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Prediction of maximum in-cylinder pressure by adaptive neuro-fuzzy inference system method

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Prediction of maximum in-cylinder pressure by adaptive neuro-fuzzy inference system method

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Abstract. A widely used method to substituting expensive experimental method in order to optimizing different parameters of technological application of equipment is using of modelling these phenomena by intelligent techniques. Hence, in this paper, an ANFIS (adaptive neuro-fuzzy inference system architecture) model has been used to predict one of the most important of the diesel engine which is cylinder pressure. Measurement of this parameter requires expensive and time consuming methods. Therefore, application of the mathematical method to prediction of this parameter is necessary. The inputs of this model are injection time, engine speed and engine load. The testing performance of the proposed ANFIS model revealed a good predictive capacity to yield acceptable error measures with, R^2=0.99 and MSE=6.8. This model is not developed based on complicated mathematical formula and is easy to use. The result of study recommends that the ANFIS model can be successfully used to perdition of cylinder pressure according to effective parameters.

Keywords. ANFIS; Intelligent system; engine; diesel

1. Introduction

Internal combustion engines is a vital part of the human life. However, they are invented many years ago, there are still some parameter that can be easily investigated about them. Some of effective parameters on engine performance and emission are very expensive and complicated to be measured. Therefore, different methods have been used to simplify the measuring or estimation of these parameters. One of these parameters is engine cylinder pressure. Some researchers have applied different mathematical method to estimate this parameter according to effective parameters [1, 2].

Artificial intelligent methods are one of most powerful method to optimizing different process [3, 4]. Artificial neural network (ANN) and fuzzy logic (FL) have been increasingly used in various fields of engineering. Neural network could be defined as an interconnection of simple processing elements whose functionality is based on the biologic neuron [5, 6].

Fuzzy systems have simple rules and are useful for simplifying the learning process [7]. With the combination of ANN and FL, the neuro-fuzzy architectures have been developed.
Useful neural network paradigm for the solution of function approximation problems by adaptive neuro-fuzzy inference systems can be presented. Combination of fuzzy logic with architectural design of neural

network leads to creation of neuro-fuzzy systems, which benefit from feed forward calculation of output and back-propagation learning capability of neural networks, while keeping interpret- ability of a fuzzy system [8, 9].

The main purpose of present study is to develop a new method to estimate maximum cylinder pressure according to some operational factor of diesel engine. Artificial intelligent methods are new methods that are widely used in different context to modelling different phenomena. One of most powerful techniques of these new methods is ANFIS (adaptive neuro-fuzzy inference system architecture) technique. Therefore, in this study an ANFIS based on the Takagi–Sugeno model has been developed [7] in Matlab software to adjusting maximum cylinder pressure.

2. Materials and methods

2.1. Data acquisition

Experimental research and necessary measurements of cylinder pressure curves were conducted on a test bench. The test engine and the experimental setup picture used for gathering data are shown in figure 1 and 2, respectively. The system for engine testing had four measurement chains for recording cylinder pressure, crankshaft angle, injection timing, engine speed and engine load. Pressure was measured by piezoelectric transducers.

Measured values were recorded as a function of crankshaft rotation angle, expressed in degrees (°CA). The value of rotation angle was recorded by a rotary pulse transducer and the system of marking and synchronization of the crankshaft position. The injections time which applied were four injection timing (22, 27, 32, 37 and 42 °CA (crank angle) before TDC (Top dead centre)) .The engine was operated under four load conditions 55%, 70%, 85% and 100% of full load. Also four engine speeds of 1200, 1350, 1500 and 1650 rpm have been used. The engine was fuelled by diesel oil. Exactly 501 measurements were performed for each cycle of a four-stroke engine. The matrix of the test conditions is given in table 1.

Figure 1. Test engine

Table 1. Test matrix.

Factors (parameters)	Level				
	1	2	3	4	5
Engine speed (rpm)	1200	1350	1500	1650	-
Engine load torque (% of rated value)	55	70	85	100	-
Fuel injection timing (°CA btdc)	22	27	32	37	42

The engine used in this experiment was a single cylinder, 4 strokes stationary DI diesel engine. The technical specifications of the test engine are given in table 2. The choice of this engine was guided by the fact that such small single cylinder DI diesels of about 0.5 litre capacity are used widely as stationary

auxiliary power sources in urban areas to meet the peak power demand and also for powering agricultural machinery in rural areas.

Table 2. Technical specifications of the test engine.

Parameter	Specification
Brand	Kirloskar
Number of cylinders	one
Combustion system	Direct injection
Air intake system	Naturally aspirated
Output power	3.68 Kw
Speed	1200
Bore	80 mm
Stroke	110 mm
Compression ratio	16.5:1
Loading type	Electrical dynamometer
Rated engine speed	1500 rpm
Torque at rated speed and load	23.0 Nm

Table 3 gives the brief specification of the main equipment. Instruments were used in this study were:
- Instrumentation for regulating and monitoring engine operating and performance:
- Engine torque and speed
- Static injection timing
- Instrumentation for measuring parameters concerning in cylinder process:
- Cylinder pressure
- Equipment for data logging and analysis
- Triggering unit for starting data acquisition
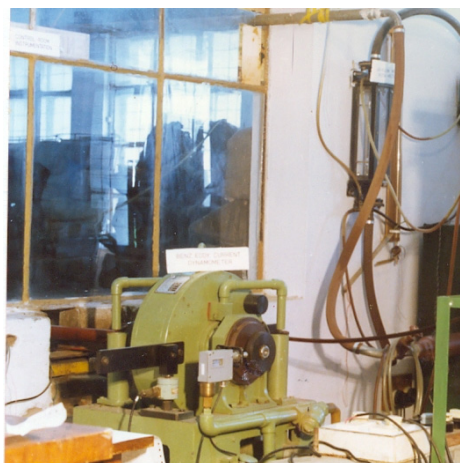
Figure 2. Engine test set-up and test instruments.

Table 3. Specifications of the instruments.

Name of instrument	Range	Accuracy	Make & Model
Quartz cylinder pressure transducer	0-250 bar	$\pm1\%$ up to 6 kHz	Kistler 6121A1, Switzerland
Eddy current dynamometer	-	-	Benz ECB 100, India
Speed indicator	4 digits	±1rpm	-
Load indicator	3.5 digits	1% const/10°c	-

2.2. Development of ANFIS Model
ANFIS is an adaptive network that permits the application of neural network topology and fuzzy logic. It is not only includes the characteristics of both methods but also eliminates some disadvantages of their lonely used case. ANFIS uses the learning ability of ANN to define the input–output relationship and construct the fuzzy rules by determining the inputs structure. The system results were obtained by thinking and reasoning capability of the fuzzy logic.
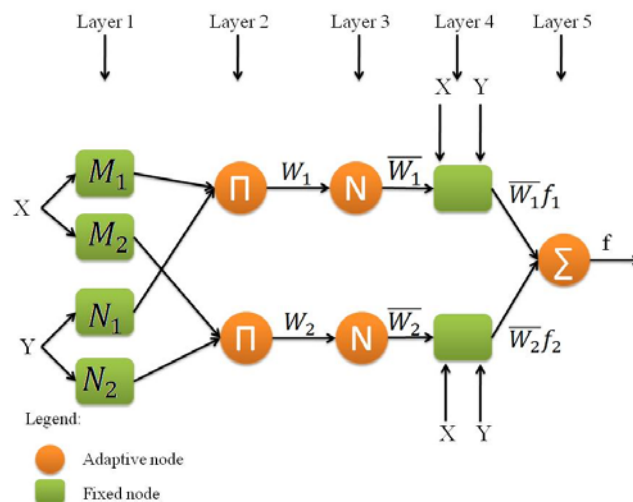
Figure 3. ANFIS network architecture.

The ANFIS network (figure 3) works as follows: Let x and y be the two typical input values fed at the two input nodes, which then transforms those values to the membership functions (say bell-shaped) and give the output as follows: [Note in general, w=output from a node; μ=membership function; and Mi and Ni=fuzzy sets associated with nodes x, y in equation (1).

$$\mu_{Mi}(x) = \frac{1}{1 + |(x - c_1)/a_1|^{2b_1}} \quad (1)$$

where a1, b1, and c1=changeable basis parameters. Similar computations are carried out for the input of y to obtain μNi(y). The membership functions are then multiplied in the second layer, e.g.

$$w_i = \mu_{Mi}(x).\mu_{Ni}(y) \qquad (i = 1,2) \quad (2)$$

Such products or firing strengths are then averaged

$$\overline{w_i} = w_i / \sum w_i \qquad (i = 1,2)$$

(3)

Nodes of the fourth layer use the above ratio as a weighting factor. Furthermore, using fuzzy if-then rules produces the following output: (An example of an if-then rule is: If x is M1 and y is N1, then f1=p1x+q1y+r1)

$$\overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i)$$

(4)

Where p, q, and r = changeable consequent parameters. The node of the fifth layer produces the final network output as a summation of all incoming signals, which is exemplified in the Eq. (5) .The description of the learning algorithm, is given by Jang and Sun [8].
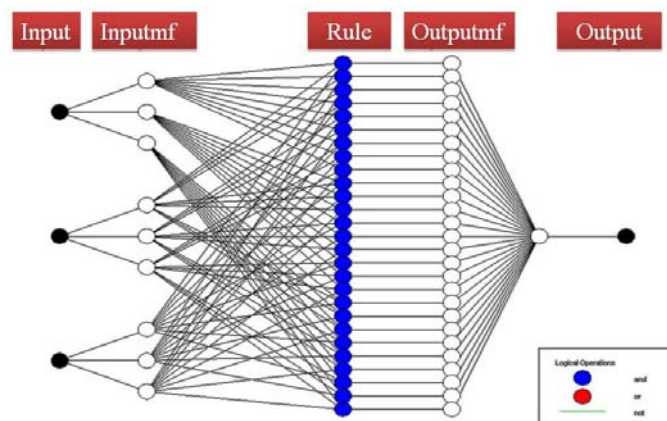
Figure 4. The ANFIS architecture for maximum cylinder pressure prediction.

The following scenarios were considered in building the ANFIS model (figure 4) with the inputs and output shown in the network. A computer program (MATLAB code) was developed to perform the analysis, and can be obtained from the corresponding writer.

The performance of ANFIS model in training and testing sets is validated in terms of the common statistical measures, such as, R2 (coefficient of determination which presents the degree of association between predicted and true values), RMSE (which is preferred in many iterative prediction and optimization schemes), SSE, and MAE (+ or −, which is a parameter commonly understood in engineering applications and which considers algebraic difference between predicted and true values).

$$SSE = \sum_{i=1}^{N} (Yi_{observed} - Yi_{estimate})$$

(5)

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Yi_{observed} - Yi_{estimate})^2}$$

. (6)

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |Yi_{observed} - Yi_{estimate}|$$

(7)

Where $Y_{estimate}$ is the estimated data, $Y_{observed}$ is the observed data. These statistical measures provides information on the strength of linear relationship between the observed and the estimated values. If the model is "perfect", SSE is zero and R2 is 1. If the model is a total failure, R^2 is zero.

3. Results and Discussion

In this study, grouped variables of input data were explored to assess their influence on the maximum cylinder pressure modeling. The ANFIS model was developed and tested for predicting output. To assess the performance of the ANFIS model, observed output values were plotted against the predicted ones. ANFIS model predicts the maximum cylinder pressure as shown in Figure 4. The number of membership function nodes has been selected by trial and error method, i.e. different numbers of membership function trained until achieving least training error between predicted and actual values. Although, higher numbers of input membership function nodes, would increase the time of training model and increased required computer memory. In other hand, lower numbers of input membership function would not satisfy the acceptable predicting ability of the model. Eventually, three nodes for each input membership function has complied two mentioned problems and least training error. The numbers of if-then rule is come from numbers of input and output membership function. The number of if-then rules is result of multiplication of numbers of input membership function nodes, here the number of inputs is three, i.e., there is 3*3*3=27 rules.

The properties of the best ANFIS model were shown in table 4. The properties which are shown in this table are determined by trial and error technique, too. Two types of Output membership function (linear and constant), eight types of input membership function (Triangular-shaped built-in, Trapezoidal-shaped built-in, Generalized bell-shaped built-in, Gaussian curve built-in, Gaussian combination, Π-shaped built-in, Built-in membership function composed of difference between two sigmoidal membership functions, Built-in membership function composed of product of two sigmoidally shaped membership functions) and two methods of optimization of model (hybrid and backpropagation) has been tried to determining the best selection of these properties.

Table 4. The properties of the best ANFIS model.

Number of membership function for each input	3
Type of membership function	trimf (Triangular-shaped membership function)
Output membership function	constant
Method for optimization	Hybrid
Number of epochs	10

The developed ANFIS model has been shown in figure 5. The inputs (injection time, engine load and engine speed) are shown in this figure. An important property of ANFIS model is shown in this figure. In classical model, such as mathematical model, some complex equation should be developed to show the relationship among inputs and outputs. But, in ANFIS model some simple if-then rules are used to show this relationship. Simplicity is one of most important advantages of ANFIS models.
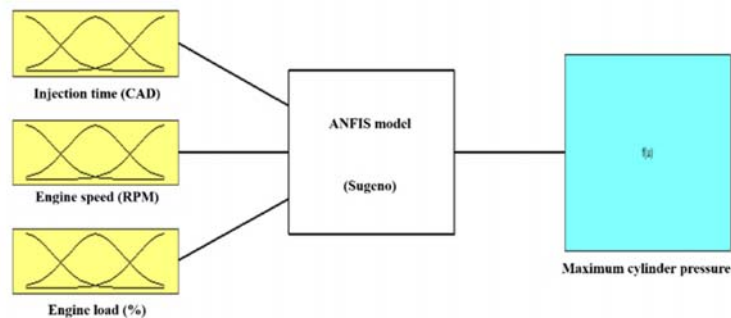
**Figure 5.** ANFIS model (inputs and output).

The corresponding rules of the developed ANFIS model are listed in figure 6. In this figure, another advantage of ANFIS model is illustrated. One of powerful ability of ANFIS models is continual of its rules. In developed model, the changes of output due to variation in individual inputs can be considered. The value of input that can be evaluated is not limited to experimented value.
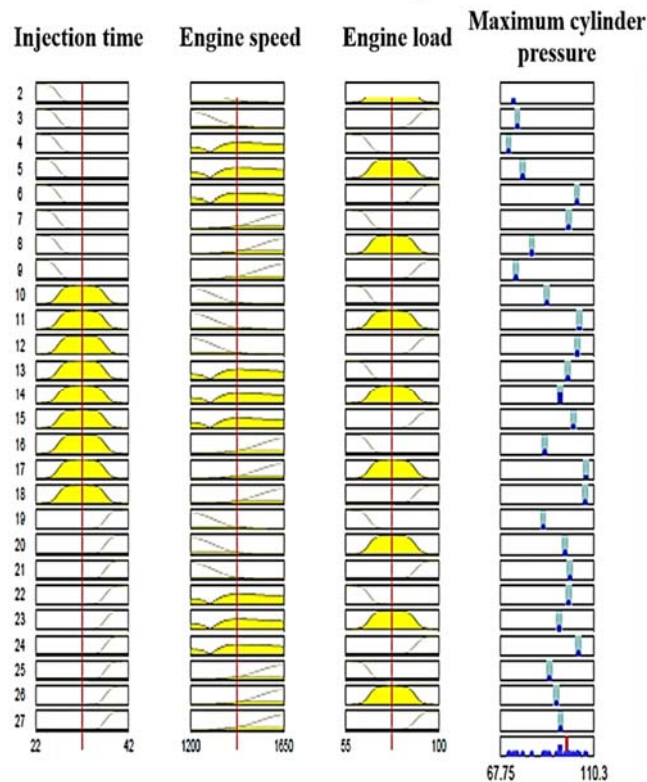
**Figure 6.** The fuzzy model rules for estimation of maximum cylinder pressure.

Figure 7 illustrates the results with the performance indices between predicted and observed data for the validating (testing) data sets. The testing performance of the proposed ANFIS model revealed a good predictive capacity to yield acceptable error measures with, R^2=0.99 and MSE=6.8, SSE= 102.3 and MAE= 2.18. This study is useful for applications of maximum cylinder pressure, particularly helping to identify parameters that most likely define cylinder pressure. ANFIS model is shown to agree well with actual measurements. As seen in this figure, the predicted value by ANFIS model was approximately equal to experimental value.
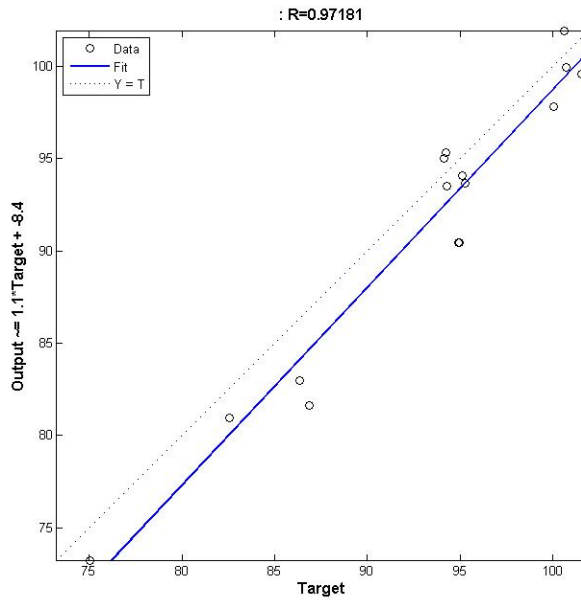
Figure 7. Observed versus predicted output.

The effect of engine speed (ES) and engine load (EL) is shown in figure 8. As exposed in the figure, the maximum cylinder pressure has increased by engine load. However, this was different for effect of engine speed on maximum cylinder pressure. As it can be seen in lower engine loads, maximum cylinder pressure start to increase and then it was decreased while this was in opposite trends for higher engine loads.
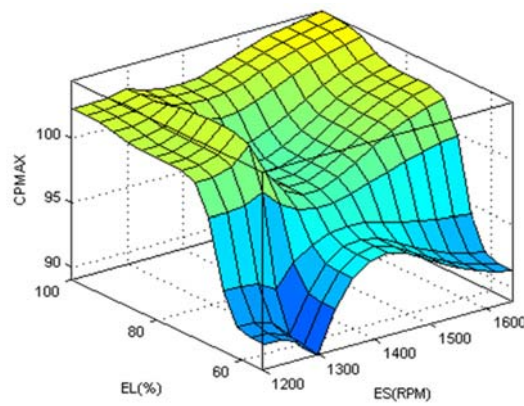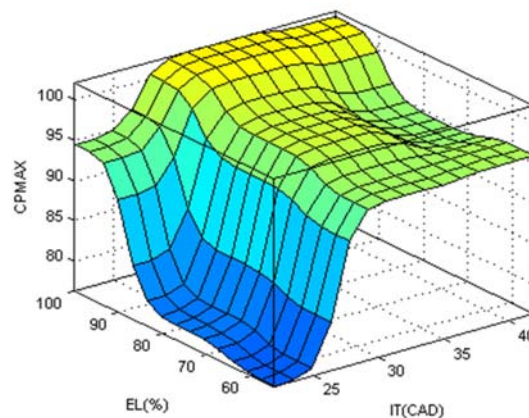

Figure 8. Final decision surface for engine load (EL) and engine speed (ES) and maximum cylinder pressure (CPMAX).
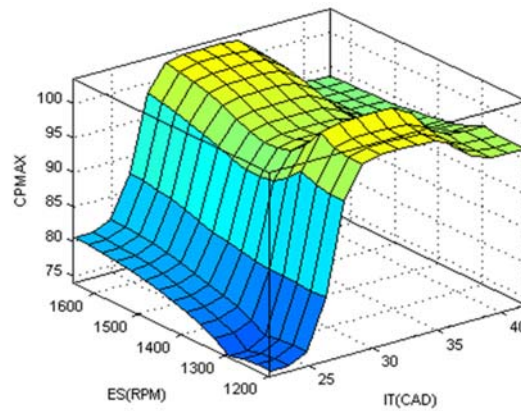
Figure 9. Final decision surface for engine speed, injection time and maximum cylinder pressure.

In figure 9 effect of injection timing and engine speed on the maximum cylinder pressure is shown. As it can be seen in this figure, advanced injection timing has increased cylinder pressure.

Figure 10. Final decision surface for engine load, injection time and maximum cylinder pressure.

Effect of the engine load and injection timing on the maximum cylinder pressure is illustrated in the figure 10. It is noticeable that same response can be seen for maximum cylinder pressure with more advanced injection timing as shown in figure 9.

4. Conclusions
Engine cylinder pressure is one of the most important parameter of the diesel engine which can be used to evaluate its combustion effectively. In this study, an ANFIS model has been developed to determine the affecting parameters on maximum cylinder pressure. Input parameters used for the ANFIS simulations were engine load, engine speed and injection timing. The results of ANFIS models using observation data records were compared and evaluated based on their performance in training and testing. The ANFIS model with Triangular-shaped membership function was chosen as the best fit ANFIS model based on performance evaluation criteria. The study recommends that ANFIS model can be used to predict maximum cylinder pressure instead of using of expensive and time wasting experimental methods.

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