

Diagnosis of within Cylinder Faults Using Instantaneous Mode Based Engine Model

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ABSTRACT

Model based approaches for engine fault diagnosis mostly address the faults external to cylinder since they predominantly use simplified averaged models which do not capture within cycle dynamics. Hence, by using an instantaneous engine model which distinctly characterizes the cylinder's modes, the events occurring within the cycle can be captured. The events happening across various modes and the engine subsystems can be due to normal operation or faults whose symptoms can be seen as features. In this work, which involves detection and classification of faults occurring in cylinders, is carried out in simulation environment, where, a Kalman filter for state estimation incorporating a nominal instantaneous mode based engine model is considered. Using this estimator as base, faults occurring repetitively (every cycle) are addressed whose features are seen across relevant modes of a cycle. The combination of features of variables such as inputs, states and residuals from a faulty case data are inspected for various engine subsystems across modes within the cylinder's cycle to detect the faulty cylinder and classify its associated fault.

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1. INTRODUCTION AND MOTIVATION

To ensure and evaluate the performance of an automobile in different aspects, diagnosis of its various components has become increasingly important. Some of the prominent driving factors for diagnosis are increasingly stringent emission norms, rising fuel costs and stiff competition as well as customer demand for better maintenance scheduling and prompt servicing. Compliance to emission regulations like Euro 5, Euro 6 and OBD-II requirements [1, 2, 3, 4] for automobiles (cars and light commercial vehicles), makes it essential to prevent malfunction of engine equipment which might cause loss in efficiency and increased emissions. Hence, it is becoming increasingly important to design fast and accurate detection and isolation systems to prevent further degradation of engine components or emissions.

Model based engine fault diagnosis methods are mostly based on the Mean Value Engine Model (MVEM) [5,6,7,8,9,10, 11] or the instantaneous crank angle model based [12,13,14,15,16,17, 18] approach. The MVEM only describes the time evolution of averaged enthalpy and mass transfers by conventional continuous dynamical models, assuming that the cylinder operates as a pump. This simplified modeling can only capture low frequency components of the evolution of the process variables and does not address within cycle dynamics and is valid only during steady state operation. The instantaneous crank based engine model, on the other hand is more complex than the MVEM because it models the cylinder dynamics

and captures the nonlinear and switched dynamics of the instantaneous time evolution of the process variables within crank angle cycles. Also, the averaging inherent in the MVEM results in suppression of important high frequency dynamics which often carry characteristic fault signatures thereby reducing sensitivity to faults as compared to an instantaneous model based counterpart [19].

In existing literature on model based fault diagnosis of engines, within cylinder faults are not commonly addressed. The within cylinder faults which are normally reported deal with misfires [14, 16, 21, 22, 23, 24] or compression faults in cylinder [16]. This is because most model based approaches in engine fault diagnosis use MVEMs which cannot capture within cylinder dynamics and hence can address only faults which occur in subsystems external to the cylinder like manifolds [9, 25, 26, and 27], throttle [7] or EGR [28, 29].

For treating the problem of fault diagnosis from a model based perspective, the described hybrid automata model in [20] which is based on the instantaneous within cycle engine model is used rather than the conventionally used Mean Value Engine Model (MVEM).

The type of faults considered in this work affect the within cycle engine dynamics in a repetitive manner (every cycle) and can only be addressed using a mode based instantaneous model.

A brief description of the implementation of methodology in this work is as follows. A nonlinear Kalman Filter based estimator using state space equations of instantaneous hybrid automata based engine model [20] is incorporated to analyze the engine dynamics. This engine model encompasses the subsystems of intake, exhaust and cylinder and all modes of the SI engine cycle (intake, compression, combustion, expansion and exhaust). Features of variables in estimator such as inputs, states and residuals from any unknown fault case data are inspected at certain modes within the cylinder's cycle and the combination of the features at different modes which constitute a unique set of sub-diagnosis statements aid in fault detection and classification. The estimation of faults using such a model and estimator is expected to extract detailed mode based within cycle features unique to the fault, thereby capturing the inherent characteristics of the fault which will be of further use in isolation.

It is to be noted that the engine dynamics and its faults are analyzed in simulation environment. In the absence of an actual engine, a realistic engine model of the industrial standard simulator AMESim [37] is used to simulate the engine dynamics as well as insert faults and generate (input and output) data required for estimation and diagnosis.

2. WITHIN CYLINDER FAULTS AND THEIR CLASSIFICATION

The faults occurring within a cylinder are events giving rise to symptoms which appear within the course of the engine cycle and are normally repetitive every cycle. In order to capture the events which evolve within a cycle, the within cycle cylinder dynamics of the engine need to be tracked which can only be possible by incorporating an instantaneous within cycle characterizing engine model.

Faults which occur within a cylinder affect its within cycle dynamics and their evolving symptoms (across various modes) are mostly seen in the states of the faulty cylinder or in the measurements or states of other subsystems (e.g. intake and exhaust manifolds which are linked to cylinders), as and when they are associated with the faulty cylinder.

For a cylinder in an engine (4 stroke), in each cycle (spanning 720°) there are 4 strokes/major events of intake, compression, expansion and exhaust, each roughly spanning 180° (or π Radians). Hence, for a 4 cylinder (all identical) engine, each cycle of data (of measurements or estimates) will contain signatures due to events from 4 cylinders. In case of a 4 cylinder engine with firing order 1-4-3-2, the same within cycle events (crank angle based) of consecutive cylinders are phase shifted by 180° . So, if the engine cycle data (duration 720°) of a variable, say, $var(s)$ (which can be a state, residual or measurement) is split into 4 consecutive sections, each of duration 180° , it will be possible to segregate contributing effects due to each of the corresponding (and consecutive) cylinders. Since the corresponding dynamics of each cylinder are phase shifted by 180° , all the 4 sections roughly belong to the same mode of the consecutive cylinders. In other words, each point in a section (belonging to a particular mode of a particular cylinder) corresponds in phase and mode to points of other sections (and hence other cylinders) which

are separated by a multiple of 180° . In Fig.1, considering the case of spark delay fault of 10° in cylinder 3, an engine cycle of exhaust manifold pressure signal is shown where the four pulsations (belonging to partitioned sections 1-4) correspond to the exhaust effects of the 4 cylinders, numbered in the same sequence. The nature of signal for all the sections (each of which correspond to a cylinder) looks identical except for the 3rd section. The exhaust signal corresponding to the 3rd cylinder has a higher peak due to the fact that the remaining pressure in cylinder 3 is higher due to late start of combustion which further leads to higher exhaust flow rate of that cylinder, thereby causing higher pressure pulsation in exhaust manifold during that time. It can also be realized that each of the consecutive sections belongs to the exhaust mode of the respective cylinder and spans roughly 180° to finally form 720° , a complete engine cycle.

A similar concept is illustrated in [30], where, the instantaneous exhaust pressure measurement signal is analyzed to monitor the exhaust system which is affected by the dynamics of all the cylinders. The nature of pulsation in the exhaust system corresponding to a cylinder reflects the behavior of the cylinder. Among pulsations corresponding to all cylinders, an anomalous pulsation and its corresponding cylinder is segregated which is used to diagnose faults such as misfires. This serves as a motivation for the present work which attempts to deal with the problem of diagnoses of various within cylinder faults by using the hybrid automata based instantaneous within cycle engine model and a corresponding estimator structure, described in [20]. Approach of this kind will be useful in extracting instantaneous and mode based fault features of engine dynamics within a cycle corresponding to the faulty cylinder which will facilitate fault detection and isolation.

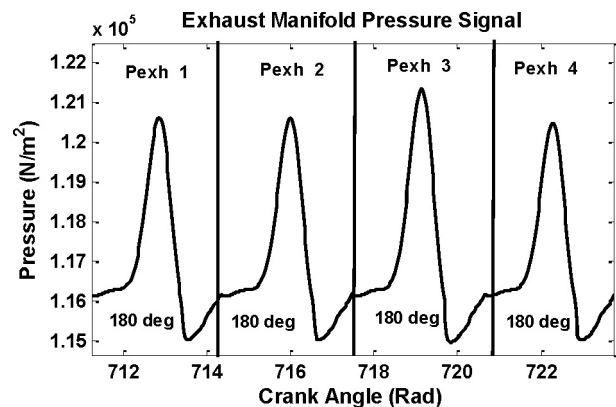


Figure 1. Exhaust manifold pressure signal in case of spark delay in cylinder 3

The variables such as states, inputs and measurements involved in the dynamical system (expressed in state space) model and the estimation structure for a 4 cylinder engine are briefly described.

The 4 cylinder engine dynamics has been captured in terms of a 'state vector', ' x ' defined as in (1),

$$x = [P_{im}^1 P_{cyl}^1 P_{cyl}^2 P_{cyl}^3 P_{cyl}^4 T_{cyl}^1 T_{cyl}^2 T_{cyl}^3 T_{cyl}^4 T_{im} P_{exm} T_{exm}]^T$$

and the physical meaning of state variables is described in the nomenclature. Here, the numbers, 1-4 correspond to the cylinder numbers for the concerned variables.

In its j^{th} mode, the engine dynamics is described by a set of nonlinear dynamic equations given by (2) which govern the states during that time,

$$\dot{x} = f_j(x, u) \quad (2)$$

where 'x' is the set of states already given by (1), 'u' is the set of inputs and ' f_j ' is the set of nonlinear dynamic equations of the states' in the j^{th} mode.

The various inputs used by the engine model are presented in Table 1. It can be realized from Table 1 that, for a 4 cylinder engine model, the total number of inputs is 18.

Similarly, the sensor dynamics for output measurements, which can be nonlinear, is of the form,

$$y = h(x, u) \quad (3)$$

where 'y', the set of sensor output measurements considered in this work is given by,

$$y = [P_{im}^m \dot{m}_{th}^m T_{im}^m P_{ex-i}^m T_{exm}^m]^T \quad (4)$$

and 'h' is the set of measurement functions for the corresponding sensors.

Table 1. Various inputs used in the engine model

Type of input	Input description(Notation)
Control inputs	Crank angle (θ)
	Throttle angle (α)
	Angular engine speed (ω)
	Intake valve lift for each cylinder (Lv(in))
	Exhaust valve lift for each cylinder (Lv(exh))
	EGR valve lift (Lv(EGR))
	Fuel Injection Pulse Width for each cylinder (FUELPW)
Environmental Inputs	Ambient pressure (Pa)
	Ambient temperature (Ta)

In this work, as most of the measurements are present external to the cylinders, the fault symptoms have to be tapped from the estimated states of cylinder dynamics as well as available measurements or states of external subsystems.

The cylinder dynamics are cyclostationary processes (periodic in phase over cycles) and hence, in case of a fault, the corresponding symptoms which appear across modes within a cycle, repeat every cycle. Further, the combination of several fault symptoms or sub-features from various modes of a cycle of engine data will

constitute the characteristic pattern for a fault which will be consistently seen in every consecutive cycle. The characteristic pattern is unique to a fault and will be useful in isolation.

Figure 2 symbolically depicts the instances of occurrences of fault symptoms exhibited across various engine modes (described in [20]) arising out of events, within a cycle of a cylinder. In the figure, the symptoms are enumerated as 1-6 for the purpose of illustration.

Considering this structure of engine dynamics, the following set of cylinder fault cases has been considered for fault detection and isolation:

1. F_1 , Spark Delay by 10°
2. F_2 , Fuel Injector Fault (Reduction to 50% of normal injection rate)
3. F_3 , Intake Valve not fully closing (not going below 1 mm lift)
4. F_4 , Exhaust Valve Not Fully Closing (not going below 1 mm lift).
5. F_5 , Intake Valve delay in opening (by 55°) and closing (by 30°).
6. F_6 , Exhaust Valve delay in opening and closing (by 50°)
7. F_7 (or NF), No Fault in any cylinder

At any time, only a single fault case is assumed to occur affecting any one of the cylinders (if not NF or F_7). These fault cases are simulated by inserting the respective faults in the existing realistic engine model in AMESim[37]. The valve faults are simulated by appropriately changing the respective valve profiles for the faulty cylinder in the AMESim model. Other faults like fuel injector (F_2) and Spark Delay (F_1) are realized by changing the parameters and then simulated. The nature of each of the faults is such that, their symptoms or features will be seen across various modes of the cycle corresponding to a particular cylinder and will repeat every cycle. The input and output data from the simulation of fault inserted engine models along with a mathematical instantaneous nominal engine model will be used in an estimator to generate states and residuals which will be evaluated for feature extraction and subsequent diagnosis. It is to be noted that the faulty inserted profiles or parameters to simulate the faults are unknown to the estimator and it assumes normal input valve profiles and parameters in all cases for the purpose of fault diagnosis.

From [20] it can be understood that the set of possible (major) modes of an engine cycle in usual order of occurrence can be given by:

1. Intake and exhaust valve overlap
2. Intake
3. Compression
4. Fuel Injection
5. Combustion
6. Expansion/compression post combustion
7. Exhaust

However, it can be realized that all the major modes are of unequal phase duration. Hence, to have major modes occupying (roughly) equal phase duration of 180° each for ease of comparison among

section data of 4 cylinders belonging to the same mode in one engine cycle data of 720° duration, the restructured set of major modes, m (numbered 1, 2, 3, 4) are assigned as follows.

1. Intake including intake and exhaust valve overlap
2. Compression including fuel injection
3. Combustion/Expansion/compression-post-combustion
4. Exhaust

For the purpose of fault feature evaluation, the considered set of variables, $var(s)$ is listed in Table 2. It is to be noted that though the faults occur in cylinder, the variables that are evaluated mostly belong to subsystems external to cylinders because of the absence of measurements in the cylinder. The effects of cylinder faults are reflected in these external variables during the intake/exhaust process of the faulty cylinder. Also, since the cylinder states are observable only during intake or exhaust modes, as discussed in [20], the estimated state of $\hat{P}_{cyl}$ is evaluated corresponding to the modes of intake and exhaust for all cylinders.

Hence, the tests, described in the subsequent sections will use only the variables in Table 2 for evaluating symptoms. An estimator is employed to estimate state variables to capture the within cycle dynamics whose details are discussed in the next subsection.

Table 2. Variables used in fault feature evaluation, $var(s)$

S	$var(s)$	Description
1	N_s	Engine Speed (input)
2	$\hat{p}_{exm}$	Exhaust Manifold Pressure (Estimate)
3	$\hat{T}_{exm}$	ExhaustManifold Temperature (Estimate)
4	$\hat{p}_{im}$	Intake Manifold pressure (Estimate)
5	$\hat{T}_{im}$	Intake Manifold temperature (Estimate)
6	$\hat{p}_{cyl}$	Cylinder Pressure (Estimate)
7	$\dot{MAF}$	Mass Air Flow (Estimate)
8	ΔP_{egr}^m Res	Differential EGR pressure (measurement residual)
9	T_{exm}^m Res	Exhaust Manifold Temperature (measurement residual)
10	P_{im}^m Res	Intake Manifold Pressure (measurement residual)

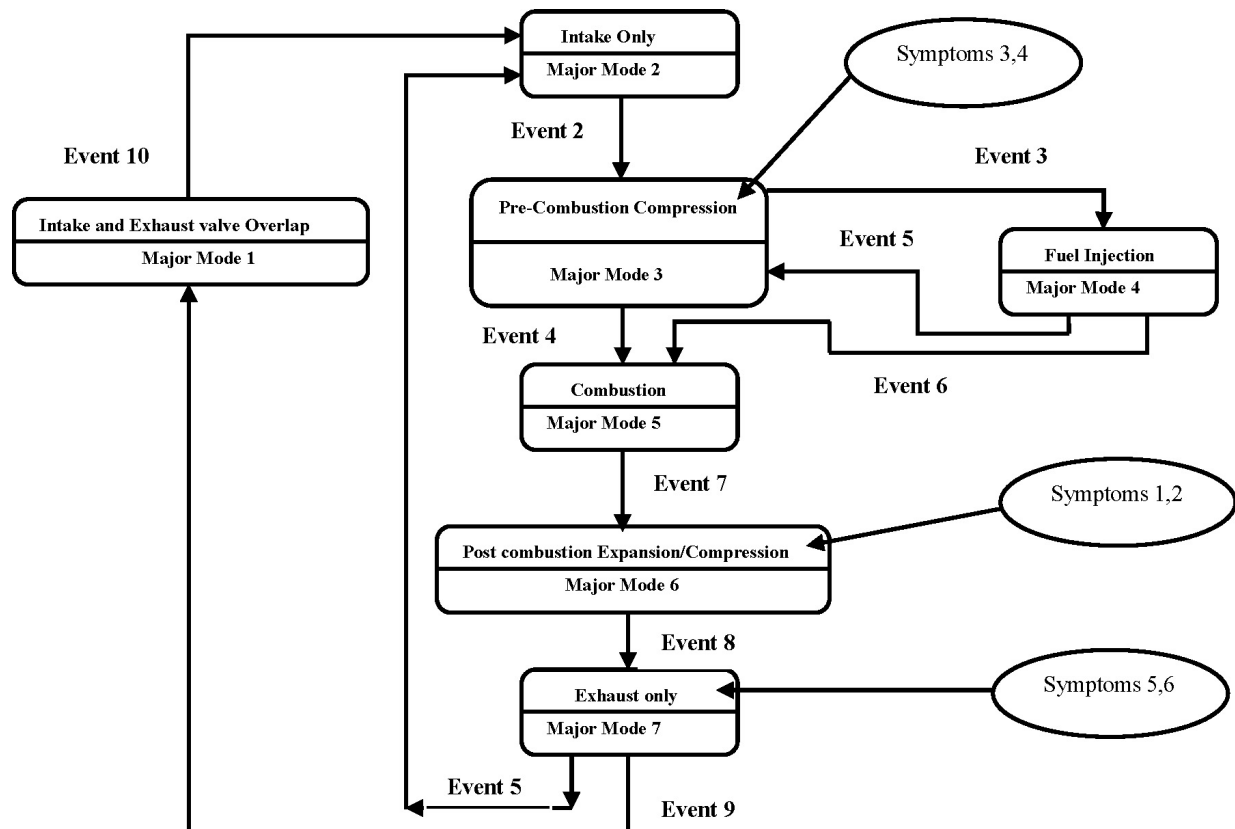


Figure 2. Various symptoms of a cylinder fault seen across modes in a cycle

2.1. Estimation Process towards Capturing within Cycle Dynamics

The details of the generic state estimator which captures the instantaneous within cycle engine dynamics are as follows:

- EKF [31] or UKF [32, 33] based state estimator used in all cases.
- For prediction update, incorporates normal (non-faulty) within cycle instantaneous hybrid engine model in state-space form, as described in [20], except, the dynamics of each cylinder in each cycle consist of 4 major modes, m occurring in a sequence.
- Assumes inputs (as per actuation command given) of spark, fuel injection, valve profiles, etc. to be non-faulty in all cases.
- Events causing the modes and fault symptoms are periodic w.r.t. crank angle.
- Dynamics of 4 cylinders in an engine can be realized as occurrence of 4 concurrent Hybrid Automata, each shifted by 180° w.r.t. each other [20].
- During compression, combustion or expansion, cylinder states receive no measurement update and they are propagated using only prediction updates.
- Effects of a cylinder's fault/event are seen as symptoms across various modes, captured by fault features for that cylinder, which repeat every cycle.
- Fault features are evaluated on $var(s)$: measurements, estimated states, residuals and input (Table 2).

Using the estimator and the features, mapped to various modes in a cycle a fault diagnostic framework is developed.

2.2. Fault Diagnostic Framework

The overall schematic diagram of the fault diagnosis framework using estimator and the mode based features from a cycle of engine data is shown in Fig. 3. While measurements and inputs are already available, the estimates and residuals (denoted by ' e ' in Fig. 3) are obtained using the estimator. The obtained estimates, residuals, measurements and inputs of each engine cycle are mapped to their corresponding modes and respective cylinders and from these data, features are extracted for each mode of each cylinder. The mapping is done by demarcation of mode boundaries for respective cylinders through knowledge of crank angle. Finally, based on the combined set of features the fault classifier assigns the probable fault for the suspected cylinder, which exhibits the fault symptoms.

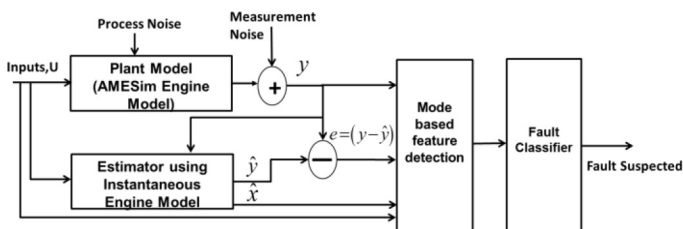


Figure 3. Overall Schematic diagram of proposed diagnosis process

To demonstrate how a within cylinder fault affects the within cycle dynamics of the cylinder, having symptoms seen across its various modes, the following case example is considered, where the symptoms repeat every cycle.

Example: Intake Valve Not Closing fully in Cylinder 3

The case example taken is that of a cylinder fault (fault case, **F3**) in which the intake valve in cylinder 3 never closes (including the modes, compression/combustion and expansion) below 1 mm of lift due to which several phenomena occur at each cycle of the faulty cylinder whose effects lead to symptoms being visible across its modes. Distinct symptoms are visible corresponding to only the faulty cylinder at its different modes and hence distinguish its behavior w.r.t other cylinders for the same set of modes.

Fault Symptoms in Various Modes of a Cycle

Distinguishable fault symptoms are seen during the occurrence of major modes of compression (C) and exhaust (Ex) in cylinder 3 w.r.t. those of other cylinders. These symptoms are shown in Fig. 4, 5, 6, 7, where, the labels C1, C2, C3, C4 and Ex1, Ex2, Ex3, Ex4 denote the compression and exhaust modes for cylinders 1, 2, 3, 4 respectively.

A. During Compression Mode

Cause

Intake Valve still open (1 mm) in compression mode (C) of cylinder 3.

Effect

During compression mode of cylinder 3, gas from cylinder leaks into intake manifold, thereby increasing its pressure (P_{im}).

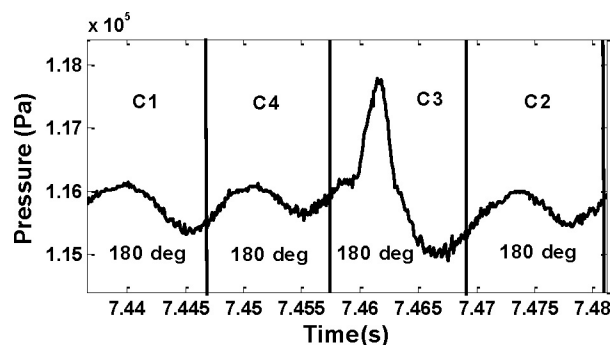


Figure 4. P_{im} estimate in compression mode of 4 cylinders over one cycle

Symptoms

- The effect is seen as sudden rise in P_{im} signal only during compression mode of cylinder 3 shown by C3 section of Fig. 4, indicating the distinct behavior of the P_{im} estimated state during the compression mode of Cylinder 3. Signature of P_{im} signals during compression modes in other 3 cylinders (C1, C2 and C4) are similar to each other.
- The measurement residual is a difference between measured (having effect corresponding to an open Intake Valve in compression mode) and the predicted P_{im} (assuming closed intake valve during C3). Since the estimator uses a fault free