Research Article

Estimation of the In-Cylinder Pressure in Diesel Engines-Synchronous Generators Sets

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Abstract

This paper deals with the estimation of cylinder pressure of a four-stroke diesel engine which drives a synchronous generator, by applying two methods. The first method is based on the utilization of the current and speed developed by the synchronous generator of the power production system along with the utilization of a mathematical model which considers the dynamic model of the crankshaft. The second method is based on system identification techniques and the development of ARMAX models based on available pressure and acceleration raw data, of an identical diesel engine. This model is applied to acceleration data obtained during the operation of the investigated diesel engine, in order to estimate in-cylinder pressure. Finally, the relevant results of the two methods are compared demonstrating the similarities and differences due to the different approach.

Keywords: Internal Combustion Engine, Condition Monitoring, In-Cylinder Pressure, Vibration Signals, System Identification Techniques, crankshaft dynamic model.

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1. Introduction

Cylinder pressure is one of the most important signals used for control and condition monitoring purposes of the internal combustion engines. Traditionally, the cylinder pressure is measured by installing pressure sensors inside the combustion chamber of a cylinder Hubbard M et al [1], Morris J and Li-Chi [2], Winter H et al [3], Chandroth G. O. et al [4], d'Ambrosio S. [5]. This is an "intrusive" and cost demanding technique due to the modification required to the cylinder head. Moreover, the pressure sensors undergo high thermal strain and thus their operational life is limited. Therefore, a lot of useful work has be done in order to develop indirect methods of pressure estimation, Brown TS and Neill WS [6], P. F. Maria et al [7], Citron SJ et al [8], Schagerberg S and McKelvey [9], Taglialatela F et al [10], Al-Durra A. et al [11], Syed Abbas Ali and Samir Saraswati [12], Jairo A. Grajales et al [13], Li Zhixiong et al [14].

P.F. Maria et al [7], introduce a mathematical model for the combustion process in order to estimate the in-cylinder pressure of a diesel engine. Citron SJ et al [8], Schagerberg S and McKelvey [9], Taglialatela F et al [10], Al-Durra A. et al [11], Syed Abbas Ali and Samir Saraswati [12], propose various mathematical models for in-cylinder pressure estimation by utilizing engine speed fluctuations or angular position. Citron SJ et al [8], use an elastic model of the engine-drivetrain system and as its input the measured fluctuating speed, in order to determine total engine torque and engine pressure torque. Then, the resultant engine pressure torque waveform is used to extract the cylinder pressure waveform. Schagerberg S and McKelvey [9], have developed a mathematical model in order to relate the

pressure of each cylinder of a multi-cylinder engine to the resulting torque of the crankshaft. Raw data from torque and cylinder pressure sensors have demonstrated the effectiveness of the proposed model. Taglialatela F et al [10], introduce a Multi-Layer Perceptron neural network to relate engine speed and the pressure peak of a cylinder with its angular location, in order to evaluate in real-time, the combustion quality. Al-Durra A. et al [11], introduce a crank angle mathematical model for the combustion process involving the definition of a burn rate function. Linear parameter varying techniques are implemented in order to cover the total operating points and conditions in steady a and transient state. Syed Abbas Ali and Samir Saraswati [12], reconstruct the in-cylinder pressure and indicated torque of a diesel engine using crankshaft speed fluctuations with the implementation of frequency response functions. The relevant results demonstrate significant agreement between the estimated and the measured pressure data. Finally, Jairo A. Grajales et al [13], determine the in-cylinder pressure of a spark ignited engine by developing a polynomial mathematical model which combines acceleration signals from the head of the cylinder along with the average rotational speed per cycle calculated between vibration peaks.

In this paper the pressure of the cylinders of a diesel engine-synchronous generator set is being estimated by applying two methods. The first method considers the current and the speed of the synchronous generator in order to estimate the diesel engine developed torque, utilizing at the same the equations describing the dynamic model of the crankshaft, which lead to the estimation of the in-cylinder pressure. The second method aims to the development of a mathematical model, in a preliminary stage, which will relate acceleration signals directly to the developed in-cylinder pressure. This is pursuit since it would be more convenient and less cost demanding, the installation of the accelerators in comparison with the installation of speed encoders due to

accessibility or sensitivity reasons. However, the method demands an existing timeseries pair of pressure and acceleration data, from a similar or identical diesel engine. This could be achieved either by deriving data directly from pressure sensors, or by the implementation of complex thermodynamic accompanied by mechanical mathematical models. In this case, there was an existing pair of pressure and acceleration data obtained in the past from now on called "original data". Two mathematical models relating acceleration to pressure are extracted based on this pair of data by applying system identification techniques. Then the in-cylinder pressure is estimated applying the extracted mathematical models to the acceleration signals obtained by the installed accelerometers on the top of the cylinders.

2. Experimental test bench

The experimental test bench is presented in Fig. 1. The electric power production set consists of a Lombardini 8LD 665-2 21kW diesel engine and a MECC-ALTE synchronous generator of 22 kVA operating as 1-phase. The data with respect to diesel engine are given in Table 1. The measurements which were performed comprise three types of sensors. Accelerometers placed on the top of the cylinders, current sensors and a speed sensor. The data acquisition system which has been developed for the collection and record of the relevant signals utilizes a PCI-1716 card. The measurement procedure considered several load conditions and tests. However, in this study the experiments were focused mainly on the start of the generator set and its settlement on a specific electric load. The placement of the accelerometers was chosen to be in vertical position due to the fact that the greatest correlation between vibration and cylinder pressure is when the accelerometers are in the vertical position, Jairo A. Grajales et al [13]. The experimental test bench is demonstrated in Fig. 1.
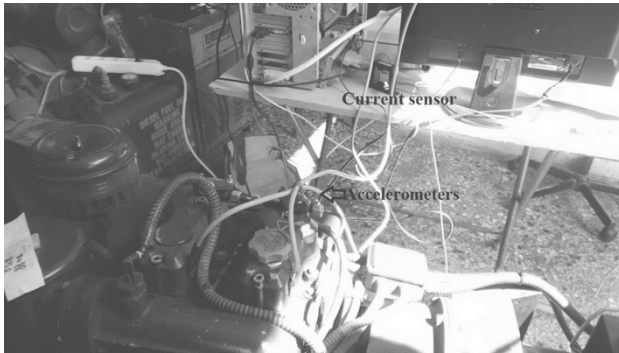

Fig. 1 Experimental test bench

3. Applied analysis

3.1 1st Method. Implementation of crankshaft dynamic model.

The calculation of the in-cylinder pressure of the diesel engine is based on two direct measurements by utilizing the crankshaft dynamic model as described by Li Zhixiong et al [14]. The two direct measurements are the current developed by the synchronous generator and the speed of the power generation set.

The crankshaft dynamic model as it is depicted by Li Zhixiong et al [14] is given by the following equation.

$$J(\Theta)\ddot{\Theta} = T_I - T_R - T_F - T_L \tag{1}$$

where T_I is the indicated torque, T_R is the torque due to the reciprocating masses, T_F is the friction torque and T_L is the load torque, which is actually the opposing counter torque induced by the synchronous generator. Θ is the angular position of the synchronous generator and diesel engine. The torque of the reciprocating masses T_R is given by Eq. 2 as follows.

$$T_R = \sum_{k=1}^{N} T_R^k = m_1 R^2 \sum_{k=1}^{N} \{[(\ddot{\Theta}f(\theta - \varphi_k) + \dot{\theta}^2 g(\theta - \varphi_\kappa)]f(\theta - \varphi_\kappa\} \tag{2}$$

Where $f(\theta)$ and $g(\theta)$ are given in Eq. 3 and Eq. 4.

$$f(\theta) = \sin\theta + \frac{\lambda\sin(2\theta)}{2\sqrt{1 - \lambda^2\sin^2(\theta)}} \tag{3}$$

$$g(\theta) = \cos\theta + \frac{\lambda\cos(2\theta)}{2\sqrt{1 - \lambda^2\sin^2(\theta)}} + \frac{\lambda^3\sin^2(2\theta)}{4\sqrt{(1 - \lambda^2\sin^2(\theta))^3}} \tag{4}$$

where λ is the connecting rod to crank radius ratio.

The term φ_κ denotes the phase of the kth cylinder as given in Eq. 5

$$\varphi_\kappa = \frac{4\pi}{N}(\kappa - 1) \tag{5}$$

The total inertia $J(\theta)$ varies according to the following formula

$$J(\Theta) = m_1 R^2 \left(\sin\theta + \frac{\lambda\sin(2\theta)}{2\sqrt{1 - \lambda^2\sin^2(\theta)}}\right)^2 + m_2 R^2 \tag{6}$$

The friction torque is approximated by using the following equation:

$$T_f = D\dot{\theta} \tag{7}$$

where D is the damping coefficient

The mechanical load imposed on the diesel engine by the synchronous generator as a counter torque is calculated by Paul C. Krause [15], I. Boldea, and S.A. Nasar [16], using the following equations:

$$P_{GEN} = \frac{E_f V_T}{X_s}\sin\delta \tag{8}$$

$$E_f = \frac{\omega L_f I_f}{\sqrt{2}} \tag{9}$$

$$V_T = E_f - (R_s + jX_d)I_s + L_s\frac{dI_s}{dt} \tag{10}$$

$$T_L = T_{GEN} = \frac{P_{GEN}}{\omega_{GEN}} \tag{11}$$

Where V_T is the terminal voltage, E_f is the internal voltage developed due to excitation current, δ is the power angle, P_{GEN} is the power produced by the generator, I_f is the excitation current, I_s is the measured current produced by the generator, and R_s, L_s, X_d, and L_f are parameters associated with the circuits of the synchronous generator.

Finally, the indicated torque is a function of the contribution of each in-cylinder pressure p(k) and it is given

in Eq. 12, where B is the bore of each cylinder. As it is obvious, the Eq. 12 has two unknown variables, i.e. the pressure p(k) in each cylinder. A solution to the problem is the calculation of a weight factor which relates the contribution of each cylinder torque to the total indicated torque of the engine, M.Kyunghan et al [17].

However, assuming equal angle-pressure relationship in all cylinders the solution of Eq. 12 with respect to in-cylinder pressure can be reduced to one variable equation.

$$T_i = \sum_{k=1}^{N} T_i^k = \frac{\pi B^2}{4} R \sum_{k=1}^{N} [p(k)f(\theta - \varphi_\kappa)] \qquad (12)$$

Combining the above equations and the relevant recorded measurements for current and speed, the in-cylinder pressure of each cylinder is obtained.

3.2 2nd Method. Implementation of system identification techniques.

System Identification techniques utilize statistical methods to determine mathematical models of dynamical systems from existing time series data with respect to input(s) and output(s) of the examined system G. Box and G. Jenkins [18], L. Ljung [19], T. Soderstrom. and P. Stoica [20].

System identification techniques relate input(s) and output(s) in the form of differences equations, i.e in discrete time domain. Two of the most characteristic models which are being involved in various scientific areas like systems modeling, control, processes e.t.c., are the ARX and ARMAX models.

The general equation of differences which describe an ARX model is:

$$y(t) + a_1 y(t-1) + \cdots + a_{na} y(t-na) = bu(t-1) + \cdots + b_{nb}(t-nb) + e(t) \qquad (13)$$

Where u(t), u(t-1),..., u(t-na) are the input time series data, and y(t), y(t-1),...,y(t-nb) are the output time series data. The e(t) is the term of the error or the 'white noise'. The maximum delay in both input and output series data is determined by the order of the ARX model.

Similarly, the equation of differences describing an ARMAX model is given by:

$$y(t) + a_1 y(t-1) + \cdots + a_{na} y(t-na) = b_o u(t-d) + b_{nb} u(t-d-n_{b)} + e(t) + c_1 e(t-1) + \cdots + c_{nc} e(t-n_c) \qquad (14)$$

The distinction between an ARX and an ARMAX model is the existence of the error terms in the equation of differences of the ARMAX model.

Several methods are implemented for the determination of the parameters of the ARX and ARMAX model. A common one for both models is the development of the following expression Eq. (15), the determination of its derivative and the set of the derivative equal to zero. $\Phi(t)$ is the vector of the input(s) and output(s) time series data at specific time observations (delays). Θ is the vector of the coefficients of the equation of differences which have to be determined. This method is also called the "least squares" method.

$$V = \frac{1}{N} \sum_{N=1}^{N} (y(t) - \Phi^T(t)\theta)^2 \qquad (15)$$

Other methods for the determination of the parameters of an ARMAX model are the "Recursive Least Square Estimation" and the Forgetting factor. The first one aims towards the minimization of the computing burden. The second one aims towards the minimization of the samples of the time series used in order to stress on the dynamical behavior of the examined system without at the same time the development of infinites in the calculations.

The general methodology for extracting a dynamical model for an examined system is summarized in the following steps.

- ➢ Filtering the time series data in frequency intervals related to the operation frequencies of the examined system.
- ➢ Time series chopping in smaller intervals (parts) and examination of the resulting models.
  Adoption of the model with the best fit (minimum divergence) concerning the entire signal.
- ➢ Examination of the frequency response of the adopted dynamical model.

4. Results and Discussion

4.1 1st case. Estimation of the in-cylinder pressure by considering the dynamic crankshaft model

In the first case the diesel engine-synchronous generator set starts from cold and settles to an operating point which corresponds to 8.1 kW electric load. The relevant figures which demonstrate the variation of current as recorded by the current sensor, its estimated true rms value and the recorded speed of the diesel engine-synchronous generator set are shown in Figs. 2 to 4 respectively. The variation of the estimated torque which corresponds to the operating point of 8.1 kW is shown in Fig. 5.
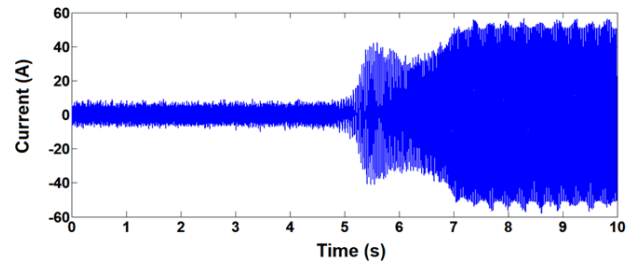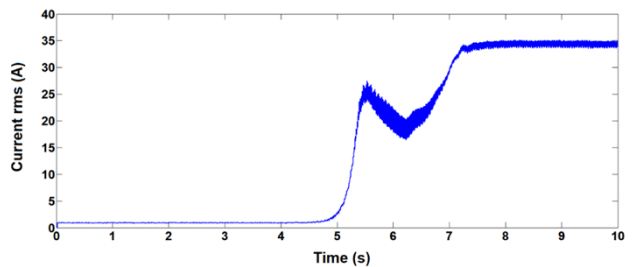

Fig. 2 Instantaneous current of synchronous generator

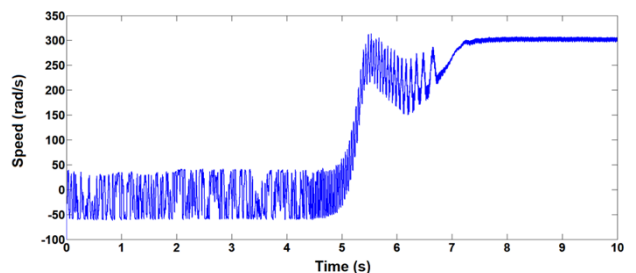**Fig. 3** Current of the synchronous generator (true rms values)

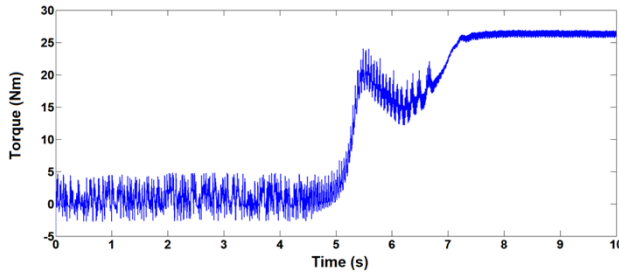**Fig. 4** Speed of diesel engine-synchronous generator set

Fig. 5 Torque developed by the synchronous generator

The output voltage of the synchronous generator was regulated to be 231 V. The synchronous generator acts as a mechanical load to the diesel engine, developing a counter-torque imposed on the diesel engine. The torque of the diesel engine-synchronous generator set is 27 Nm at steady state. The speed at steady state is approximately 307 rad/sec, i.e. 2933 rpm. This means that he rotation frequency is 48.883 Hz and the frequency of the four-stroke cycle is 24.44 Hz since it takes two revolutions to be completed. In time domain this corresponds to a time interval of 0.0409 seconds. The relevant results which show the variation of the in-cylinder pressure with time when the system is settled to its operating point are demonstrated in Figs. 6 and 7 respectively.
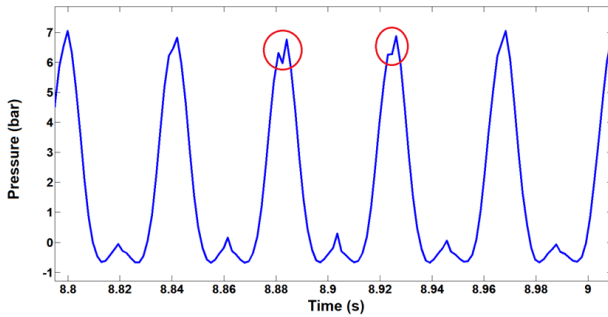

Fig. 6 Estimated in cylinder pressure of diesel engine
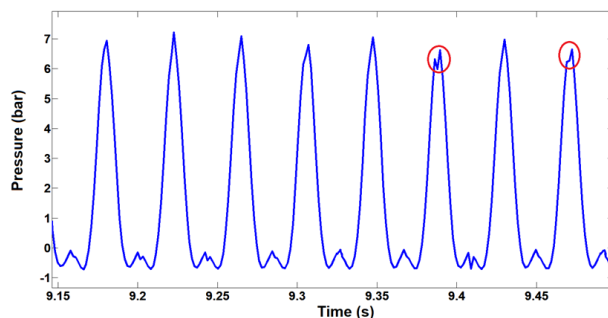

Fig. 7 Estimated in cylinder pressure of diesel engine

The red marks at the top of several points indicate combustion delay. Since, there were no direct measurements of the in-cylinder pressure of the specific operated diesel engine, an indirect method was followed to validate the relevant results. This was accomplished by the calculation of the average in-cylinder pressure per cycle and the comparison with the mean effective pressure given by the following formula.

$$T = \frac{P_{me}V_d}{2\pi n_r} \tag{15}$$

The Eq. 15, relates the developed torque of a diesel engine with its mean effective pressure (P_{me}), where V_d is the engine displacement and n_r corresponds to 2 for a four-stroke engine. The mean effective pressure for the total developed torque of 27 Nm was found to be 2.545 bar for each cylinder, whereas the average pressure value in each complete four-stroke cycle was found to be 2.62 bar.

4.2 2nd case. Estimation of the in-cylinder pressure by implementing system identification Techniques

As it has already been discussed in the introduction section, this method of relating acceleration data directly to pressure data is based on an existing pair of data (original data) obtained in the past from an identical diesel engine. The speed of the identical diesel engine during operation was about 2866 rpm. This means that the characteristic frequencies like combustion frequency and the valve seating for each cylinder are 23.88 Hz, and 47.76 Hz respectively. Also, the frequency of the piston side thrust impact is expected to be at 95.52 Hz by assuming 4-point contact of the piston with the cylinder bore. A small portion of the original data is demonstrated in Fig. 8, after processing it in a low frequency band which contains the above-mentioned frequencies.
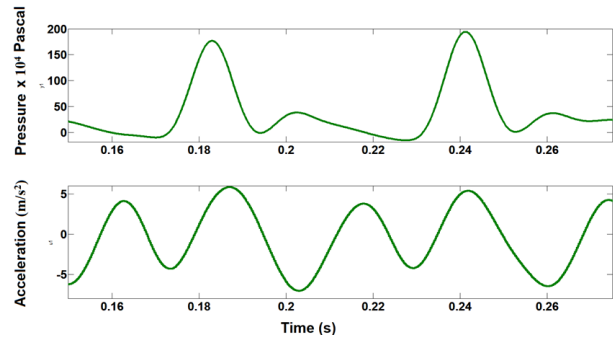

Fig. 8 Original pair of data

The procedure as discussed above in section 3.2 was implemented on the original pair of data in order to estimate suitable mathematical models relating acceleration directly to in-cylinder pressure. Several tests were performed with ARX and ARMAX models of different orders, however the most suitable one proved to be the ARMAX 4441.

Two ARMAX 4441 models were identified. The first one is given below after its conversion from the domain of discrete time to the domain of continuous time is given by the following equation.

$$H(s) = \frac{-5630.4s^3 + 3.53782e6s^2 + 1.2078e8s + 1.139e11}{1s^4 + 195.255s^3 + 1.6765e5s^2 + 5.1769375e6s + 3.185e09} \tag{16}$$

The obtained in-cylinder pressure by implementing the above transfer function on the original acceleration data is compared to the original (measured) in-cylinder pressure, as it is demonstrated in Fig. 9. The relevant results are compared to a portion of the total combustion cycle which comprises the compression, the expansion and the exhaust. The evaluation of the extracted ARMAX models was evaluated by calculating Mean Squared Error which was found to be 0.002893.

The frequency response of the above transfer function (1st ARMAX model) is demonstrated in Fig. 10, where the expected characteristic frequencies of the operating point of the original data are identified.
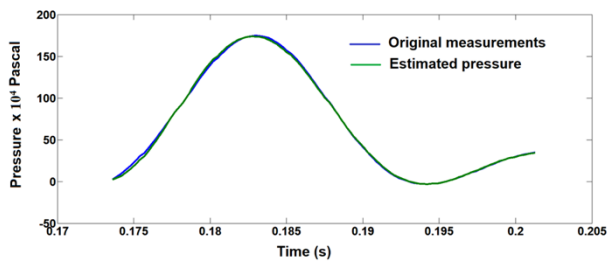
Fig. 9 Comparison between the measured in-cylinder pressure of the original pair of data and the estimated from the 1st ARMAX model
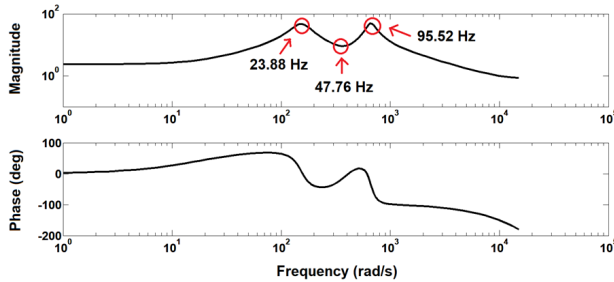

Fig. 10 Frequency response diagram of the 1st ARMAX model

Then, the in-cylinder pressure of the diesel engine of the experimental test bench was obtained for the same scenario of section 4.1, by using the Eq (16) and the acceleration data as they are given in Fig. 11 after being processed to a lower frequency band. The relevant results are demonstrated in comparison to the results of the crankshaft dynamic model in Fig. 12.
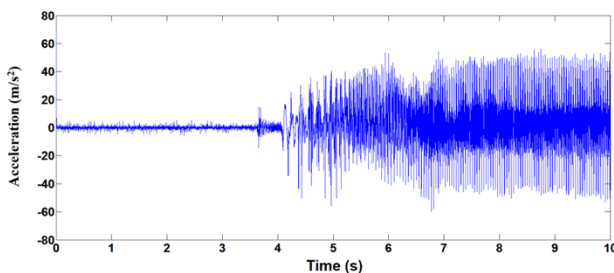

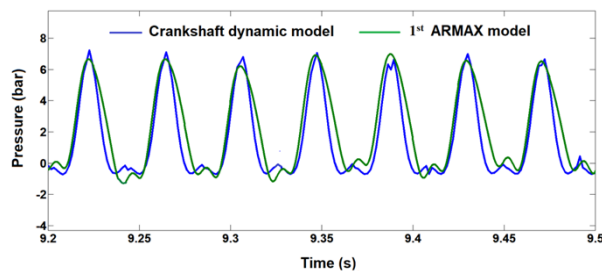**Fig. 11** Acceleration data from the operating diesel-engine

Fig. 12 Estimated in-cylinder pressure. 1st ARMAX model in comparison to first method.

A second ARMAX model was identified by focusing only to compression and expansion. The transfer function corresponding to this model is:

$$H(s) = \frac{-6294s^3 + 2.662e5s^2 + 6.156e8s + 8.646e08}{1s^4 + 342.4s^3 + 1.998e5s^2 + 1.078e7s + 4.367e09} \qquad (17)$$

The relevant results in compared to the results from the implementation of the crankshaft dynamic model are given in Fig. 13.
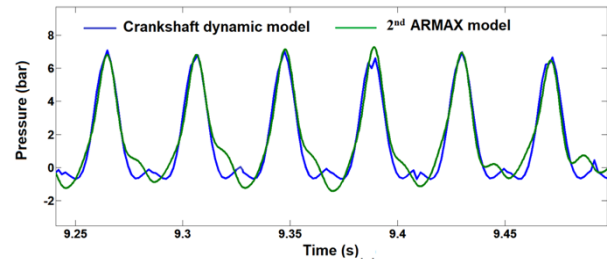

Fig. 13 Estimated in-cylinder pressure. 2nd ARMAX model in comparison to first method.

As it is obvious the results obtained for the in-cylinder pressure, derived from the implementation of the 1st ARMAX model have a greater resemblance to that obtained by the implementation of the crankshaft dynamic model particularly in the region of intake, compression and exhaust. As for the case of the results obtained from the implementation of the 2nd ARMAX model demonstrate a great coincidence in the region of compression and expansion with the results obtained from the implementation of the crankshaft dynamic model, as it was expected to be. A diversification between the two methods is the detection of the combustion delay only in the first method. An optimization of the algorithm which calculates the ARMAX method in several regions of the combustion problem will alleviate the problem and improve the sensitivity to the detection of possible faults.

5. Conclusions

The in-cylinder pressure of a diesel engine-synchronous generator set is estimated by following two approaches. The first one deals with the application of a mathematical model considering the dynamics of the crank shaft system, and the synchronous generator. The relevant results are compatible with the existing experience in the field. The second one deals with the implementation of system identification techniques in order to relate directly acceleration data to the in-cylinder pressure. The relevant results are very promising and in the future an optimization technique will be implemented in order to improve the procedure and to ensure reliability for the whole region of the combustion process. Several experiments will be carried out with the application of several faults like valves clearance, piston slaps e.t.c., in order to improve the sensitivity of the identified models to the possible faults.

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