essence, car designers can make use of simulation software in making appropriate decisions; such decisions are expected to contribute to designing competitive vehicles regarding important factors such as performance, fuel efficiency, emissions, and drivability.

1. Ricardo Wave (RW)

Ricardo Wave (RW) is used worldwide in industry sectors including ground transportation, rail, motor sport, marine, and power generation for 1D engine and gas dynamics analysis (Ricardo Wave, Wave) The engine simulation package of RW has been proposed for the analysis of the pressure wave dynamics, plenums, energy losses in ducts, mass flows, and manifolds of a variety of machines and systems (Ricardo Inc, 2009). RW makes use of two-zone model to simulate time-dependent fluid dynamics and thermodynamics. Several key features of Ricardo Wave are as follows (Ricardo Wave, Wave):

- Advanced SI and combustion models (non-predictive, semi-predictive and predictive models) allowing accurate single or multiple fuels handling
- State of the art compressor and turbine physics
- Comprehensive 1D and 3D aftertreatment library including TWC, DPF, LNT, DOC, SCR and user models
- Advanced acoustic features including, engine speed audio player, modeling absorptive materials, porous ducts user defined flow noise calculation
- Graphical plotting on the fly and interactive input control using the WAVELive interface

2. Lotus Engineering Software (LESoft)

Lotus Engineering Software (LESoft) which is an in-house code has been developed by automotive engineers (Lotus, LESoft) .Engine simulation is processed by this package in two modules, i.e., the data module and the solver module (Lotus Group plc, 2011). The former provides users with the possibility of inputting the engine dimension data. The latter is a built in combustion and heat transfer zero-dimensional equation and fuel/gas composition solver based on data input by the user in the previous module. The code is capable of predicting combustion, gas flow, and overall performance of the IC engines.

LESoft has several modules as follows (Lotus, LESoft):

- Lotus Suspension Analysis (SHARK & RAVEN)
- Lotus Engine Simulation (LES)
- Lotus Vehicle Simulation (LVS)
- Lotus Concept Valve Train (LCVT)
- Lotus Concept Crank Train (LCCT)

3. GT POWER

The professional software company of Gamma Technologies is mainly focused on engine and vehicle industry. GT POWER, provided by Gamma Technologies, has various vehicle and engine technical applications, including vehicle dynamics and engine performance modelling (GT POWER Overview, 2009). GT-POWER is used to predict engine performance quantities such as power, torque, airflow, volumetric efficiency, fuel consumption, turbocharger performance and matching, and pumping losses (GT POWER). GT POWER is fundamentally a greatly adaptable multi-physics platform that can be used to construct a variety of engineering models through combining the flow, thermal, acoustics, electric, chemistry, mechanical, and controls. GT-POWER includes physical models for extending the predictions to include cylinder and tailpipe-out emissions, intake and exhaust system acoustic characteristics (level and quality), in-cylinder and pipe/manifold structure temperature, measured cylinder pressure analysis, and control system modeling (GT POWER).

The application of GT can be as follows (GT POWER):

- Combustion and Emissions
- Cylinder Pressure Analysis
- Intake and Exhaust Acoustics
- Exhaust Aftertreatment
- Valvetrain
- Waste Heat Recovery
- Performance, Fuel Economy, and Emissions
- Control, MiL, SiL, and HiL
- Real-Time Engine

4. AVL CRUISE

Powertrain analysis and vehicle simulation can be done using AVL CRUISE (AVL Product Description Cruise, 2009). This product is applicable to the development and optimization of reliable powertrains, low emission engines, complex control systems of engine, as well as cooling and transmission systems. The application field covers fuel efficiency, driving emissions and performance analyses along the vehicle development process with model re-use from concept design through to HiL and testing (AVL, AVL CRUISE). AVL CRUISE is able to support engineers during the process of developing the engine and vehicle in standard applications, e.g., fuel economy and full load acceleration tests, traction diagrams, hill climbing performance, and computational concept studies including the thermal,

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electrical, mechanical, and control systems. AVL CRUISE supports everyday tasks in vehicle system and driveline analysis from the concept phase to control function development and testing. Its modular and open structure enables applications for different architectures (conventional, hybrid, electric) and engineering focuses (transmission, engine, electric system, controls, etc.) in all relevant industries (passenger, commercial, 2-wheeler, off road) (AVL, AVL CRUISE).

5. mathematica

Mathematica provides a single integrated, continually expanding system that covers the breadth and depth of technical computing—and with Mathematica Online, it is now seamlessly available in the cloud through any web browser, as well as natively on all modern desktop systems (Wolfram). Mathematica excels across all areas of technical computing—including neural networks, machine learning, image processing, geometry, data science, visualizations. For example, SystemModeler 4 module gives users the possibility to control simulations directly from Mathematica (Wolfram, ME).

2.2 Code Languages for Simulation

The development of simulation software can be done by writing source code in the program in a way to implement the required functions through programming languages for example Java, C, C++, VC, Python, VF, Openfoam, R, etc). Some of the programming software such as MATLAB, Dymola, Modelica, VB, VS, V#, and VisSim has been designed particularly for data processing and mathematical operations. Such software comprises algorithmic components and toolbox comparable to statements or blocks; by simply entering the equation or logical relationship, they will be operational. For writing source code, there is a need for expertise in a variety of subjects such as knowledge of the application domain, formal logic, specialized algorithms, and so on. Many researchers have developed their own software for example Koto has developed several software using VB code such as Subsea Pro Software, Offshore Pro Software, Navigation Integrated System, Ice Ship Software Heli Pro Software, Mobile Harbour Pro Software, Ship Manoeuvring Pro Software, DSM-SP Pro Software (Koto, OCaRI).

When, in the late 1970s, Cleve Moler was attempting to make an interactive access to FORTRAN linear algebra software packages (i.e., LINPACK and EISPACK). FORTRAN is an imperative programming language which is for general-purpose and numerical computation and analysis. FORTRAN has rapidly developed from FORTRAN to FORTRAN 2015.

Among other languages, MATLAB is a programming language of a high level; it makes available such a problem-solving environment that makes easy the scientific and mathematical computations. MATLAB was originated, and then in was developed by Mathworks founded in 1984 (Moler, 2004). The MATLAB is used for machine learning, signal processing, image processing, computer vision, communications, computational finance, control design, robotics, and much more (Mathworks, Matlab). This software is capable of analyzing data, developing algorithms, and creating applications and models. Furthermore, in 2002, an additional package, i.e., SIMULINK, was developed by Mathworks. It offers a graphical block diagramming environment for multi-domain simulation and model-based design. This software provides a unified integration with the rest of the MATLAB environment; it has the capacity to either drive the MATLAB software or be scripted from it. MATLAB/SIMULIINK makes a great experience for users. SIMULINK and MATLAB have been rapidly promoted by much higher performance requirements of signal processing and numerical analysis based on evolution occurring in the Science and Engineering fields. It can be said that one of the three or four key developments, which have taken place in numerical computation during the last decade, is the advent of the MATLAB software that has been widely preferred by thousands of foremost engineers and scientists (Chan *et al*., 2013).

There are several reasons for choosing MATLAB/SIMULINK to develop engine simulation platforms and design engine control systems. Firstly, MATLAB offers a high level of programming language as well as user-friendly, powerful graphics and many math tool boxes. MATLAB has ability to read in a wide variety of both common and domain-specific image formats and also ability auto-generate C code, using MATLAB Coder.

Then, language, built-in math functions, and tools of MATLAB help to find multiple approaches and achieve solutions faster compared to those in spreadsheets or conventional programming languages like C/C++ or Java. MATLAB allows the users to test algorithms immediately without recompilation.

MATLAB/SIMULINK contains toolbox called Simulink Control Design (SCD) makes designing and analyzing the control systems very easy. For instance, users are able to design and analyze control systems modeled, the gains of PID controllers can be tuned automatically by users in a way to satisfy performance requirements (Mathworks, SCD). The users can also automatically tune arbitrary SISO and MIMO control architectures (Mathworks, SCD). Using such toolbox, users are also capable of exploring non-intrusively the operating points and calculating the accurate linearization of the SIMULINK models in a variety of operating conditions (Mathworks, SCD). The tools provided by the Control Design toolbox help users to calculate the simulation-based frequency responses with no modification on the simulation model.

MATLAB/SIMULINK also contains Simulink Design Optimization (SDO) which has useful functions, interactive tools, and blocks for analyzing and tuning model parameters (Mathworks, SDO). Using the SIMULINK Design Optimization toolbox, controllers are able to design improvements through estimating and tuning the model parameters by means of numerical optimization. In addition, the model accuracy can be enhanced using test data for the calibration of physical parameters. Then, the design parameters in the SIMULINK models can be automatically tuned by users.

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3.0 HFLC AFR CONTROL FOR SI ENGINE

The principal idea behind this paper was to develop an engine simulation model that included all dynamic engine parts and to develop a Hybrid Fuzzy Logic Controller (HFLC) that combined a fuzzy logic and PID controller using MATLAB/Simulink. A fuzzy controller was used for the online tuning of the PID controller gains $\mathbf{k}_p$, $\mathbf{k}_i$, $\mathbf{k}_d$. The target of the thesis was the AFR control of SI engines.

Figure 4 provides a block diagram of the HFLC for the AFR in a SI engine which has divided into two sectors. The first sector was the air to fuel ratio (AFR) setting controller developed for this study. It was important that this controller operate under the various working conditions found in an engine. Second sector was the perfect air to fuel ratio controller. Fuel injection must be controlled by this controller according to the model AFR settings. This type of control scheme has some benefits:

1. The developed air to fuel ratio setting controller concentrated on the best AFR analysis
2. The performance of the transient control may be improved by the ideal AFR controller.

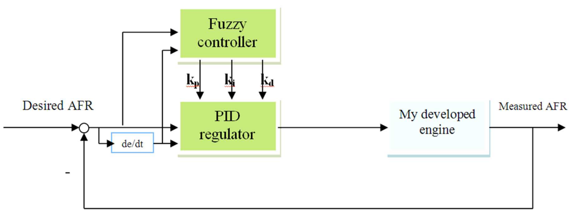

Figure 4: Block diagram of HFLC AFR control of SI engine

For HFLC and PID AFR controls, the engine must operate under stable conditions. The ideal AFR was set with respect to fuel output. By using the PID and HFLC controller the variations were corrected.

4.0 SIMULINK IMPLEMENTATION OF ENGINE MODEL

The simulation model for the engine dynamics with associated with all operational dynamics of the engine including fuel, air, and AFR dynamics, and engine speed. There were two sub-models for air dynamic as listed below: throttle model and intake manifold models as shown in Figure 5.

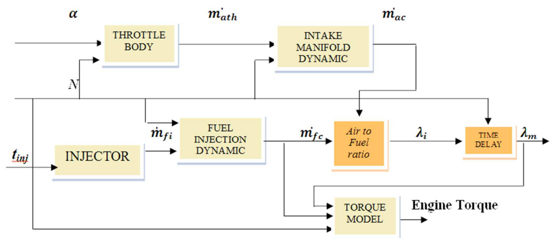

Figure 5: Proposed New Engine Model.

An experimental process was used to obtain all the parameters used in the throttle body model. Using the idle intake method together and the throttle valve directly operated method, the throttle opening cross-sectional area was effectively described using the equation for throttle mass air flow and the accuracy of the simulation was improved. The effects of charges and discharges for the intake manifold were fully represented by the Intake manifold dynamics model. Realistic dynamic responses were provided and reasonable control over dynamic errors was produced.

Fuel injection models were included in the fuel dynamics. Using various injectors, fuel injection dynamics can be modeled. In this study, fuel was measured using air to fuel ratio (AFR) controller and fuel injection outputs. This model required engine events and engine speed to control the inputs. Engine speed and AFR were the two sub-models used for combustion dynamics.

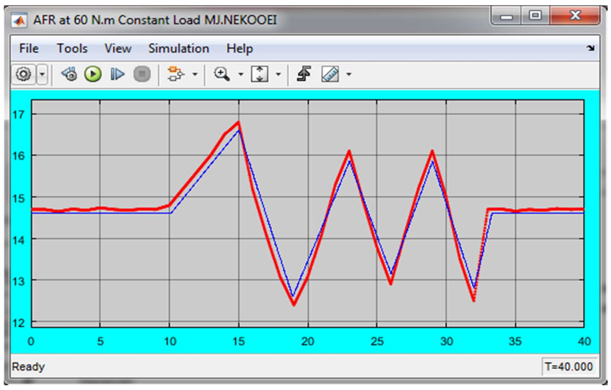

Figure 6: AFR validation at 60 N.m (Experiment and simulation results are shown in red and blue, respectively)

Figure 6 shows AFR comparison between simulation and experiment at 60 N.m of constant loading condition. It was founded that results of the experimental and the simulation model were very similar indicating that our model was valid. The research also conducted a comparative analysis of the results of simulation and test results under transient conditions using step and sinusoidal throttle inputs. The outputs of the model of

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constant engine load, such as the lambda, air to fuel ratio, engine speed and manifold pressure, were very close to the experimental results.

4.0 PID SIMULATION

A PID controller was designed to facilitate tuning and collaborate with the toolbox. Figure 7 illustrates a PID controller in which the Gain, Integrator and Derivative blocks were used to comprehend the PID controller.

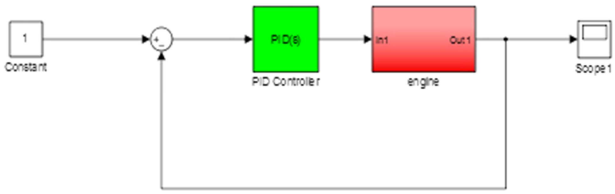

Figure 7: PID Structure in SIMULINK

After the simulation finished, the research set the PID gains to tune the simulation. By double-clicking on the PID block, the window shown in Figure 8 becomes visible.

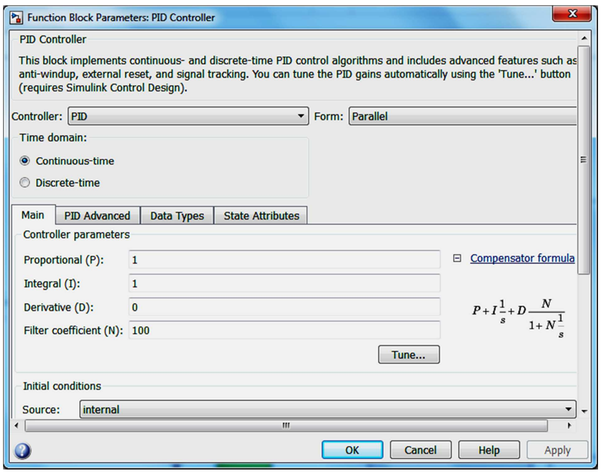

Figure 8: Function block parameters for the PID controller

Table 1: Ziegler-Nichols (Z/N) method (Ziegler and Nichols, 1942)

Control Type	K_p	K_i	K_d
P	0.5 K_u	-	-
PI	0.45 K_u	$1.2K_p/T_u$	-
PD	0.8 K_u	-	$K_pT_u/8$
Classic PID	0.6 K_u	$2K_p/T_u$	$K_pT_u/8$

In this study, the research set the PID gains using the Ziegler-Nichols (Z/N) method based on Table 1 and as shown in Figure 9.

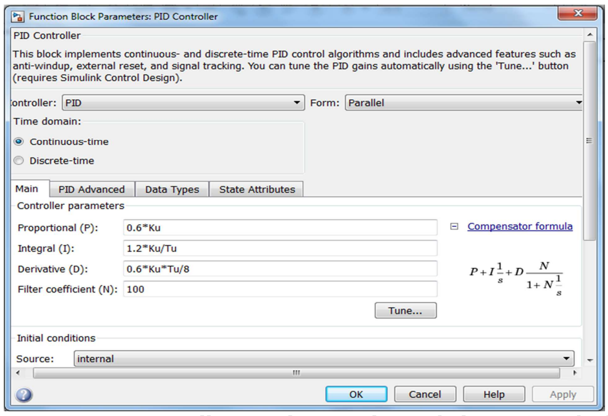

Figure 9: PID Controller Based on Ziegler-Nichols (Z/N) method

5.0 HFLC SIMULATION

The research designed fuzzy logic in MATLAB was writing in the command window. The fuzzy tool box is shown in Figure 10.

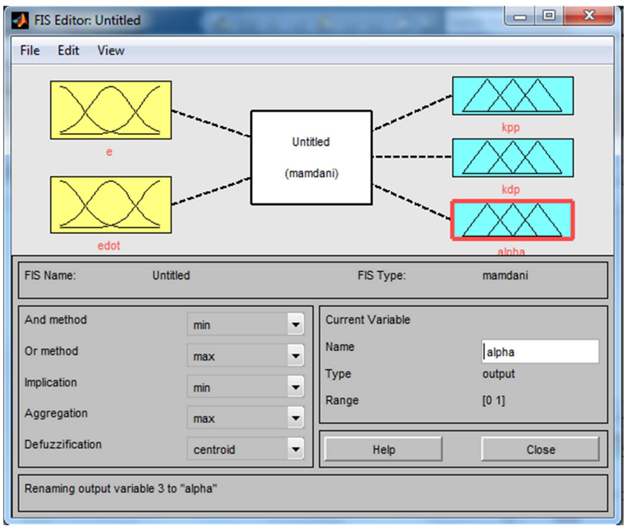

Figure 10: Fuzzy logic editor windows

As shown in Figure 11, the research added two inputs: $\boldsymbol{e}(\boldsymbol{K})$ and $\Delta\boldsymbol{e}(\boldsymbol{K})$ and three outputs $\boldsymbol{K}'_p, \boldsymbol{K}'_d$ and $\propto$. In the next section, the research defined the MF as shown in Figure 12, Figure 13 and Figure 14 and Figure 15.

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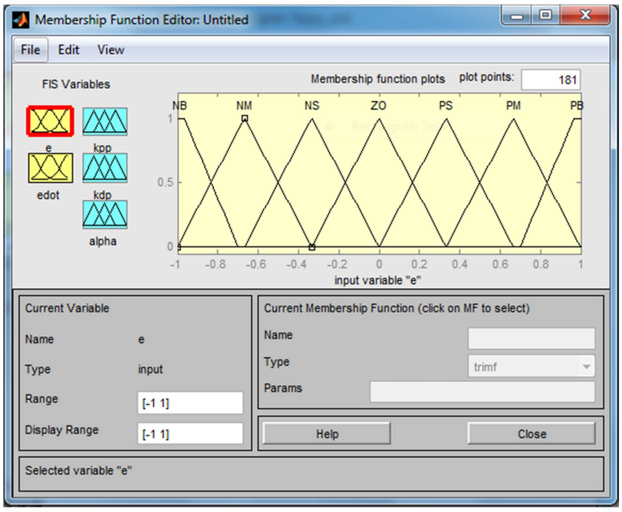

Figure 11: $\boldsymbol{e(K)}$ membership function in Matlab

As shown in Figure 8, the research used 7 triangular functions with the range [-1 1] to define the $\boldsymbol{e(K)}$ and $\Delta\boldsymbol{e(K)}$, and MF. To define the MF of $\boldsymbol{K'_p}, \boldsymbol{K'_d}$ we used 2 gaussian functions with range [0 1] as shown in Figure 12.

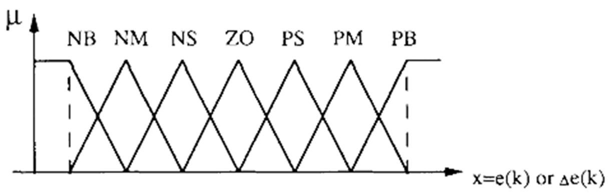

Figure 12: Membership functions for $\boldsymbol{e(K)}$ and $\Delta\boldsymbol{e(K)}$ (Zhao, 1993)

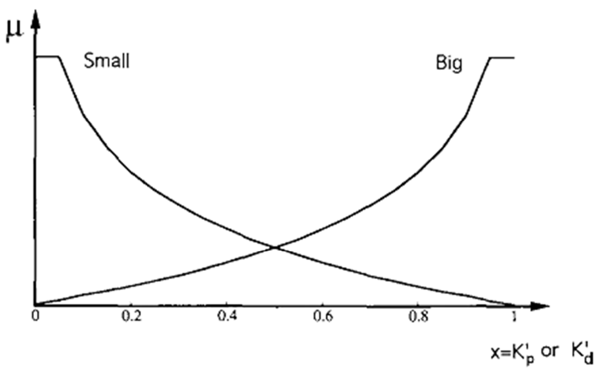

Figure 13: $\boldsymbol{K'_p}$ and $\boldsymbol{K'_d}$ membership functions (Zhao, 1993)

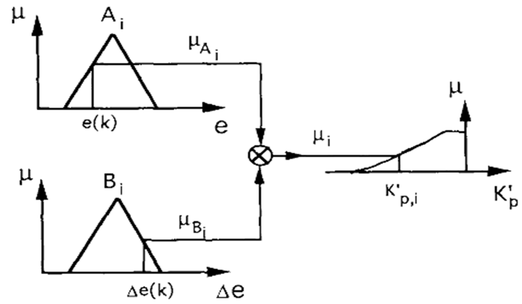

Figure 14: Singleton- membership functions for $\propto$ (Zhao, 1993).

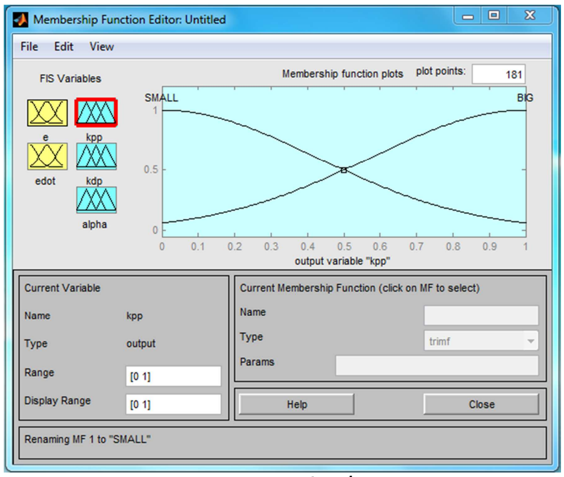

Figure 15: MF for $\boldsymbol{K'_p}, \boldsymbol{K'_d}$ in Matlab

To define $\propto$ the research used the 4 triangular functions instead of singleton functions with the range [1 6] as shown in Figure 16.

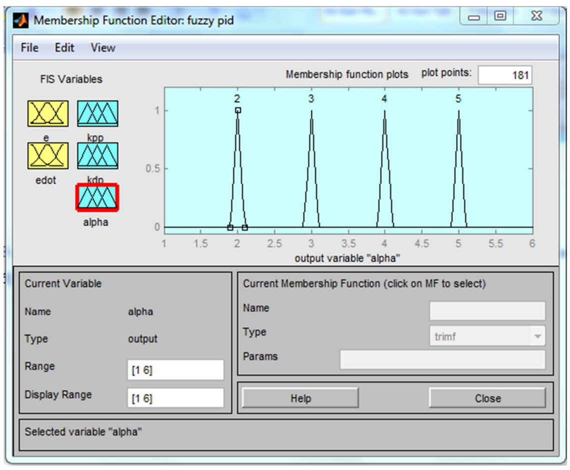

Figure 16: Membership function for $\propto$ in Matlab

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After the defined membership function the research defined the 49 rules based on Tables 2 ~ 4 as shown in Figure 17.

Table 2: Fuzzy-tuning role for K_p' (Zhao, 1993)

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 3: Fuzzy tuning role for K_d' (Zhao, 1993)

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	s	s	S	S	S	S	S

Table 4: fuzzy tuning role for $\propto$ **(Zhao, 1993)**

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

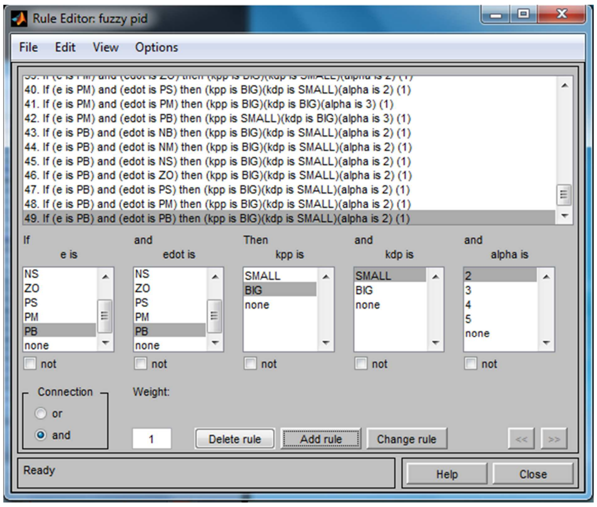

Figure 17: The 49 rules in MATLAB

As shown in Figure 18, the rules surface are visible and they show that the surface is symmetrically colored due to the use of truly defined rules in MATLAB.

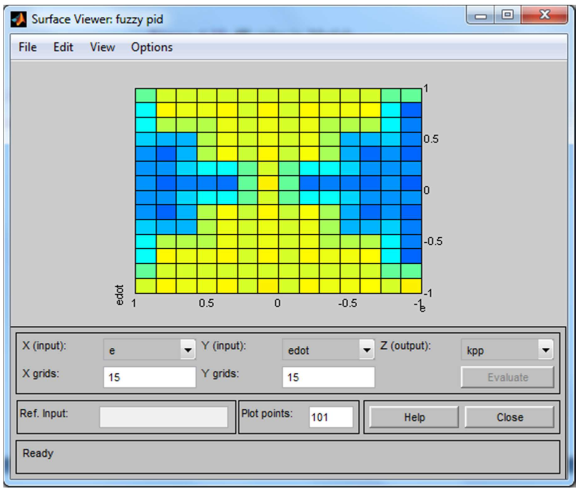

Figure 18: Rules surface viewer in Matlab

After designing the fuzzy model, the research applied it to the PID control to online adjusting the PID gains. Figure 19 illustrated a HFLC structure in MATLAB.

At the beginning of this study, the built-in PID tuning tool block in SIMULINK was used to tune and optimize the PID

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controller. According to the experimental analysis, the PID Tuning Tool was not appropriate for nonlinear systems. This was due to delay factors as well as other problems associated with the linearizing plant process.

Fuzzy control theory was used for further optimization. A single factor was applied by the fuzzy controller to parameterize three PID parameters. The PID controller was used as a basic control and as a recompensing formula when the process drifted away from a real-time parameter. Hence, the automatic adjustment of the process output to the given value was possible. Five fuzzy values were used in the fuzzy control. To maintain the smoothness of the control, a triangular membership function was used at the start before the Gaussian membership function was applied.

To generate the Fuzzy Rule Table, the method developed by Zhen-Yu Zhao was used according to the typical second-order system error curve and the PID air to fuel ratio control errors.

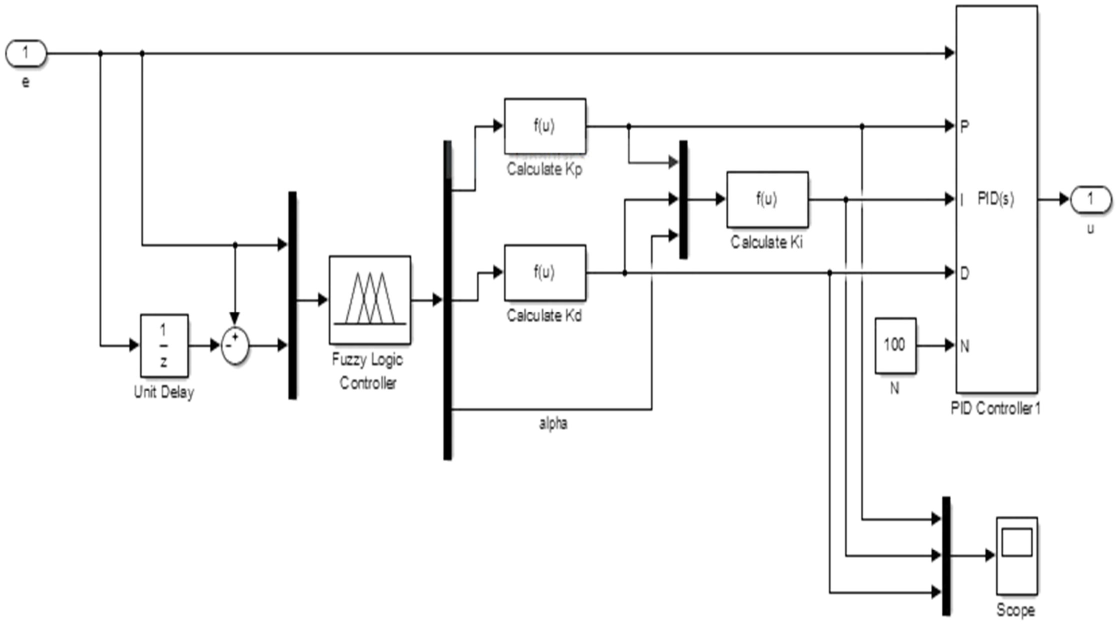

Figure 19 HFLC in SIMULINK

3.2 HFLC Simulation for SI-Engine

The HFLC was applied to simulate AFR of SI engine “Peugeot 405 1.8i Engine” as shown in Figure 20. Experimental tests were performed at the Engine Research Laboratory (ERL) at Shiraz University in Iran. The experiment was conducted under various constant loading conditions which is 40m 50 and 60 N,m. This paper only discussed on 60 N.m of loading condition.

Figure 20: Peugeot 405 1.8i Engine.

Figure 21 illustrates this comparison and the percentage of improved HFLC performance. The red line represents the HFLC results and the blue line is the developed PID AFR Controller at a constant load of 60 N.m.

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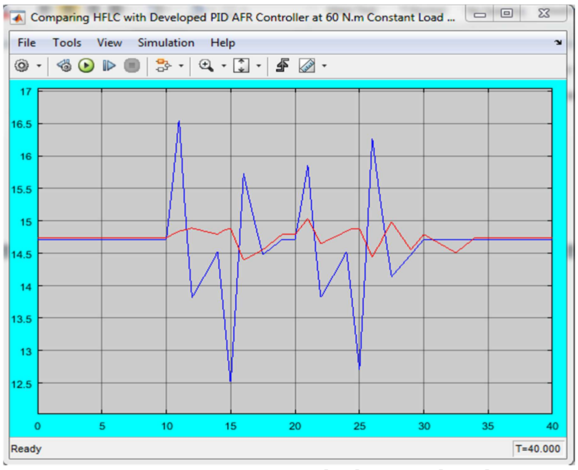

Figure 21: Comparing HFLC with the Developed PID AFR Controller at 60 N.m of constant load.

The maximum AFR in the real engine using the lookup-table controller was 16.8 and it was 15.02 for the HFLC. The minimum AFR in the real engine using the lookup-table controller was 12.4 and it was 14.4 for the HFLC. Table 5 shows the comparison of AFR results for the HFLC and Convectional Look-up Table.

Table 5: Comparison of AFR results for the HFLC and Convectional Look-up Table

	Maximum AFR Result	Minimum AFR Result
Convectional Look-up	16.80	12.40
HFLC	15.02	14.4

Three different types of control methods for controlling AFR from studies conducted by other researchers used for comparison purposes. In Table 6, the results of a comparison study between an AFR control using Neural Networks (NN), a sliding mode control (SMC), a PI control, MPC and our developed HFLC method are presented. Table 6 shows Comparison between the AFR results for the developed HFLC with NN, SMC, MPC and PI Controller.

Table 6 showed that, the developed HFLC can control the AFR very good in comparison with the reviewed methods. The average error between the maximum and minimum AFR with stoichiometric AFR was just approximately 7 % .The control methods have been reviewed in the Table 6 also controlled the AFR but still there is too big deviation between the AFR and stoichiometric AFR.

Table 6: Comparison Between the AFR results for the developed HFLC with NN, SMC, MPC and PI Controller.

	Maximum AFR Result	Minimum AFR Result
NN (Zhai et al 2010)	17.7	13.25
PI (Zhai et al 2010)	22.5	12.8
SMC (Pieper et al 1999)	17.64	11.76
MPC (Wang et al 2006)	16.2	14.05
Developed HFLC Proposed model in thesis	15.02	14.4

4.0 CONCLUSION

In conclusion, this paper discussed on Hybrid Fuzzy Logic Controller in Matlab/Simulink for Controlling AFR of SI Engine. A new simulation model using Matlab Simulink for a SI (Spark-Ignition) engine has been developed that included all engine dynamic models. The model was validated using the results from engine for operation at 60 N.m. In order to control the AFR in SI engines, new controllers were proposed to maximize fuel economy and minimize exhaust emissions. A hybrid fuzzy logic controller (HFLC) was created by combining a PID control and fuzzy control. The simulation results founded that the maximum and minimum AFR for convectional look-up and HFLC methods were (16.80, 12.4) and (15.02, 14.4), respectively. Simulation results from HFLC was also compared to other control methods such as, sliding mode control (SMC), neural network (NN), Proportional–integral controller (PI) and model-based predictive control (MPC).

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