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DEVELOPING AN ALGORITHM FOR SI ENGINE DIAGNOSIS USING PARITY RELATIONS

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ABSTRACT

Diagnosis is an algorithm for finding and isolating faults in a dynamic system. In 1994, California designated some regulations which were called OBD II. According to these regulations, there is a system installed in an automobile which can analyze the function of the automobile continuously. The decrease of pollution for the expansion of diagnostic system is necessary in the future. To reach the aims of diagnosis, some redundancies are required in the system, either hardware or soft ware. In the hardware redundancy methods, the installation of additional sensors or actuators on the system is required which is costly and takes up a lot of space, whereas in software redundancy methods, this is done with no expense. In this article, one of the software redundancy methods or analytical methods is implied for solving the problem. At first a discussion on literature survey is mentioned, and then a modified mathematical model for SI engine is acquired. The usage of this method and parity space relations, which is a model based method, accomplished the process of diagnosis. Developing a modified SI engine model and diagnosis of MAT sensor which less has been considered besides other components are this article contributions.

KEYWORDS: Diagnosis, SI Engine, Mean Value Engine Modeling, Analytical Method, Parity Space Relations.

INTRODUCTION

Diagnosis is an algorithm for finding and isolating faults in a dynamic system. Diagnosis is important in some fields like:

- chemical plants
- nuclear plants
- aerospace industry
- automotive industry

The first important research about diagonis was done in 1971 by Beard [1] and Jones in 1973 [2] introducing the linear system diagnosis based on observaton. Then, in 1976, Willsky summarized their works [3]. Gradually, through time, diagnosis systems advanced. Parameter Estmation Method was introduced and developed by Bakiotis in 1979 [4] and Gerger [5] and Fillbert [6] in 1982. Parity Space Relations were used for diagnosis systems by Patton [7] and Gertler [8] in 1991 and Hoffling in 1993 [9]. Intelligent systems also are used for diagnosis. For the first time McClelland [10] in 1989, studied the the possible usage of Neural Networks in diagnostic systems. Also, Patton [11] in 1994, used Fuzzy Logic for this purpose. In the field of automotive engineering, lots of papers and dissertations have been published which are briefly listed as follows: Pfeuffer [12] in 1997, Rizzoni [13] in 1998, Isermann [14] in 2000, Nyberg [15] in 2002, Naidu [16] in 2005 and so on.

In this article after reviewing the methods for diagnosis systems, a mathematical model for SI engine will be developed. By using one of the prescribed methods, some parts of the engine will be diagnosed.

DYNAMIC SYSTEMS DIAGNONSTIC METHODS

In this section, different methods used for diagnostic purposes will be listed and briefly described.

Generally, diagnosis methods are classified into two categories:

- Hardware Redundancy Methods
- Software redundancy Methods

Hardware redundancy methods are done by adding extra sensors and actuators to a dynamic system. These methods are simple and useful but expensive and occupy much space.

Other methods which can be used are called Software Redundaicy Methods. One of these methods is briefly listed :

- Data Driven Methods
- Knowledge Based Methods
- Analytical Methods

one of the analytical method which is used here is categorized:

- Parameter Estimation
- Parity Space Equations

Also, diagnosis consists of two steps:

- Fault Detection
- Fault Isolation

One of the parity space equations method, which called “Parity Equations from State Space Model” will be used.

SI ENGINE MODELING

In this section, a Modeified Mean Value Engine Modeling Method will be developed. This model is a modification developed in [17]. Because the details of this model has been mentioned before, in the following subsections, the final differential equations will be shown. Note that, this engine has been assumed to be equipped with an Ehhaust Gas Recirculation (EGR) system.

Crankshaft Dynamics

Based on Euler’s Law for rotational systems, equation (1) will be resulted.

$$\dot{n}=(1-E)\frac{60}{2\pi I_t}\left\{\frac{\eta_{fc}\,Q_{HV}\,\dot{m}_f}{\frac{2\pi}{60}n}-\left[a_0+a_1 n+a_2 n^2+(a_3+a_4 n)\,p_i\right]\right\} \qquad (1)$$

Note that, Notations and descriptions about the parameters and constants used here, are listed in nomenclature.

Fuel Dynamics

Based on Mass Conservation Law, equation (2) will be resulted.

$$\ddot{m}_{ff}=\frac{1}{\tau_{ff}}\left(-\dot{m}_{ff}+X(1-Y)\dot{m}_{fi}\right) \qquad (2)$$

Manifold Air Dynamics

Based on Mass Conservation Law with isothermal assumption, the equation (3) for the manifold air pressure dynamics will be developed as follows:

$$\dot{p}_i=\frac{R(1-E)}{V_i}\times \left\{\left[\dot{m}_{at0}+\dot{m}_{at1}\,\beta_1(\alpha)\beta_2(p_i)\right]T_m-\frac{V_d\,\eta_v\,n\,p_i}{120\,R}\right\} \qquad (3)$$

Because of the fact that, the isothermal assumption naturally never can model the manifold air temperature, adiabatic solution for temperature dynamics is applied here.

From the first thermodynamic law, it is exerted that:

$$\dot{m}_{at}\,h_a+\dot{m}_{EGR}\,h_{EGR}-\dot{m}_{ap}\,h_i=\frac{d(mu)}{dt}= \dot{m}_i\,c_v\,T_i+m_i\,c_v\,\dot{T}_i \qquad (4)$$

Assuming air as a perfect gas, the equation (5) which shows final differential equation for manifold air temperature dynamics will be resulted as below:

$$\dot{T}_i=\frac{R\,T_i}{p_i V_i}(1-E)\times \left\{\left[\dot{m}_{at0}+\dot{m}_{at1}\,\beta_1(\alpha)\beta_2(p_i)\right](T_m\,\kappa-T_i)-\frac{V_d\,\eta_v\,n\,p_i}{120\,R}(\kappa-1)\right\} \qquad (5)$$

Notations and descriptions about the parameters and constants used here, are listed in nomenclature.

SIMULATION AND VALIDATION

With 10% of EGR, and 300 K ambient temperature, the following figures will be acheived as follow.

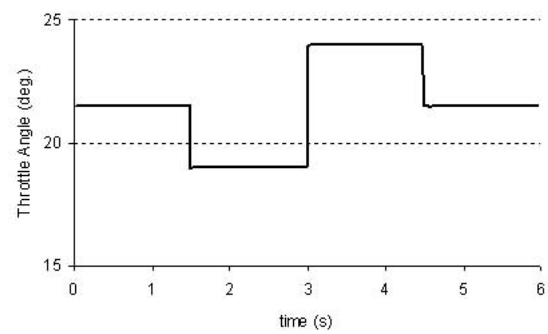

Fig. 1: Behavior of throttle angle as input through the time

As it can be seen, figure 1 shows the behavior of throttle angle as the system input.

With the above input, figures 2, 3 and 4 show the response of the system to the input as follows. In addition, these results have been validated by the experimental results in [17]. Solid lines indicate model results and dashed lines represent experminetal ones.

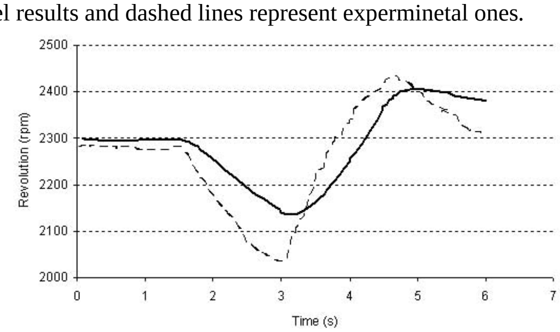

Fig. 2: Engine revolution behavior through time without EGR

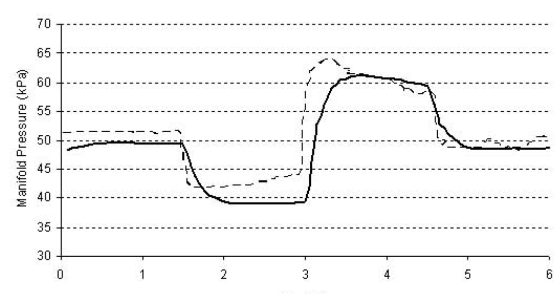

Fig. 3: Manifiold air pressure behavior through time with 10% EGR

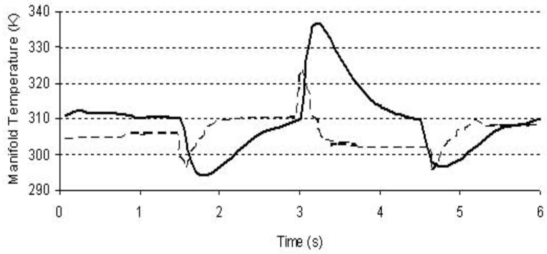

Fig. 4: Manifold air temperature through time with 10% EGR

DIAGNOSTIC SYSTEM DESIGN

With the modified model resulted in section 3, the state space model will be designed with throttle angle as input and engine revolution, manifold air pressure and manifold air temperature as the state variables and also as the outputs. Equation set (6), shows the state space equations.

$$\begin{aligned} \dot{x}_1 &= \frac{60(1-E)}{2\pi I_t}\left\{\frac{\eta_{fc}\, Q_{HV}}{4\pi}\frac{V_d\,\eta_v(x_1,x_2)x_2}{R\,x_3}\frac{1}{14.6}-\left[a_0+a_1\,x_1+a_2\,x_1^{\ 2}+(a_3+a_4\,x_1)x_2\right]\right\} \\ \dot{x}_2 &= \frac{R(1-E)}{V_i}\left\{[\dot{m}_{at0}+\dot{m}_{at1}\,\beta_1(u)\beta_2(x_2)]\,T_m-\frac{V_d\,\eta_v(x_1,x_2)x_1\,x_2}{120\,R}\right\} \\ \dot{x}_3 &= \frac{R\,x_3}{x_2\,V_i}\left\{[\dot{m}_{at0}+\dot{m}_{at1}\,\beta_1(u)\beta_2(x_2)](T_m k-x_3)-\frac{V_d\,\eta_v(x_1,x_3)x_1\,x_2}{120\,R}(k-1)\right\} \end{aligned} \tag{6}$$

In these equations, x_1, x_2 and x_3 represent engine revolution (n), manifold air pressure (p_i) and manifold air temperature (T_i) respectively and u means throttle angle (α).

Four different subjects will be diagnosed:

- Throttle Angle Actuator Fault
- Engine Revolution Sensor Fault
- Manifold Air Pressure Sensor Fault
- Manifold Air Temperature Sensor Fault

Thus, regarding to the mentioned issues, state space model for the faulty system can be expressed:

$$\begin{aligned} \dot{X} &= A\,X + B_u\,U + B_f\,F \\ Y &= C\,X + D_u\,U + D_f\,F \end{aligned} \tag{7}$$

In this case, equations (7) will be modified to:

$$\begin{aligned} \dot{X} &= A\,X + B_u\,U + B_f\,F \\ Y &= X + D_f\,F \end{aligned} \tag{8}$$

With linearization of the nonlinear model, which has been derived by Jacobian Method in this article, multiplier matrices in equation (8) will be in hand. With introducing the matrices hereafter called parity matrices and deriving them and in iddition, design the time window, the material for designation for the diagnostic system will be available. Regarding to equation (9):

$$\breve{Y} = J\,X + K\breve{U} + L\breve{F} \tag{9}$$

Which "smile" on the characters mean:

$$\breve{Z} = \begin{bmatrix} z(k-\sigma) \\ z(k-\sigma+1) \\ \vdots \\ z(k) \end{bmatrix},\ Z = Y, U, F \tag{10}$$

In result, residual matrix related equation will be:

$$R = W\left(\breve{Y} - K\,\breve{U}\right) = W\left(J\,X + L\,\breve{F}\right) \tag{11}$$

Which W in the above equation, means weight matrix that should be designed to satisfy the conditions of the residual matrix. The final step of the residual generation, is the design of the weight matrix. Residual matrix must satisfy the following conditions:

- Should be insensitive to the state variables
- Should be insensitive to the noise, disturbance, uncertainty etc.
- related to the strategy which has been used in fault isolation, residual should be sensitive to some faults and insensitive to some other faults

in this article, Global Observer Scheme (GOS), which means that, each residual is sensitive to all faults except one of them, has been applied.

Regarding to the above conditions, residual genrator equation will be resulted:

$$R = W\,L\,\breve{F} \tag{12}$$

Coding set related to this article has been shown in table (2).

	r_1	r_2	r_3	r_4
f_α	0	1	1	1
f_n	1	0	1	1
f_p	1	1	0	1
f_T	1	1	1	0

Tab. 1: Diagnostic system coding set

This table shows which residual is sensitive to which faults and insensitive to which fault.

By solving the equation (12) and choosing the sampling time, the design phase of diagnostic system will be finalized.

FAULT SIMULATION

In this section, three case studies have been done. Because of the similarity of the results, in this article, just the results of the rpm sensor will be shown. In this paper, noise and disturbances have not been shown because in the experiments, short range of errors was occurred and this paper hasn't mention to the disturbances and noises, but, in this paper some uncertainties are used for the throttle angle which effect all of the other parameters of the system.

First Case Study

In this subsction, for the first case study, 300 rpm bias fault form "t = 0" has been simulated and in continueation of that, The residuals response to the fault has been illustrated.

Figure 5 shows the illustration of faulty rpm sensor through first case study.

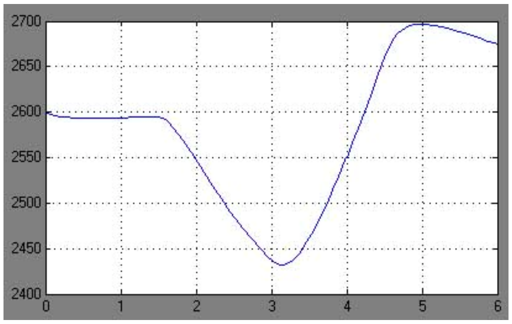

Fig. 5: First simulated faulty rpm sensor

Figures 6 – 9 show the response of the reiduals.

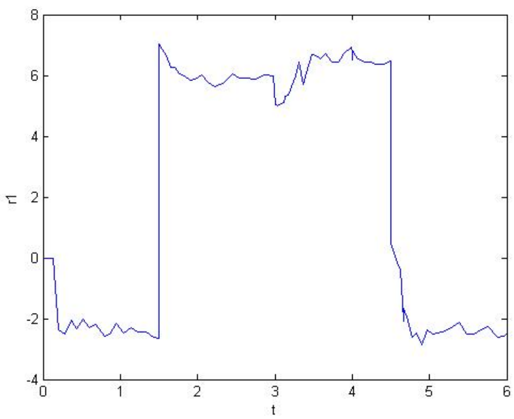

Fig. 6: Residual No. 1 resoponse to the fault

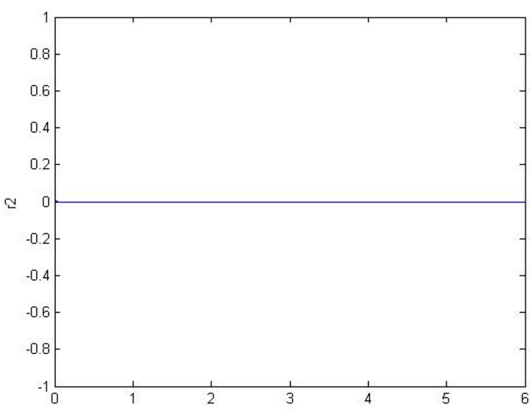

Fig. 7: Residual No. 2 response to the fault

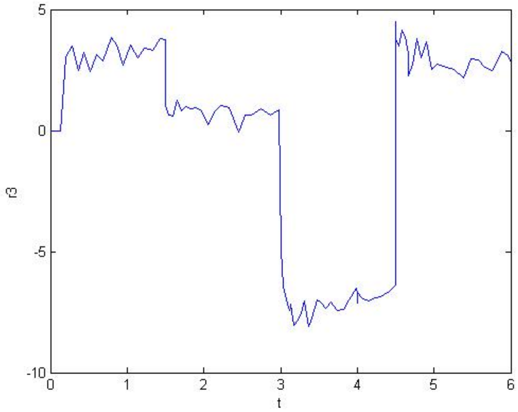

Fig. 8: Residual No. 3 response to the fault

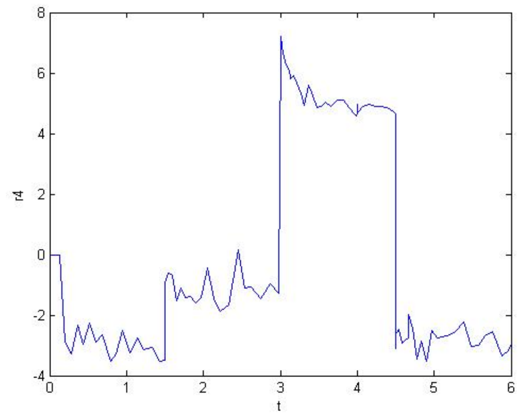

Fig. 9: Residual No. 4 response to the fault

As can be expected based on the codes shown in table 2, the residual No. 2 is insenitive to the rpm sensor fault but the other residuals, are sensitive. As can be seen in figures 6, 8 and 9, the residuals have sudden change in certain times (t = 1.5, 3 and 4.5). this is significantly affected by the behavior of the input. It is clear that, in that certain times, input esxperiences sudden changes. In addition, in the sensitive residuals, from "t = 0" to about "t = 0.2 s", residual doesn't have significant firing. This is because of the delay existence regarding the time window.

Second Case Study

In this case study, similar fault acts on the system with this difference that, this fault occured in "t = 2". Figure 10, illustrates the faulty rpm sensor.

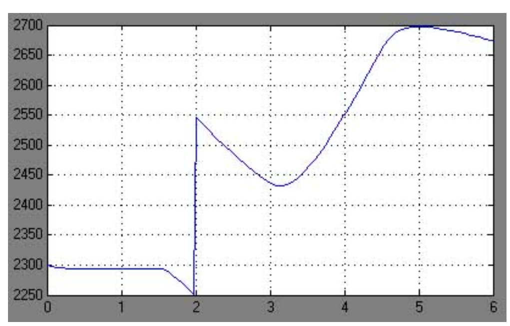

Fig. 10: Illustration of the faulty rpm sensor in the second case study

Figures 11 – 14 show the responses of the residuals against the faulty rpm sensor.

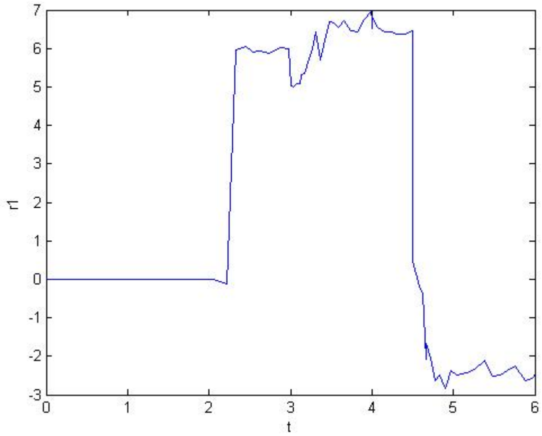

Fig. 11: Residual No. 1 response to the fault

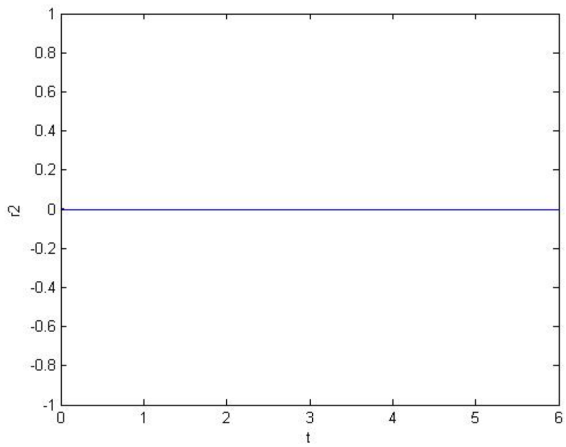

Fig. 12: Residual No. 2 response to the fault

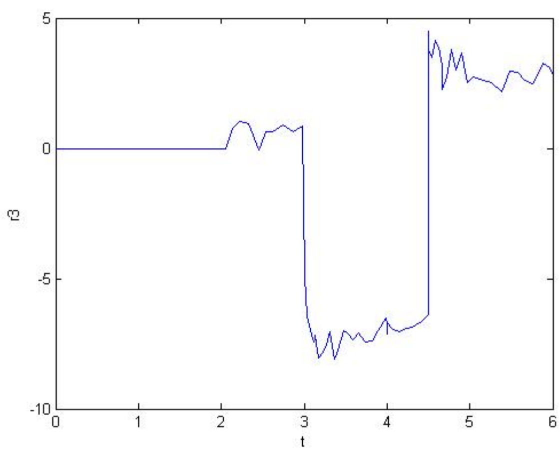

Fig. 13: Residual No. 3 response to the fault

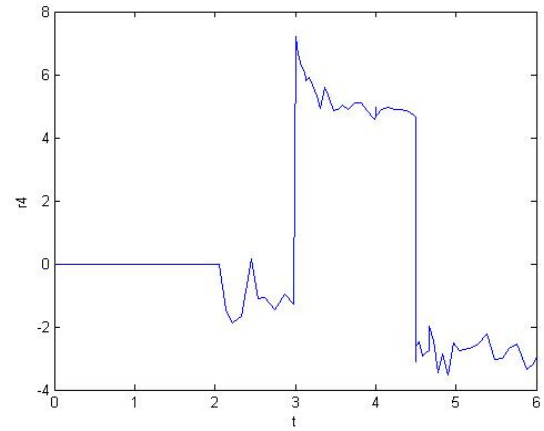

Fig. 14: Residual No. 4 response to the fault

As it can be seen, until "t = 2 s", all resduals remain zero but after that, resduals No. 1, 3 and 4 start a sudden response to the system.

Third Case Study

In this case study, fault simulated in the second case study applied, with this difference that fault occurence is not sudden. Figure 15, shows the behavior of the faulty rpm sensor.

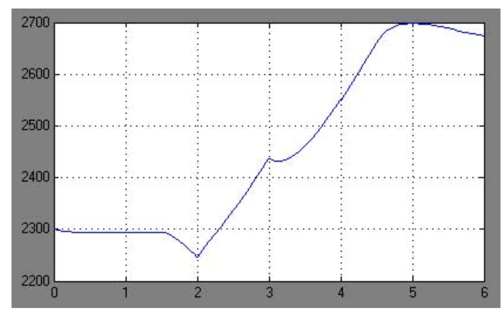

Fig. 15: Illustration of the faulty rpm sensor in the third case study

Figures 16 – 19 show the responses of the residuals against the faulty rpm sensor.

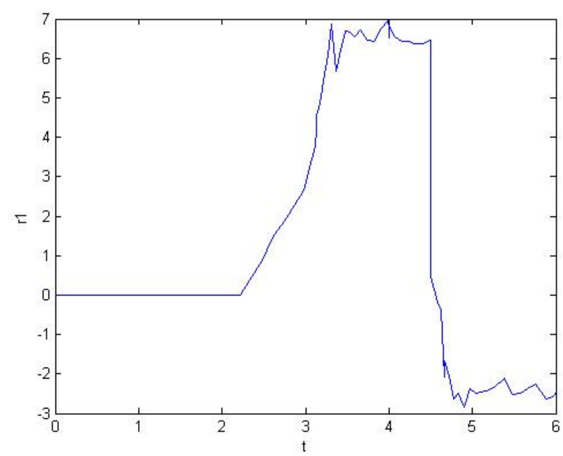

Fig. 16: Residual No. 1 response to the fault

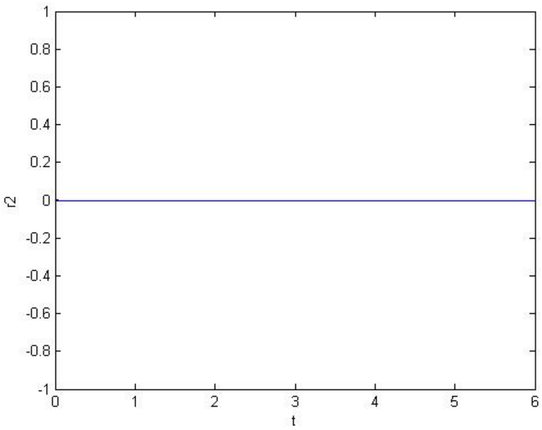

Fig. 17: Residual No. 2 response to the fault

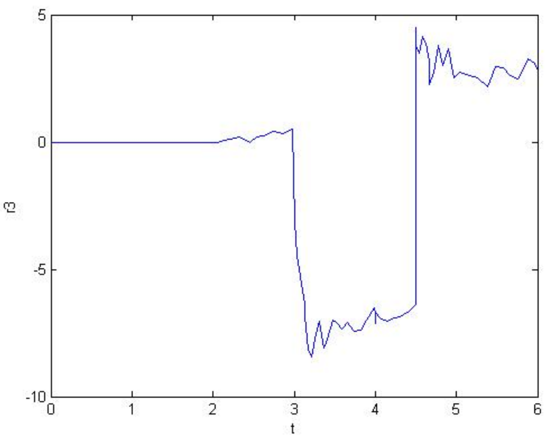

Fig. 18: Residual No. 3 response to the fault

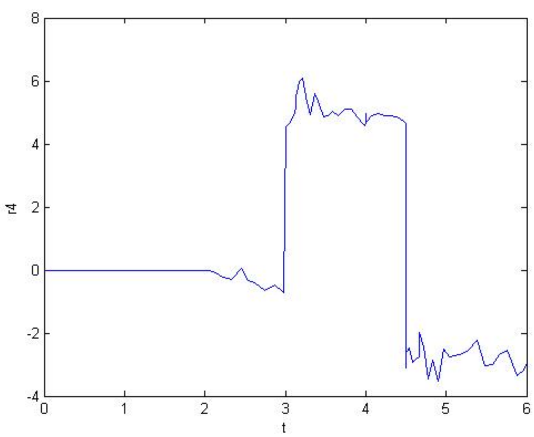

Fig. 19: Residual No. 4 response to the fault

As it can be seen, in addition to the observations of the first and second case study, trends to the firing is slower than that in the second case study. This trend from “t = 2” until “t = 3” is obvious.

CONCLUSION

In this paper, a modified mean value engine model has been developed and validated with a real engine. Using this model in order to dianose the system is this paper first contribution. Engine manifold air temperature dynamics is neglected in most of the papers, but changes in temperature in secific cases such as rapid change in load torque or throttle angle will be resulted in significant change in manifold air temprature (MAT). As the second contribution of this work, this paper diagnoses the MAT sensor besides the other important sensors and actuators of the engine. In addition, with consideration to the MAT dynamics, software redundancy in order to diagnose other important parameters of the engine which haven’t een stated here, will be resulted to more valuable work.

NOMENCLATURE

n	engine revolution (rpm)
M	torque (Nm)
Q	heating value
$\dot{m}$	mass flow rate $\left(\frac{kg}{s}\right)$
p	pressure (kPa)
T	temprature (K)
X	part of the fuel which accumulated on the wall
V	volume (m^3)
E	EGR ratio
p_r	manifold to ambient pressure ratio
f	fault

Greek Letter

α	throttle angle (deg)
η	efficiency
κ	gas atomicity coefficient
τ	time coefficient (sec)

Subscripts

t	total
g	gross
f	fuel
a	ambient
at	past over the throttle plate
ap	past over the intake valve
i	intake manifold
fc	fuel conversion
v	volumetric
ff	fuel film
d	displacement
EGR	related to EGR
m	mean
n	engine speed
p	intake anifold pressure
T	temperature

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