Control Engineering Practice 70 (2018) 63–76

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

# First principle based control oriented model of a gasoline engine including multi-cylinder dynamics

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ARTICLE INFO

*Keywords:*
Gasoline engine model
Control oriented engine model
Multi-cylinder engine model

ABSTRACT

The growing complexity of vehicle powertrain systems and stringent emissions requirements placed on these systems has necessitated the introduction of accurate and generalizable engine models that will be suitable for control and diagnostics. A first principle based control oriented model of a multi-cylinder gasoline engine is developed and shown to be also suitable for fault diagnosis. This model takes into cylinder-to-cylinder behavior and spatial orientation while maintaining a simple structure suitable for real time control. A model of the torque production mechanism is coupled with an analytical cylinder pressure model to capture the engine torque. The model of the torque production mechanism is derived using the Constrained Lagrangian Equation of Motion and simplified to a form suitable for integration in an overall engine model. The analytical cylinder pressure model is taken from literature and extended to a four cylinder engine. While it is common to model torque production subsystem as a continuously operating volumetric pump, the methods used in this work allow details including angular speed fluctuations of the crankshaft to be captured. In addition, the engine model is able to describe the dynamics of the system under faultless as well as faulty conditions, which is demonstrated for misfire. The proposed model is also leveraged for a novel fault tolerant control framework and is tuned and successfully validated for a $1.3L$ four cylinder gasoline engine.



## 1. Introduction

It is often advantageous to have mathematical models of nonlinear dynamical systems that are simple, yet high-fidelity and robust. These conflicting goals are particularly pronounced in the mathematical modeling of IC engines (abbreviations used in the paper are explained in Table 1). Engine constraints evolve over time due to technological evolution and forced evolution. The former evolution includes development of more powerful embedded platforms, which relaxes the trade-off between model complexity and real-time performance. The forced evolution includes more stringent environment legislation and new technologies (such as flex fuels and dynamic skip fire, Serrano, Routledge, Lo, Shost, Srinivasan, and Ghosh (2014)). The progression of these constraints facilitates, and sometimes dictates, the development of more accurate but complex control oriented models of IC engines. Application-specific and advanced embedded system architectures are ready to handle more powerful and relatively complex control and diagnostic algorithms in automotive power-train applications. In addition new power-train architectures, flex fuel and autonomous vehicles require more detailed control oriented models to enable advanced control and diagnostic techniques in order to ensure proper performance.

The development of mathematical models of IC engines is not a trivial task. The occurrence of discontinuous events (such as opening and closing of intake/exhaust valves) and non-linearities (for example, reciprocating motion of the piston) pose major challenges in the mathematical modeling. Such issues were handled by introducing assumptions (such as time scaling and mean values, discussed in Hendricks and Sorenson, 1990), adding analogical replacements (replacing the torque producing mechanism by a volumetric pump (Guzzella & Onder, 2004, Ch. 2) and considering different independent variables (for instance, time or crankshaft position). These assumptions, analogies and considerations led to the development of application specific areas of IC engine modeling, which include MVEMs (Hendricks & Sorenson, 1990), DEMs (Guzzella & Onder, 2004), hybrid models (Rizvi, Bhatti, & Butt, 2011) and CCEMs (Eriksson, Eriksson, Frisk, & Krysander, 2013).

Some of the foundational efforts in this area produced MVEMs, which were the very first class of control oriented models, Athans (1978).

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https://doi.org/10.1016/j.conengprac.2017.09.020
Received 24 November 2016; Received in revised form 27 September 2017; Accepted 30 September 2017

**Table 1**
List of abbreviations.

| Abbreviation | Description |
|---|---|
| IC | Internal Combustion |
| MVEM | Mean Value Engine Model |
| DEM | Discrete Event Model |
| CCEM | Cylinder-to-Cylinder Engine Model |
| FPEM | First Principle based Engine Model |
| FTC | Fault Tolerant Control |
| EOM | Equation of Motion |
| ODE | Ordinary Differential Equation |
| SOC | Start of Combustion |
| EOC | End of Combustion |
| MFB | Mass Fraction Burnt |
| NVH | Noise vibration and Harshness |
| OBD | On-board Diagnostics |
| DAQ | Data Acquisition |

These models were simple and developed under assumptions of different analogical replacements. Such a simplicity in IC engine models was required due to limitations in embedded systems. With the passage of time, environment legislation became stringent and embedded systems gained enhanced throughput capability. Consequently, more refined and capable control oriented engine models were both necessary and feasible. Thus, the concept of CCEM was introduced.

The early foundations of MVEM were laid in Dobner (1980) and extended in Dobner and Fruechte (1983), where a basic engine model was proposed. Detailed modeling of engine intake air dynamics was presented in Aquino (1981). After these pioneering works, there exist two major chains of research efforts on MVEMs, one carried out by J. J. Moskwa and the other by E. Hendricks.

Following the concept of MVEM, a detailed model of port injected gasoline engine was proposed (Moskwa & Hedrick, 1987). The model included intake air dynamics, fuel dynamics and angular speed dynamics. This work was extended in Moskwa (1988) and Weeks and Moskwa (1995). The other chain established by Hendricks and Sorenson (1990) leveraged a classification basis for variables in engine modeling. The work was extended in Chevalier, Muller, and Hendricks (2000) and Hendricks and Vesterholm (1992). Though the two chains of research cited above were variants to each other, the basic MVEM concept was the same in both.

A variant of the torque production subsystem model was devised in Falcone, De Gennaro, Fiengo, Glielmo, Santini, and Langthaler (2003). The kinematics of the torque producing mechanism was used in the model development and a combustion model was employed to evaluate the forces acting on the piston. However, a full dynamic model of the torque producing mechanism was not derived. Instead, an abstract model based on kinematic analysis was used to estimate the torques generated due to the forces acting on the piston, evaluated as follows:

$$F(\theta) = p(\theta)A_p \tag{1}$$

where, $F(\theta)$, $p(\theta)$ and $A_p$ represent force acting on the piston, in-cylinder pressure and area of the piston respectively. The complete torque producing mechanism was modeled as two lumped masses, i.e. a mass in reciprocating motion and a mass in rotational motion. This was in contrast to the conventional analogy of a volumetric pump found in MVEMs. These masses were used to calculate the translational and rotational inertia, and the component of the force orthogonal to the crank-offset was transformed to torque using trigonometric analysis. This mathematical model included the design of a torque producing mechanism but it did not have the capability of extension to multi-cylinder engine model without adding further complexity. Considering a couple of cylinders with this trigonometric approach could double the complexity of the model (Falcone et al., 2003). Furthermore, the added complexity to the model did not provide other information in addition to the angular speed of the crankshaft.

The other significant approaches aimed at describing the multi-cylinder dynamics include (Kiencke & Nielsen, 2005, Ch. 6). The presented approach described the individual cylinder dynamics but the complexity of the model increased with additional number of cylinders and as such its use would be limited to diagnostics. A dynamic model of the torque production subsystem corresponding to a multi-cylinder engine was proposed by Potenza, Dunne, Vulli, and Richardson (2007), in which kinematic analysis and torque/force balancing was used to derive the equations of motion in Newtonian Mechanics. The authors presented a model with a single piston and crankshaft with its extension to multi-cylinders. Since it was derived using Newtonian Mechanics, it resulted in a complex model for constrained motion as the model complexity relied on the number of cylinders. Eriksson et al. (2013) modeled the flywheel angular velocity for misfire and driveline disturbance using the motion of a piston. This model was more accurate than previous ones but the order of the mathematical model was dependent on the number of engine cylinders.

Moreover, in conventional MVEMs many inputs to the system are described as empirical relations, such as spark advance. As a result of these approximations, some significant dynamics, e.g. crankshaft angular speed fluctuations, are suppressed. These fluctuations are caused by two main factors: (1) the dynamics of the torque producing mechanism, and (2) rapidly changing in-cylinder conditions.

The CCEM approaches mentioned above are detailed ones, but either the numerical complexity or the system order (or both) increase with an increase in the number of engine cylinders.

The application of FTC algorithms mainly requires two model attributes: (1) the control oriented model should be capable of describing the fault-free and faulty conditions (Blanke, Kinnaert, Lunze, & Staroswiecki, 2016, Ch. 1); (2) There should be a sensing and/or actuator redundancy. Using a lumped cylinder approach and empirical relations in some cases, render the MVEMs unable to describe the system dynamics in faulty conditions such as misfire. Therefore, MVEMs have a limited capability to describe the engine under fault-free as well as faulty conditions. Thus, the development of control oriented models describing the gasoline engines comprehensively in both faultless and faulty conditions could be a major step in the development of FTC frameworks for the gasoline engines.

To deal with the growing needs, efforts were made to develop a more capable engine model (Falcone et al., 2003), but this model had its own limitations, as explained earlier. Other efforts include Kiencke and Nielsen (2005) and Eriksson et al. (2013). Different approaches to formulate an FTC framework for engines were proposed (Kim, Rizzoni, & Utkin, 2001); however, application of conventional FTC techniques requires that the system model describe the system dynamics under both faultless and fault conditions. Based on the gap indicated in existing literature, recent efforts and the changing requirements, a novel first principle based multi-cylinder gasoline engine model is proposed.

This article extends an FPEM (Yar, Bhatti, & Ahmed, 2017), by taking into account multi-cylinder dynamics and the different processes of the Otto cycle. A model of the torque producing mechanism, corresponding to a four cylinder gasoline engine, is derived using a constrained EOM in Lagrangian Mechanics. A gasoline engine cylinder pressure model is used to evaluate the force acting on each piston. This model of the torque producing mechanism is integrated with a closed form analytical gasoline engine cylinder pressure model. It is shown that the developed model of a gasoline engine, not only describes the dynamics of a faultless engine more accurately; it also describes the engine dynamics with an enhanced region of fault conditions. To demonstrate this, case studies on persistent and intermittent misfire are presented. The description of system dynamics under persistent and intermittent misfire conditions is a distinguishing feature of the proposed model. The structure of the proposed FPEM is shown in Fig. 1.

The rest of the paper is organized as follows: Section 2 explains the derivation of the model of the torque producing mechanism. A