Condition Monitoring of CI engine running on Biodiesel using Transient Process

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Abstract

Various research groups across the globe have developed models for engine condition monitoring and fault diagnosis based on the data from steady state performance measurements over the last two decade. However, these performance data are not amenable for easy collection in some situations and some of the data may show little performance deviation at the steady state conditions of operation. In addition, the motion of an automobile in urban settings is mostly transient due to stop-go nature of the traffic. It has been extensively reported that the transient operation results in higher undesirable emission level in the exhaust gases as compared to steady state condition of operation, especially if there are faulty engine components. The above discussion implies that the transient measurements may provide large performance deviation as compared to the steady state measurements for diesel engine condition monitoring and diagnostics purposes. The aim of this study is to identify engine operating conditions and parameters that can be used to develop a diagnostic tool for internal combustion (CI) engine running on biodiesel blends fuel.

In this work a 4 cylinders, 4 stroke, and water cooled diesel engine is modelled with Ricardo wave to generate data for diagnostic modelling. Diesel-Wibie combustion model, Woschni heat transfer model and map based turbocharger models have been used for engine running with 10% by volume biodiesel fuel in the model. The model is validated using test results from real CI engine running under steady and transient conditions of operation during the healthy state of the engine. After validation Wave model has been used to analyse the deviations of critical parameters during actual as well as degraded conditions of steady state and transient state operations. Since injectors fault is one of the most basic problems in biodiesel fuel utilization due to higher viscosity of the fuel, the faults in fuel injectors have been used for developing the diagnostic model of the engine under degraded condition of operation. The the degraded condition of operation was created by forcing one one injector to work with 90%, 80% and 70% of the normal fuel flow efficiency. The measurable performance parameters such as brake power, brake torque and exhaust temperature and in-cylinder pressure have been used to compare the deviations during steady and transient condition. From the comparison of the data obtained from transient and steady state simulation of the engine with and without injector fault, it can be concluded that the transient parameters show higher deviations and hence are better suited for condition monitoring and diagnostic modelling in engine working speed.

Key words: Biodiesel; Transient Performance; Condition Monitoring; Accumulated Deviation;

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I.Introduction

The performance of engine components deteriorates during their routine operations because of the difficult operating conditions. Therefore necessary maintenance is required to keep the engine condition healthy to ensure continuous availability. Traditionally engine maintenance is carried out as per the plan developed by the manufacturer and since this method can turn out to be post-failure maintenance in several cases, the condition monitoring maintenance has become more popular [1]. Jones and Li [2] have summarized that the main consequence of faults in diesel engines as the power loss, emission quality deterioration, noise and vibration, and thermal overload in cylinder. Generally, the causes of fault, the fault consequence and performance parameters measured for typical condition monitoring operations for a diesel engine are shown in figure 1.

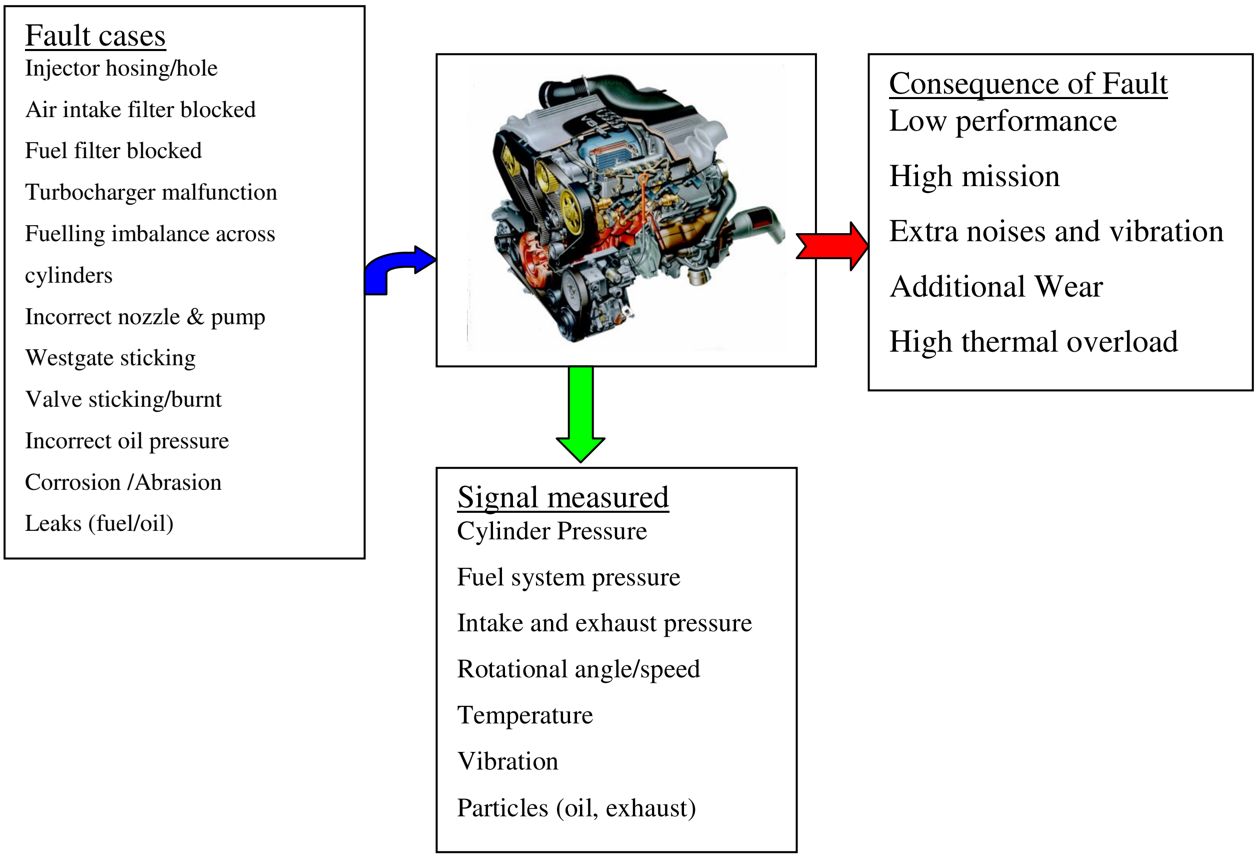

Fig 1 Diesel engine faults, measured parameters and the consequence of faults

Most of current diagnostic techniques being used are usually developed at specific engine working conditions under steady state conditions of operation. However, a typical diesel engine may work under different ambient conditions, loads, and other dynamic features reflecting a transient nature of operation [2]. These operating conditions have wide ranging effects on performance characteristics of the engines. It is very vital in current situation to have condition monitoring tools using transient conditions performance to cope with the stringent automotive emission legislations.

In most automotive drive routes engine start, warm up, accelerations and drive cycles based on changes in the slopes and geometric features of the roads etc are the common transient operations in urban and extra-urban transportation [3]. It has been reported that roads' geometric features such as road gradient and horizontal road curvature (round about) highly influence the performance and emission of the engines [4]. Generally during the transient conditions of operation, the emissions are worse in quality than that under the steady state conditions and the performance parameters show greater deviations as compared to steady state processes [3].

Currently most of the diesel engine condition monitoring and diagnostic tools use data from engines under steady state measurements. In most situations the good-quality performance and emission data are difficult to obtain. Moreover the automotives moving in urban and extra urban engines operates most of the route time under transient conditions. In addition the performance and emission deviation due to fault is very likely to be magnified during transients compared with that of steady state conditions [5].

In this paper the suitability of transient operation performance measurements has been shown for diagnostic purposes. For this purpose the transient performance deviation due to the engine injector's faults has been quantified. For modelling the engine, the Ricardo wave software package has been used. On the developed model injectors fault has been incorporated and its impact on performance of the engine has been evaluated.

II.Modelling

As mentioned above, for the simulation of engine performance Ricardo wave model has been used. This software has been preferred for engine modelling because of its flexibility in selecting sub-models, efficient calculation, well tested transient simulation capabilities and for being a highly accepted platform in the research community requiring less time and low cost for predicting systems' performance [6].
In the Ricardo wave package many engine related processes have been modelled with a number of common mathematical and empirical formulae. In this study, the combustion process in a direct-injection diesel engine has been modelled using Weibe combustion model that includes correlations for pre-mixed, diffusion burn regimes and tail burning as illustrated in Fig 2. In particular, the model calculates the cumulative mass fraction burned *W* by the equation (1) [7].

$$W = p_f\left\{1-[1-(0.75\tau)^2]\right\} + d_f\left\{1-[1-(cd_3\tau)^{1.75}]^{5000}\right\} + t_f\left\{1-[1-(ct_3\tau)^{2.5}]^{5000}\right\}. \tag{1}$$

In this equation P_f is the premixed fuel fraction. d_f which is given by the equation $d_f = (1-p_f)(1-\alpha)$, is the diffusion fraction. t_f given by the equation $t_f = (1-p_f)\alpha$ is the tail burning fraction. The other term used in equation above is α that is calculated by $\alpha = 0.60[\min(\phi,0.85)]^2$. The other terms are defined as given below. τ is from $\tau = \dfrac{\theta-\theta_b}{125\left(\dfrac{RPM}{BRPM}\right)^{0.3}}$, $cd_3 = \dfrac{0.055}{1+0.5\min(\phi,0.85)}$. Further, ct_3 is also a variable given by the expression $ct_3 = \dfrac{3.7cd_3}{1.12\min(\phi,0.85)+1}$. The other parameters used in equation (1) are ϕ (the equivalence ratio) , θ_b (start of combustion), θ (the crank angle), RPM (engine speed) and BRPM (speed of engine during burning of fuel).

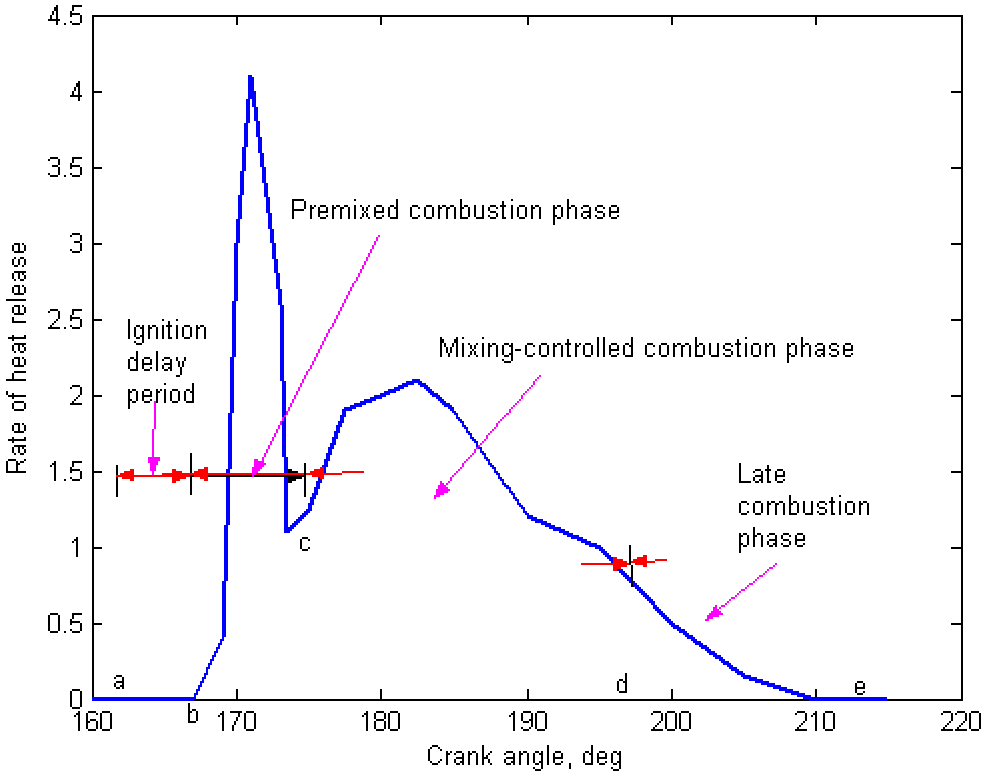

Fig. 2: Direct Injection Wiebe Function (3-step combustion: pre-mix, main, and tail combustion)[8]

The heat transfer phenomenon is modelled using the Woschni correlation, which expresses the convective heat transfer coefficient (h_g,) as described by equation (2).

$$h_g = 0.0128 D^{-0.20} P^{0.80} T^{-0.53} V_c^{0.8} C_{enht}. \tag{2}$$

In the above equation D is cylinder bore, P is cylinder pressure, T is cylinder temperature, C_{enht} is scaling multiplier and V_c is characteristics velocity. Using this convective heat coefficient the heat transfer from gas to the walls is formulated as per the equation (3) [9].

$$\dot{Q} = h_g [A_{head}(T_g - T_{w-head}) + A_{piston}(T_g - T_{w-piston}) + A_{linear}(T_g - T_{w-liner})]. \tag{3}$$

In the equation (3) $\dot{Q}$ is instantaneous heat transfer to the walls, A_{head}, A_{piston}, and A_{liner} are the head, piston and liner areas respectively. T_g, $T_{w\text{-head}}$, $T_{w\text{-liner}}$ and $T_{w\text{-piston}}$ are the instantaneous temperatures for gas, gas-side head-wall, gas-side piston-wall and gas-side liner-wall, respectively.

Zeldovich's [10] extended mechanism has been used for NOx emission modelling, and Newhall's [11] correlation has been used for CO and CO2 modelling.

Frictional effects within the engine have been modelled using Friction Mean Effective Pressure (FMEP) correlation. This is used when calculating net output quantities such as Brake Mean Effective Pressure (BMEP) and Brake Horse Power (BHP). This correlation uses maximum pressure and average piston velocity terms to calculate hydrodynamic friction [7]

In the simulation model the turbocharger is modelled using the “classic” quasi steady methodology [7]. In this method the flow through the compressor or turbine has been calculated from steady state compressor or turbine maps at each time step using instantaneous inlet and outlet pressures, temperature and turbocharger speed.

The model of the internal combustion (CI) engine, which has been simulated in the present investigation, is shown in fig 3 and this model includes inlet manifold, valves, injectors, cylinders, exhaust manifold and a turbocharger. The engine used for the simulation is a four-cylinder, four-stroke, turbocharged direct injection engine with a bore of 103 mm, a stroke of 132 mm, a displacement of 4.399 litre and a compression ratio of 18.3:1. Full engine characteristics and operating parameters of the model are shown in table 1 and table 2 respectively. This engine is available within Advanced Automotive Laboratory, University of Huddersfield, U.K. The engine set up includes the state of the art performance and emission measurement facilities. After the model has been developed, basic simulation results are validated using the experimental results obtained from the above mentioned engine. The fuel used in the simulation is 20% rapeseed biodiesel. It has a calorific value of 39.74 MJ and a density of 885 kg/m^3, and a kinematic viscosity of 4 mm^2/s.

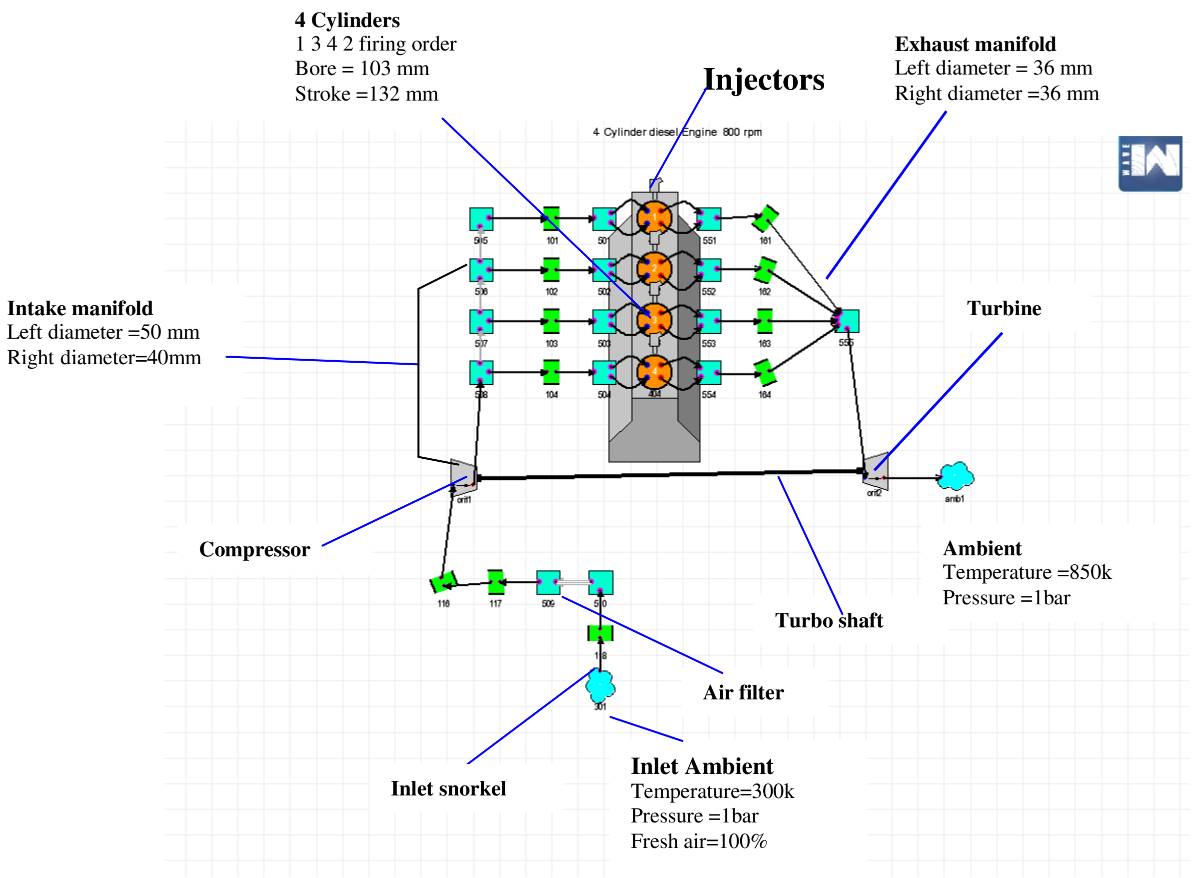

Fig. 3 Internal Combustion Engine Ricardo Model

The steady and transient models have been simulated for healthy (nominal) engine as well as faulty engine conditions. The faults in the engine have been created by using faulty injectors. In the simulations, various levels of injector fault have been taken as conditions causing degradation in the performance. The faults on the fuel line have been created by blocking one injector to have fuel flow of 90%, 80% and 70% of that of the healthy condition. The injectors’ faults is a common problem noticed in engines using bio-diesel as a fuel because biodiesel causes coking and trumpt formation on the injectors to such an extent that fuel atomization does not occur properly which may ultimately lead to plugged orifices [12].

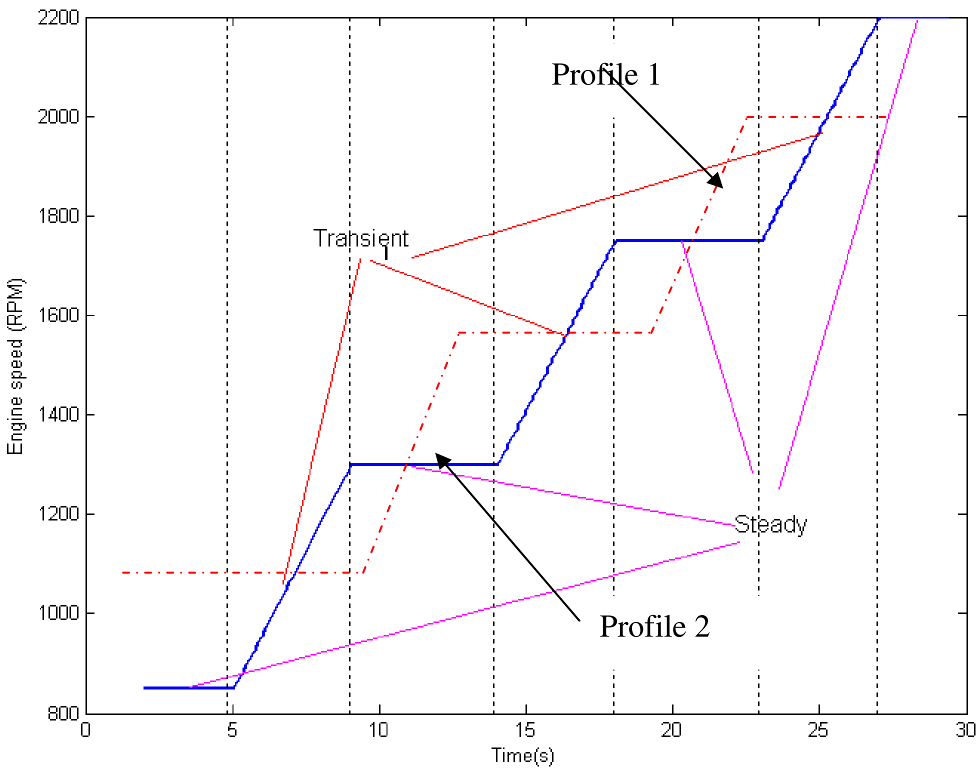

Fig.4 Engine speed profile verses time

Both the healthy and faulty engines were stimulated in multi-steady and multi-transient conditions as described in fig 4 for 30 seconds. During this time period the engine speed varied from the ideal engine speed (850 rpm) to the maximum engine speed (2200 rpm). The simulation includes three transient state operations and four steady state operations. The two types of speed-time profiles were used in simulations that were carried out as depicted in figure 4.. The model was used to simulate four conditions of engine operations: a) healthy engine b) Faulty engine(One injector working at 90% efficiency of normal injector) c) Faulty engine(One injector working at 80% efficiency of normal injector d) Faulty engine(One injector working at 70% efficiency of normal injector

Table 1 Engine characteristics

Type of engine	Turbocharged diesel engine
Number of cylinders	4
Bore	103 mm
Stroke	132 mm
Inlet valve diameter	36.2 mm
Exhaust valve diameter	33.5 mm
Compressor inlet diameter	60 mm
Compressor outlet diameter	60 mm
Turbine inlet diameter	100 mm
Turbine outlet diameter	80 mm
Compression ratio	18.3:1
Number of valves	16
Injection system	Direct injection
Displacement	4.399 litre
Cooling system	water
Recommended speed	850rpm
Maximum power	74.2 kw @ 2200 rpm

Table 2 Operating parameters of the model

Parameters	*Values*
Speed range	600 – 2100 rpm
Fuel to air ratio	0.05
Standard tolerance	0.001
Compressor speed	60,000 – 220,000 rpm
Firing order	1-3-4-2
Heat transfer model	Woschni model
Combustion model	Diesel Wiebe model
Injector	Fuel/air total type, with 100% liquid fuel
Valve	Lift type Maximum lift inlet: 9.37@ 101^0 after top dead centre Maximum lift exhaust: 9.42@115^0 before top dead centre Inlet close 32^0 after bottom dead centre Exhaust open 60^0 before bottom dead centre Exhaust closes 10^0 after top dead centre
Compressor model	Classic Compressor physics

III. Basic and Accumulated Performance Deviation

There are many approaches used for internal combustion condition monitoring and fault diagnostic systems, such as Ferrographic Oil Analysis, Rotary Particle Depositor (RPD), Particle Quantifier (PQ), Spectrometric Oil Analysis, Image Analyser Systems, Contamination, Diesel Engine Fault Diagnosis (DEFD) system of Lloyd's Register, Knowledge-Based system for Marine Engine Diagnosis (KBMED), and Condition/Performance Monitoring and Predictive System for Diesel Engines (CPMPS) [2]. CPMPS is the current most powerful performance analysis based engine diagnostic method. CPMPS does not depend on historical data for engine condition monitoring and diagnostics, instead it gives instant information about the condition of the engine with built-in sensors. In this method, the performance of deviation of any equipment is defined as the shift of the parameters from their nominal values at steady state operation due to performance degradation and it can be expressed as equation (4).

$$\Delta Z = \left| \frac{Z - Z_n}{Z_n} \right|. \tag{4}$$

Where Z is the current value of performance parameter and Z_n is the nominal value of the parameter. This relation is derived based on measurements conducted during steady state operation point. The nominal value Z_n, is measured when the engine is new, and Z is measured when the engine is degraded. Govineusky *et al.*[13] modified the equation (4) by including constant offset of residual γ_o, parameter change caused by changing ambient conditions, $\delta_{n,}$ and γ_n is the measured parameter change caused by a fault as described by equation (5).

$$\gamma_n = \gamma_o + \Delta Z + \delta_{n'}. \tag{5}$$

However, such expressions or deviation concepts cannot be easily applied to transient process diagnostics [14]. In order to use transient measurement, the analysis of performance deviation for the whole transient process is more useful than at a certain operation point.

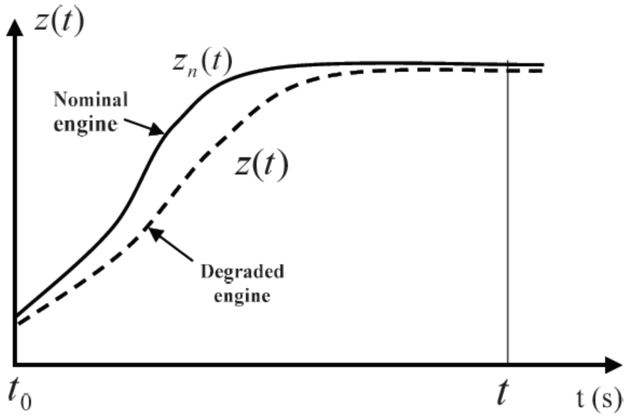

Fig. 5 Trajectories of a normal and degraded performance parameter [5]

Equation (6) and (7) can be used to calculate a parameter indicating performance deviation of the engine as given below.

$$\Delta \tilde{Z} = \frac{\int_{to}^{t} [Z_n(t) - Z(t)]\, dt}{\int_{to}^{t} Z_n(t)\, dt}. \tag{6}$$

$$\Delta \tilde{Z} = \frac{\sum_{i=I_{t0}}^{I_t} [Z(t_i) - Z_n(t_i)]}{\sum_{i=I_{to}}^{I_t} Z_n(t_i)}. \quad \ldots. (7)$$

In the above equations t_i is the initial time and t is the time during the transient operations.

In the above equations, instead of taking single point, an accumulated deviation is computed to measure the shift of a parameter trajectory as shown in fig 4, from its nominal position owing to engine component degradation. This can be quantified by computing the area between the two trajectories divided by the area under the nominal trajectory during the transient period as expressed by equations (6) and (7).

IV.Results and Discussion

Simulation results corresponding to healthy and faulty engines have been illustrated and the characteristics obtained during have been explained. As mentioned previously, simulations with various injector faults have been carried out. To compare the performance deviations during the steady state and transient state conditions of operation brake power, brake specific fuel consumption, the exhaust temperature and CO emission have been measured at different engine speeds. Fig 6 (a) shows multi-steady and multi-transient profile of engine speed verses time used in the present study. The engine starts from an ideal speed (850 rpm) to a maximum engine speed (2200 rpm). The steady and transient stages have 5 sec and 4 sec duration respectively for each stage. In transient engine test, the acceleration duration normally reported is in the range of 1.0 to 10 seconds [15]. The transient tests in this investigation have been carried out for 4 seconds which is well within the range specified.

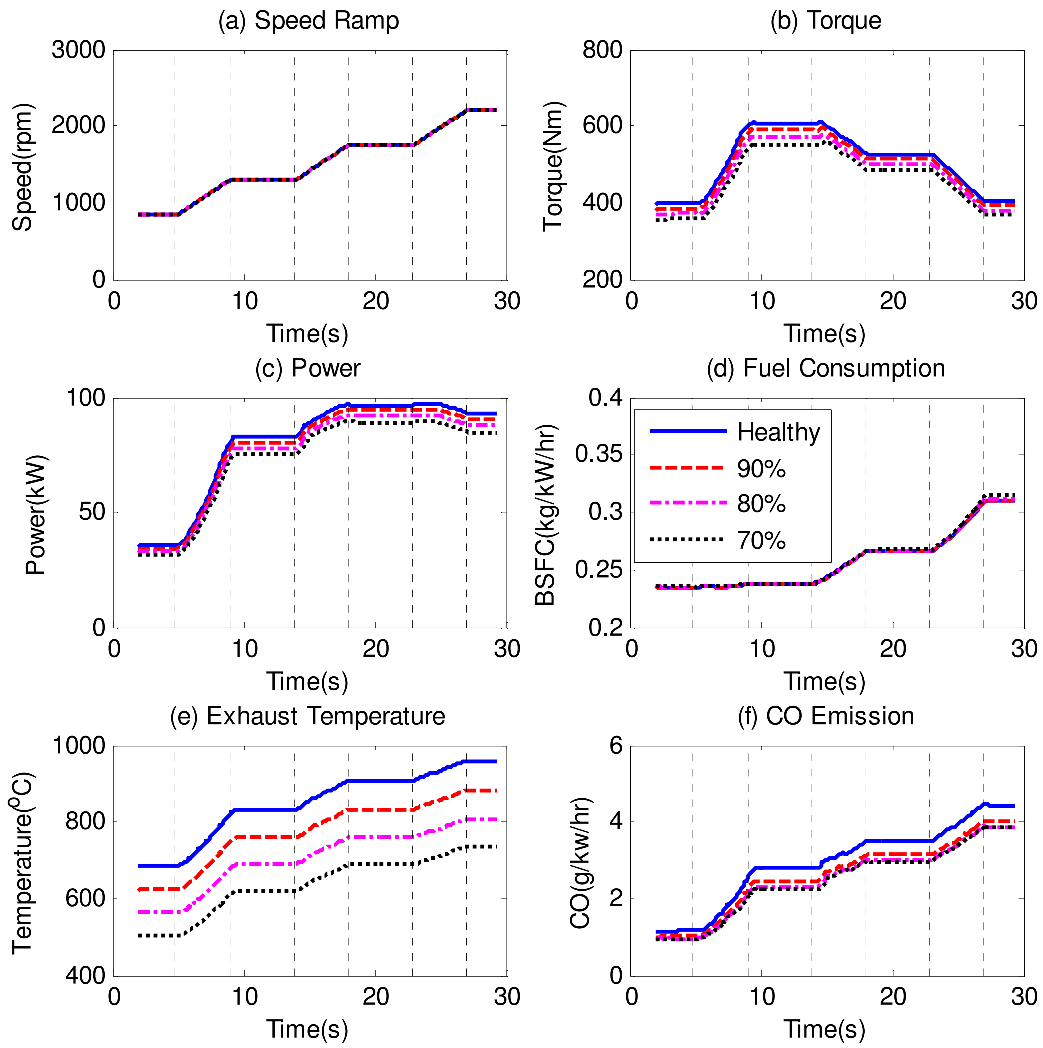

Fig 6 Healthy and faulty engine performance parameters verses time

Fig 6 (b) depicts the variation of brake torque with respect to time for the same operating conditions. The brake torque increases from the ideal speed up to a speed of 1300 rpm and then it decreases when running through the rest of the engine speed profile. Fig 6 (c) shows the variation of brake power obtained from the engine with respect to time for both healthy and faulty engines during the steady and transient multi stage operations. It is seen that the brake power increases with increase in engine speed for both the healthy and faulty cases up to a speed of 2000 rpm. As expected the healthy engine develops more power as compared to the faulty engine. The steady stages shows constant power values, while the transient stages show power increase at a rapid rate with increasing engine speed. The figure 6 (d) shows the variation of brake specific fuel consumption with respect to time for the operating conditions mentioned earlier. It can be seen that the brake specific fuel consumption shows a small increase both the engines with increasing speed. However, the brake specific fuel consumption for normal engine is always lower than the brake specific fuel consumption for the faulty engine. The temperature at exhaust manifold is another parameter whose variation has been observed and depicted in figure 6 (e) for the same operating conditions. It can be seen that the exhaust temperature is higher for the healthy engine as compared to the faulty engine over the entire operating range. Fig 6 (f) shows the CO emission behaviour for both steady and transient conditions. It can be seen that the healthy engine have higher CO emission than the faulty engine. The possible reason behind this can be lower fuel input to the engine when injector is faulty. The excess oxygen in the air oxidized the CO into carbon dioxide.

The deviation values of both steady state and transient values have been calculated using the basic deviation formulation given by equation (4). Fig 7 shows comparisons of the performance parameters in non-dimensional form (percentage deviations) of healthy engine and for the three fault conditions (injector with 90%, 80% and 70% fuel flow efficiency).

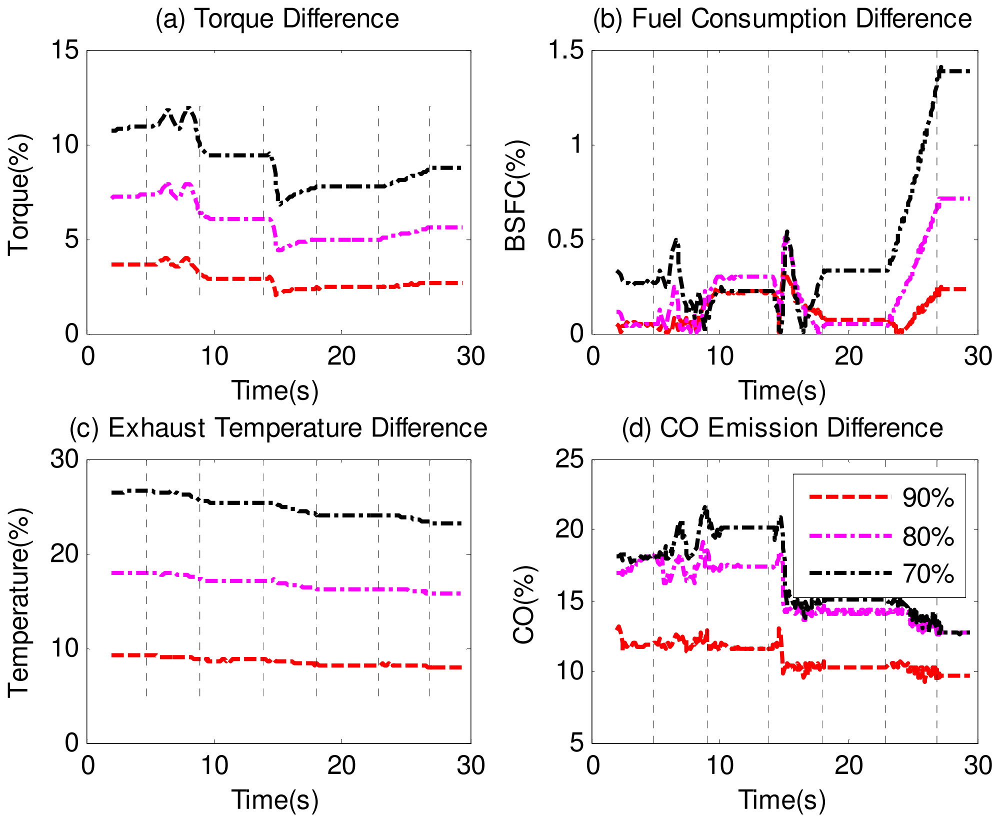

Fig. 7 Percentage Performance deviation of faulty engine for speed profile two

Fault in one injector in fuel supply system causes decrease in all performance parameters measured. Fig 7 (a) shows that at various levels of injector's faults i.e. 90 %, 80% and 70% fuel flow efficiency reduce the brake torque by 4%, 7.5% and 12.5% at the working engine speed of 1200 RPM respectively. At higher engine speed the percentage deviation is lower. Fig 7 (b) shows that the specific fuel consumption is less sensitive with injectors faults and shows small variations when running under healthy and faulty conditions. This is because brake power and fuel consumption both reducing proportionally during faulty conditions of operation. Fig 7(c) illustrates the difference in exhaust temperature for the given operating conditions. Due to various levels of faults (90%, 80%, and 70% fuel injector's efficiency) the exhaust temperature reduces by 9%, 19% and 28% respectively. The exhaust temperature variations are fairly systematic with engine operating conditions.. Fig 7 (d) shows the CO emission is reduced by 12 %, 18% and 21% for various levels of injector faults (90%, 80% and 70% of one fuel injector's efficiency) respectively.

In the following a detailed analysis of the performance deviation as observed for healthy and faulty engine has been carried out. Figure 8 (a) shows the comparison between the brake torque deviations obtained for transient and steady state conditions of operation at engine speeds of 1086, 1328, 1533, 1772, 1979, 2094 RPM. At working engine speeds the transient condition of operation has given higher brake power deviation as compared to steady state condition of operation. At higher values of engine speed both steady and transient have equal values of deviation. In fig 8 (b), it can be seen that the brake specific fuel consumption deviation during the transient condition of operation is higher than that of the brake specific fuel consumption deviation under the steady state condition of operation for working engine speed. The other important parameter used for comparison is the exhaust manifold temperature and its variation has been shown in fig 8 (c).

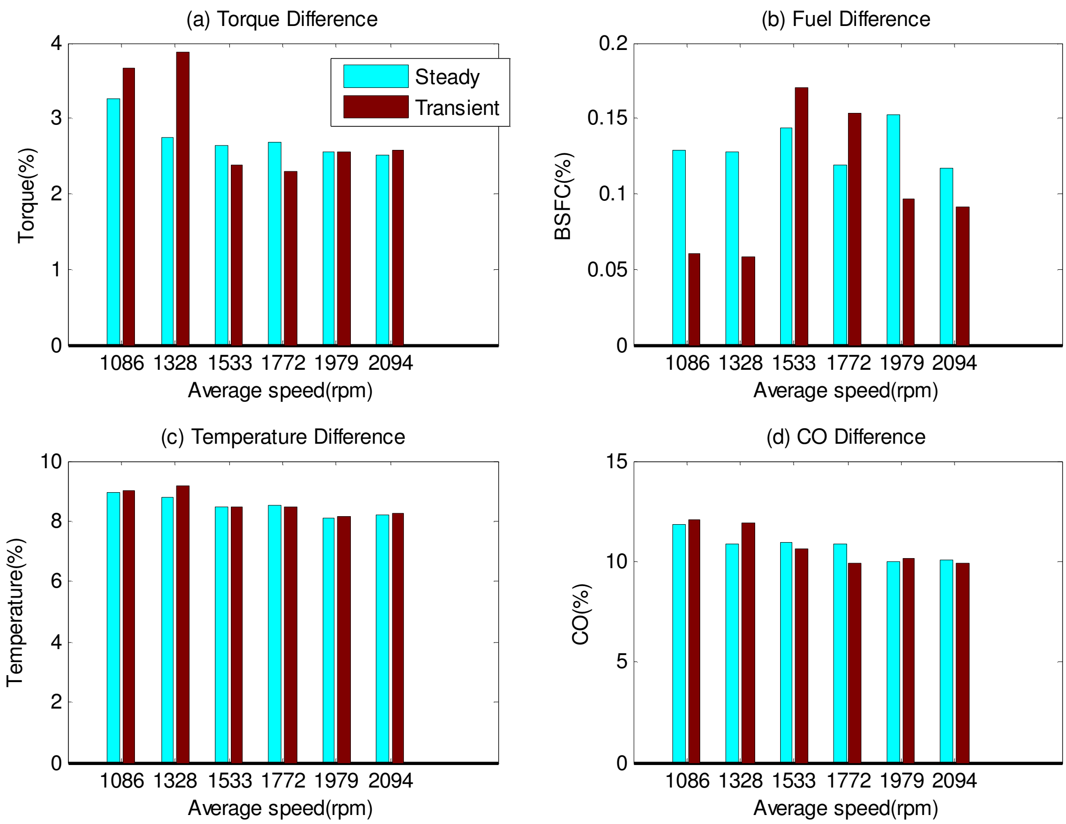

Fig. 8 Performance deviation during transient and steady operation at 90 % injector fuel flow efficiency speed profile 1 and 2

It can be seen that the deviation of exhaust temperature during the transient operation is slightly higher than the deviation during the steady state operation. Fig 8 (d) depicts that the CO emission deviations during transient state operations are higher than the deviation of steady state operation for working engine speed range.

It can concluded form the above discussion that the performance deviations during the transient states of operation are higher than that of steady state operations for the same component fault and operating parameters within engine working speed range. The higher value of deviations in performance parameters during transient operations can be used as a characteristic for condition monitoring and fault diagnosis model. The deviations can be further improved by using accumulated deviations as given by equation (6). The accumulated brake torque deviation during transient condition of stage one is shown in fig 9 in a time span duration of 5 sec to 9 sec. The absolute magnitude of the accumulated performance deviation corresponding to transient process increases till it reaches the maximum values. The accumulated deviation reaches its maximum absolute value before the end of the accelerations in this case (t=8 sec). Then it decreases to steady state value. This maximum value of accumulated performance deviation could be used as the indicative parameter for the condition monitoring alarm of the engine.

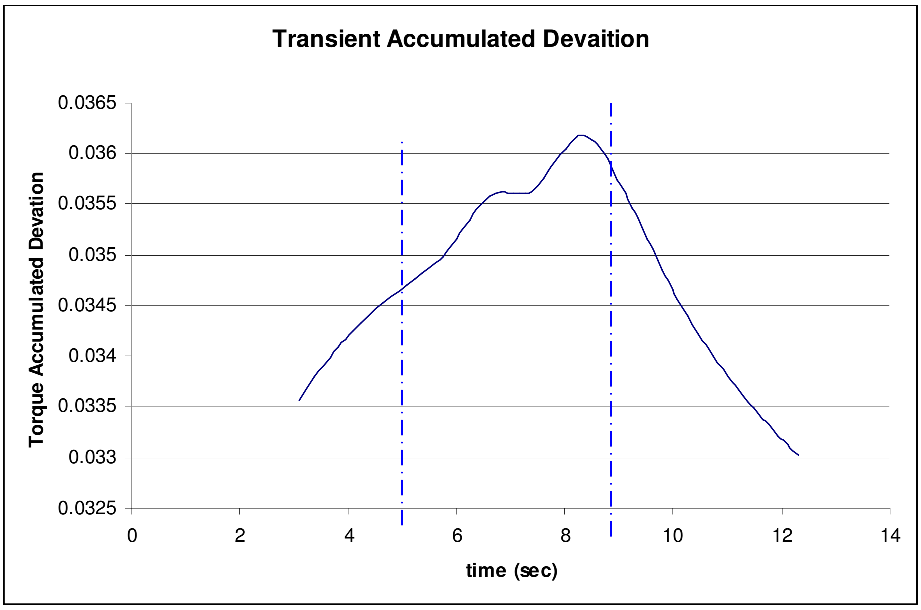

Fig 9 Brake torque accumulated deviation changes with integration time of transient operation

Fig 10 shows the performance deviation of four parameters during transient operations to find which parameters is most suited for diagnostic purposes. It can be seen that the brake specific fuel consumption has the lowest performance deviations. On the other hand the, exhaust temperature and CO emission has higher performance deviations. It is clear that the performance parameters with higher deviations are ideal for condition monitoring and diagnostic modelling purposes. However the choice of the ideal parameter for diagnostics may depend on technical and economical considerations

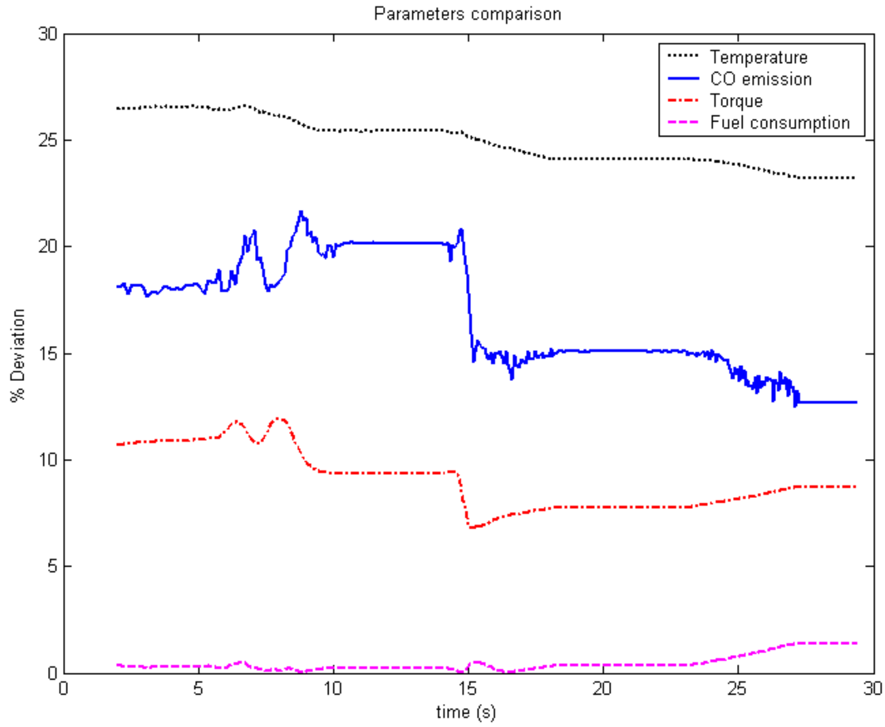

Fig. 10 Performance deviations comparison different parameters during transient operation during 90 % injector fuel flow

V.Conclusion

The present study has clearly indicated that the measurable performance parameters vary by a greater magnitude during the transient operating conditions as compared to steady state operating conditions for engine working speed range. It has further been clearly shown that the accumulated performance deviation parameter of transient process can be effectively used as a condition monitoring parameter. It has also been found that exhaust temperature gives the maximum deviation but looking at difficulty in measuring the exhaust temperature the brake power can be used as an effective diagnostic parameter. It has clearly been established that the condition monitoring and diagnostic with transient performance measurements is more useful than steady state measurements especially for stop-go traffic with higher emission levels on urban and semi-urban automotive routes.

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