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Modeling of Average Pressure of Homogeneous Mixture Compression Ignition Engine using Neural Network

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Abstract: Homogeneous mixture compression ignition (HCCI) internal combustion engines are considered to be a potentially new kind of combustion due to the combustion mechanism that occurs inside these engines. This is because it improves the efficiency of the engine and efficiently lowers the levels of nitrogen oxides. Furthermore, the improvement and control of internal combustion engines, which are amazingly homogeneous mixture compression ignition engines, have always been something that has captured my interest. The cylinder pressure is used as a form of feedback by controllers for internal combustion engines. A costly method that requires the use of dependable computer systems is required to get an exact measurement of the pressure inside the cylinder via the utilization of pressure sensors. This research has developed a model that uses a dynamic multilayer perceptron neural network to determine the ideal average pressure for a homogeneous mixture compression ignition engine. A dynamic model of a homogeneous mixture compression ignition engine was utilized using the MATLAB program in order to get the required data for neural network training. This was done prior to the training of the neural network.

Keywords: Homogeneous mixture compression ignition engine, neural network, simulation, medium pressure, internal combustion engine

1. INTRODUCTION

There are significant problems on a global scale that are caused by the overuse of fossil fuels and the associated release of greenhouse gases. Internal combustion engines are accountable for a considerable percentage of the fuel that is used as well as the pollution that is produced [1-5]. In light of this, efforts have been made to develop internal combustion engines that are not only more efficient but also more environmentally friendly. Homogeneous mixture compression ignition engines, which are more efficient than traditional engines, have the ability to solve this issue. These engines display higher efficiency in comparison to conventional engines. To function, HCCI engines are able to achieve self-ignition of a homogeneous mixture via the process of compression[6-10]. In light of this, it is possible to envision this engine as a combination of spark and compression ignition[11-14]. This specific engine's cycle is broken down into individual stages, as seen in Figure 1.

This engine is renowned for its quick and non-combustion process after the uniform mixture's spontaneous ignition. This is one of the engine's distinguishing characteristics. One of the advantages of this engine is that it has the capacity to improve efficiency[1, 15, 16] and reduce fuel consumption [17-22]by changing the compression ratio and the pace at which heat is released.

Figure 1: Stages of the homogeneous mixture compression ignition engine cycle

In contrast to engines that spark ignition or compression ignition, no mechanism directly initiates combustion in internal combustion engines. In engines that use spark ignition, the combustion process is started by lighting the spark plug, while in engines that use compression ignition, the combustion process is started by injecting gasoline[17, 23-25]HCCI engines, on the other hand, determine the fuel condition at the beginning of the compression process. This condition affects on the ignition time, which is determined by the volumetric compression ratio from the beginning of the compression process. When the suction valve is closed, the fuel mixture conditions are referred to as the particular temperature, pressure, and composition of the contents. If these conditions are changed, it is feasible to accurately predict the ignition time[26-29].

When it comes to these types of engines, high-temperature ignition zones are eliminated thanks to the presence of several ignition sites inside the combustion chamber and a more constant combustion process[30-33]. On the other hand, the maximum temperature that may be reached by this specific kind of internal combustion engine is still quite modest[33]. As a consequence of this, the generation of soot is successfully prevented by the mode of combustion being used. In addition, nitrogen oxides and suspended particles are decreased as a result of the lower maximum working temperature, which is below 1700 K.

There is a simultaneous occurrence of self-ignition throughout the combustion chamber in the ideal homogeneous mixture compression ignition engine. This results in a considerable and sudden release of heat, which may lead to spontaneous combustion and pounding or thermal stresses inside the engine[17, 34]. When this happens, the engine may stop working. These engines function by using a method known as lean burning.

Onishio Noguchi is credited with being the first person to study and regulate the auto-ignition phenomenon in fuel ignition in engines as a separate phenomenon in 1979. This is despite the fact that the auto-ignition phenomenon has been present in gasoline engines for a considerable amount of time. The majority of research publications that have been published in the past have considered homogeneous mixture compression ignition engines to be a novel ignition mechanism in reciprocating internal combustion engines[34, 35].

It is generally agreed that Onishi and Noguchi were the ones who conducted the first systematic experiments of the new ignition mechanism. However, the theoretical and practical foundation of this engine can be traced back to the work that was done in the 1930s by Nikolai Somno, a Russian scientist, and his colleagues during that time period. In order to express his theory in the field of combustion, he carried out experiments to govern combustion by chemical-kinetic mechanisms. In their studies, Wei and Giusak[36], who carried out their research in this industry throughout the 1970s, used input fuel that had been homogenized and reduced in concentration. Next, Honda conducted research and development on two-stroke gasoline engines, which finally led to the creation of the ARC 250, which was the first homogeneous mixture compression ignition engine designed specifically for bikes. According to Honda, this engine has achieved a decrease of 29% in fuel consumption and a reduction of 50% in emissions of unburned hydrocarbons.

In 1983, Najt and Foster conducted study on the four-stroke incarnation of these engines because of the efficiency with which they reduced the amount of fuel used and the pollution produced [8]. Tring [9] contributed to the advancement of the study by investigating the effects of reintroducing foreign gases and the influence of mixture dilution on the efficiency of these engines. In order to define this particular kind of combustion in diesel and gasoline engines, Tring coined the term "homogeneous compression ignition engines" to describe this particular sort of engine. This term has since been extensively used by other researchers to describe this type of combustion. For the first time, in 1992, it was proved that it was possible to have a gasoline engine with four cylinders that used a self-ignition mechanism. The use of a greater compression ratio and the heating of the intake air were the means by which this was accomplished. This allowed the engine to function within predetermined limitations of speed and load [36]. In the latter part of the 1990s, Elsano and his colleague were successful in building the biggest gasoline engine ever made, which used the auto-ignition technique for the purpose of combustion and the creation of power[36]. A diesel engine with a capacity of twelve liters and six cylinders served as the basis for the construction of this diesel engine. In order to achieve self-ignition at engine speeds and loads that were higher than the typical limit, this engine used a mixture of gasoline with heptane and isooctane, a high compression ratio, and an intake air heating system.

2. Advantages of HCCI engines

One of the most important advantages of HCCI engines is the amount of gasoline that they can consume. Both gasoline and diesel fuel are able to be used in these engines [36-39].

The emissions of pollutants produced by HCCI engines are lower than those produced by diesel and gasoline engines when the loads and speeds are low to moderate. The soot produced by these engines is far lower than that of the other two engines because of the thin-burning nature of these engines and the homogeneous combination of air and fuel that occurs inside the cylinder. Additionally, it is important to point out that the highest temperature seen in these engines is far lower when compared to the temperature seen in gasoline engines. As a consequence of this, the amount of nitrogen oxides that are produced by these engines is unacceptable [35-38, 40].

Some thin-burning engines have the potential to be built with a higher compression ratio, which would make them more efficient than the gasoline engines that are already in use[17, 36].

Engines with HCCI configurations are useful for hybrid cars, which are vehicles that combine electric power with internal combustion engines. Within the confines of these automobiles, the internal combustion engine runs within a certain speed and load range configuration. Therefore, there is no need to address the problems of homogenous mixture compression ignition engines at high speeds since the internal combustion engine in these vehicles does not run within this range[36]. This means that there is no demand to solve these shortcomings.

3. Disadvantages of HCCI engines

When it comes to HCCI engines, one of the most important drawbacks is the need for more control over the ignition start time. When referring to diesel engines, the ignition timing control system is referred to as the direct fuel injection system. On the other hand, when referring to gasoline engines, it references the ignition system. On the other hand, homogeneous mixture compression ignition engines do not have a specifically designed way to start the combustion process. As was said before, no particular mechanism may start the combustion process, which is comparable to the other two kinds of internal combustion engines with the same characteristics. As a result, the most significant challenge of these engines' widespread use is efficiently regulating the ignition start time over a wide range of loads and speeds[17].

The limits and shortcomings of these engines become apparent when they are exposed to high loads and speeds, despite the fact that they have shown adequate performance under low and moderate loads and speeds. When there is a high load and a high velocity, the combustion process is characterized by a strong and quick nature. This results in an unwanted loudness, an increased susceptibility to engine knocking and impairment, and the production of a significant amount of nitrogen oxides [17].

The inhomogeneous mixture created by compression ignition engines presents a big challenge when it comes to cold starting, which is a key disadvantage of these engines. It is not possible to heat the gases that are entering the combustion chamber during the first restart of the engine since the engine is cold at that time. Therefore, any temperature increase that occurs within the gases that are contained inside the cylinder as a result of compression is rapidly dissipated due to the heat transfer that occurs with the cool wall of the cylinder. This means that the low temperature of the gases within the cylinder during engine ignition might potentially delay the commencement of combustion in such engines [39, 41]. This is because there is no compensation mechanism that is suitable for this situation.

On the basis of the considerations raised above, the only way that this engine may be used successfully is if appropriate steps are taken to reduce the downsides. For the purpose of constructing the controller for this engine, it is unquestionably necessary to develop a model that has qualities that are both accurate and sensitive. There are a few different methods that have been developed in order to ascertain and compute the average pressure measurement. In the majority of these methods, the mean suitable pressure is determined by evaluating the fluctuations in the crankshaft velocity[40, 42]. In order to determine the speed and acceleration of the crankshaft in a four-cylinder engine, one method requires the use of a pressure sensor. Through the examination of this data, it is possible to ascertain the average pressure value for each of the four cylinders. After then, the information is used in order to control the torque balance of the engine[41, 43]. Making use of the discrete Fourier transform is still another method that may be used in order to translate the changes in the rotational speed of the crankshaft from the time domain to the frequency domain. Practical average pressure values may be achieved by the use of a multi-layered perceptron neural network[42, 44]. This is accomplished by doing an analysis of both the real and imaginary components of the processed data.

For the purpose of accomplishing this goal, a dynamic model of the engine has been developed. This model may be used to ascertain the proper average pressure for the HCCI engine. After completing the verification process for the system's operational correctness, it is used as a virtual engine to extract the data required for the training of neural networks.

The need for a significant amount of data during the training of neural networks is the impetus behind using this model as a platform for collecting facts and information. Because of this need, the engine may be subjected to severe strain, which may result in its operating restrictions or failure. It is a danger, and there is a possibility that it may cause damage to the engine. When a software simulation of the engine with a corresponding function is used, it is possible to prevent the engine from experiencing excessive strain. In light of the fact that this investigation aims to show the neural network's capability to mimic internal combustion engines, it is necessary to meet the stated aim mentioned earlier.

4. Engine Dynamic Modeling

In the sections that came before this one, we discussed how important it is to have a dynamic model that can precisely compute the ignition start time for the HCCI engine after considering various input conditions. The interaction between two succeeding cycles in terms of thermal effects is what gives rise to the need for a dynamic model. Some high-temperature gases from the cycle before this one are still present in the cylinder, which is the cause of this connection and dependence. Because of the interaction that they have with the input mixture, the leftover gases have the effect of increasing both the temperature and the heat capacity of the mixed substance.

It has been shown that the homogeneous mixture compression ignition engine may be approximated using a single-zone thermodynamic model 2. This paradigm is very helpful in easing the supply of essential data for training neural networks. According to this model, the gases are assumed to be in pristine condition, and the temperature within the cylinder and along its walls is assumed to stay constant. The dynamics of gas flow inside the cylinder, gas leakage within the cylinder, and friction between the sump and the cylinder are not taken into consideration. The modified equation[6] is used to calculate the amount of heat transfer that occurs between the gases that are contained inside the cylinder and the wall.

In the beginning, it is essential to determine the variables that are entered into the engine. The model inputs for this engine are the temperature of the intake manifold, the pressure of the inlet manifold, the percentage of smoke that is recirculated, the speed of the engine, the equivalency ratio of the inlet mixture, and the octane number of the fuel that is being injected. When a real engine is being watched, the inputs of the engine are chosen to be observed. The purpose of this model is to make a prediction about the moment at which combustion will begin and how long it will last based on the input elements that have been provided[6].

After the inputs to the engine have been determined, the geometric dimensions and timing of the engine and the timing of the intake and exit valves are computed. After that, the volume and area contained inside the cylinder are determined by using the angle of rotation of the crankshaft as the basis for the calculation. In accordance with the supplied parameters, the volume and area inside the cylinder have been computed using the equations presented in reference [6].

Calculating the ignition start time requires creating the proper equations based on the thermodynamic characteristics of the engine at the moment the intake valve is closed. This is done in order to provide the necessary information. However, since it is not possible to measure these parameters directly, their values are measured in the inlet manifold. After that, the values are connected to the thermodynamic variables by applying the relationships that have been developed. The empirical data that is accessible in the references provides a quantitative representation of the values that are related to the closing moment of the intake valve. The first thing that needs to be done to finish the calculations associated with the gases still present in the cylinder after the first cycle is to figure out the mass of the gases still there. On the basis of the temperature that is being considered, NASA polynomial curves are used to ascertain the specific heat capacity at constant volume and pressure.

According to what was said earlier, the existence of residual gases in the cylinder causes a change in both the specific heat capacity and the temperature of the mixture that is being introduced. Utilizing the specific heat capacity of the new mixture in conjunction with the mass component of the gases that are still present in the cylinder is one method that may be used to ascertain the temperature of the composite. When calculating the ignition start time, it is necessary to take into account the mass component of the leftover gases and use the modified Kobash integral method. When a polytropic process is assumed to be taking place, there is no longer a need for temperature and pressure control inside the cylinder during the compression phase. According to this assumption, all heat release that occurs before ignition as a consequence of pre-combustion processes is ignored[43]. Using the polytropic equation to explain the process between the closing of the intake valve and the beginning of combustion, one can calculate the temperature and pressure at the beginning of combustion. This is accomplished by computing the angle that is connected with the beginning of combustion. In order to accomplish this goal, the equations (1) and (2) are used to calculate the temperature and pressure, respectively[6].

$$\mathrm{T_{soc}} = \mathrm{T_{mix}} \cdot \left(\frac{\mathrm{V_{ivc}}}{\mathrm{V_{soc}}}\right)^{\mathrm{k_c}-1} \tag{1}$$

$$\mathrm{P_{soc}} = \mathrm{P_{ivc}} \cdot \left(\frac{\mathrm{V_{ivc}}}{\mathrm{V_{soc}}}\right)^{\mathrm{k_c}} \tag{2}$$

After calculating the ignition start moment in the step before this one, it is necessary to determine the ignition completion time. To determine the crankshaft angle at which 99% of the fuel is burnt, the time it takes for the combustion to be completed is converted. For this reason, the Web function determines the mass percentage of the fuel consumed, and the crank angle is used as the independent variable. The Web function is represented by equation (3), which can be found here. By using this function, it is possible to compute the instant when the combustion process is finished and the angle of the crankshaft associated with the ignition of fifty percent of the fuel available[6].

$$x_b(\theta) = 1 - \exp\left(-A\left[\frac{\theta - \theta_{soc}}{\theta_d}\right]^B\right) \qquad (3)$$

The equation states that A is a fixed value, and the combustion duration is determined by equation (4), in which C, D, and E are all fixed values[6].

$$\theta_d = C(1 + X_d)^D \varphi^E \qquad (4)$$

In the second phase, the temperature and pressure are accurately calculated at the point in time when the combustion process is complete. By considering the combustion chamber as if it were an isolated system and using the first law of thermodynamics between the first and last seconds of combustion, we are able to estimate the temperature at which the combustion process is finished. The rapid combustion of HCCI and the small cross-sectional area that results from the close proximity of the beginning and ending of combustion to the high pause point both contribute to the poor heat transfer. The mass component of the fuel that has been burned is shown in Figure 2 as a function of the crank angle beginning at the moment of ignition. The tiny period of time that elapses between the beginning of combustion and its conclusion is shown in this image in a manner that is both clear and succinct. According to this graphic, the length of the combustion process is similar to 7.15 degrees of the crank angle.

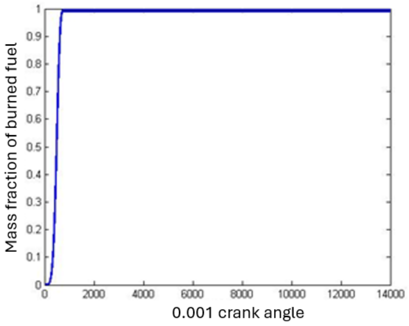

Figure 2: Diagram of the mass component of the burned fuel in terms of the crank angle from the moment of ignition

When the polytropic process is considered, it is feasible to ascertain the temperature and pressure when the exhaust valve is opened. This is accomplished by using the temperature present at the combustion process's end.

It is possible to obtain the adequate average pressure for the various operating modes of the homogenous mixture compression ignition engine by integrating and averaging the pressure measurements taken inside the cylinder at various angles.

This model's outputs were compared to the experimental outputs for around fifty cycles to determine whether or not it was accurate. The input conditions were the same during all of these cycles. The findings of this comparison are shown in Figure 3, which can be seen here.

Experimental data has been collected from the Ricardo laboratory engine, which is situated at the thermodynamics laboratory of the Faculty of Mechanical Engineering at Amirkabir University of Technology. Furthermore, a dynamic software model customized specifically for this engine has been developed.

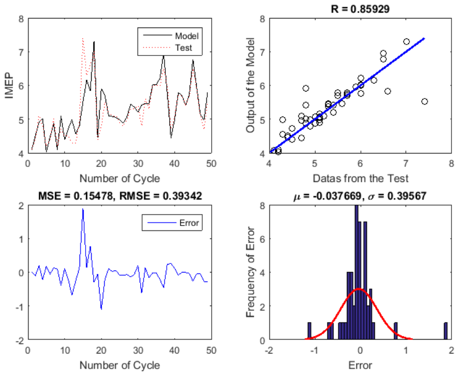

Figure 3- The results of comparing the software model and experimental data

5. Neural Network Training

The neural network that is used for the purpose of modeling this engine is named a multilayer perceptron neural network. Both dynamic and static systems may be imitated with the help of this network, which is a suitable tool. Figure 3 illustrates the network architecture that applies to the model.

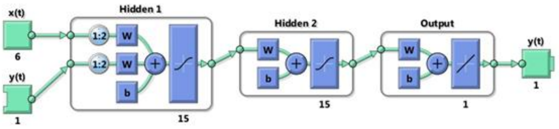

Figure 3: Network architecture used to model the HCCI engine

Because of the dynamic nature of the system being investigated, the system's output has an effect on the inputs of the cycle that comes after it, and the inputs of the system are not restricted to the cycle that they belong to within the system. The future cycle or cycles will be the ones in which their influence will become apparent. It has been accomplished by using two delays for both the inputs and the outputs in order to accomplish this goal. In each cycle, the inputs regarded as inputs are the outputs from the two cycles that came before the current cycle, the inputs from the current cycle, and the inputs from the past two cycles [44]. Throughout the course of its training, the network is able to estimate the average ideal pressure of the engine by making use of the data that it has received. The outputs of the simulation of the HCCI engine's mean ideal pressure are shown in Figures 4 and 5, respectively.

An illustration of the training and test data of the neural network that has been trained can be seen in Figures 4 and 5, respectively. Each of these figures has four graphs. In the top figure, the real outputs of the HCCI engine, namely the average suitable pressure, are displayed against the outputs created by the neural network for the same inputs when compared to the outputs generated by the neural network. For each of the two distinct categories, a linear regression coefficient has been computed, and a line representing the equation representing the intermediate point between these two points has been shown. It is necessary for all of these locations to be on a straight line with a slope of one, which contacts the origin, in order for the network to attain a rate of accuracy of one hundred percent. This is seen in Figure 5, which shows that the linear regression coefficient for the test data is 0.98257, which is very close to being equal to one. The application of the created network to the test data demonstrates an astonishing level of accuracy, as shown by this. According to the training data, the coefficient is 0.99937, which indicates that the network's performance is remarkable. There is a display of the values in Table 1.

In Figures 4 and 5, the graph in the upper left corner illustrates not only the actual outputs but also the outputs created by the network for the same inputs they were given. The exam, the training, and all of the data are all subjected to this. These figures provide evidence that the graphs are organized in an effective manner.

As a representation of the test data and the training data, respectively, the error scatter diagram can be seen in the bottom diagram of Figures 4 and 5. This set of graphs demonstrates that the majority of errors are clustered around zero and that the number of errors that occur decreases as the distance from zero increases. The graph displays information on the average errors and the standard deviation of the errors located at the surface. Table 1 contains complete and unambiguous statements of the values in dispute.

Error graphs for test data, training data, and all of the data listed in the bottom left graph are shown in Figures 5 and 6, respectively. There is no problem using these numbers since they correlate to output values that fall within the range of 5 to 8. The errors that are shown above these graphs are the average and the root mean squared errors. Table 1 has the values that were specifically addressed.

Table 1 displays the outcomes obtained from using a multilayer perceptron neural network in the modeling process.

Data type	R	MSE	RMSE	μ	σ
Test	0/983	0/019	0/138	-0/010	0/138
Education	0/999	0/000	0/029	0/000	0/030
All Data	0/993	0/009	0/095	0/000	0/095

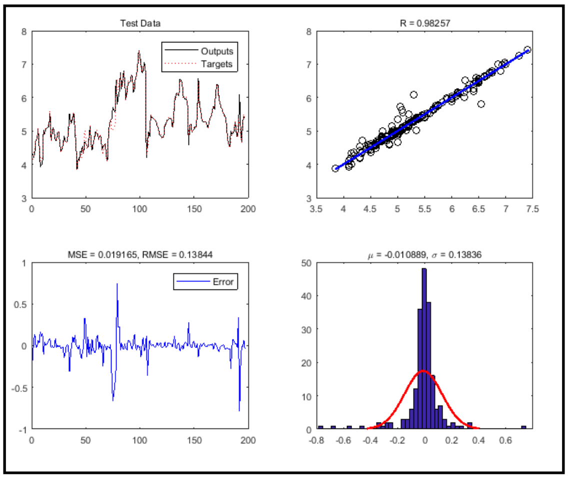

Figure 4 illustrates the comparison between the multilayer perceptron neural network's outputs and the test data's actual outputs.

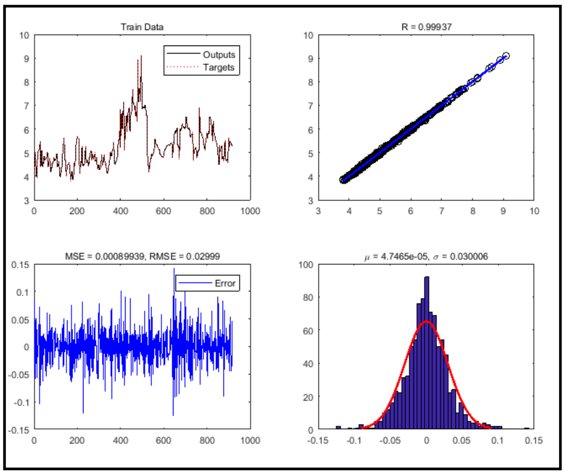

Figure 5 illustrates the comparison between the outputs of the multilayer perceptron neural network and the actual outputs of the training data.

6. Conclusion

Based on the information shown in Table 1 and Figures 4 and 5, it was determined that this network can accurately determine the appropriate mean pressure (IMEP) of the homogeneous mixture compression ignition (HCCI) engine. An approximation to add insult to injury, the network's training time and response speed are excellent candidates for implementation in microcontrollers.

During the process of training a neural network, it is necessary to be aware that the model being used is dynamic. As a result, the selected network needs to demonstrate dynamic behavior, which may be accomplished by including delays in the system input.

To simulate the different components of an HCCI engine, the neural network is a more realistic alternative to the modeling models currently in use because of its high accuracy and quick response time.

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