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A survey on modeling, biofuels, control and supervision systems applied in internal combustion engines

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ABSTRACT

In this work, we present a survey on different topics related to Internal Combustion (IC) engines. The purpose of this work is to show the evolution on modeling, use of biofuels, simulation and/or implementation of different types of control laws applied to the IC engines. In the modeling section, we present a classification of the IC engines models according to their type; in this classification linear, nonlinear, and based on Neural Networks (NN) models are included. In the biofuels section, we included different works classified according to the used biofuel. In this classification, we consider pure biofuels (ethanol, methanol, hydrogen), gasoline-alcohol blends and gasoline-alcohol blend plus hydrogen as additive. In the control section, we include a classification according to the type of control, these are model-based control, observer-based control and intelligent control. Furthermore, in this section we include a review about Fault Diagnosis strategies applied to IC engines. Moreover, we present an overview of the failures provoked by corrosion effects when biofuels are used.

1. Introduction

In this work, a literature investigation related to the Internal Combustion (IC) engines was developed. The main idea is giving an overview of different topics related to the IC combustion engine since the 70s to date; the purpose is to detect opportunity areas for future research related to the IC engine. Topics such as IC engines modeling, use of biofuels in the IC engine, design of control strategies applied in IC engines, design of supervision systems for the IC engine and corrosion effects due to the biofuel use were introduced. The importance of the IC engine modeling lies in the fact that the models are commonly used to show the IC engine variables behavior and prove different research hypothesis, they are also used to design control strategies and supervisory systems. In general, the IC engine modeling gives a wide perspective of the evolution of the system behavior allowing the user to take decisions on their research works. Otherwise, the biofuel importance lies in two facts: the gasoline use reduction and the noxious exhaust gases emission reduction; in this sense different experimental works have been developed in order to offer alternative fuels blends that could be used in the IC engines. In the present work, we show relevant research made in this field with the purpose of showing the biofuel use trends and the opportunity areas for possible future investigations. A critical issue concerning to the IC engines is the air fuel ratio control, in this sense different research works have been developed. In this overview, we present different control strategies focused on it; mainly we explored the model-based control, the observer-based control and the intelligent control. An important area of control is the design of supervision systems, which include fault diagnosis systems. The importance of the fault diagnosis lies in the fact that allows to know the exact moment of a fault occurrence. In this section we show the main findings on diagnosis systems applied to the IC engines and the possible opportunity areas in future investigations. Finally, due to the use of biofuel corrosion effects can be presented in IC engines provoking failures, thus we present important research papers on this field, where the authors present experimental analysis of the biofuels use to show the effects on the main IC engines components.

2. Internal combustion engines modeling

At the early 70s, different characterizations of the Internal Combustion (IC) engines of 4, 6, 8 cylinders used in energy centrals

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were developed [1–3]. In Flower and Hazell [2], the authors discussed the application of these models in velocity control purposes using the *Z*-transform technique in combination with the root locus in order to develop an analysis of the behavior of the systems in time domain, whereas, Hazell and Flower [3] developed and proposed a discrete model for a spark ignition gasoline engine for control purposes.

The first IC engine nonlinear dynamic models were reported at the late 70s and early 80s [4–6], in these models, the dynamic of the intake manifold was considered, meanwhile in Aquino [7] the dynamics of the fuel was analyzed, the analysis was performed using experimental data obtained from a central injection engine. In [8] the authors developed a compact model of an IC engine that includes the intake manifold dynamics, the fuel dynamics and the process delays inherent in the four-stroke engine cycle, the advantage of the mentioned model is that it can be used to develop control algorithms. Based on works such as [5,6,9], authors in [10] presented a dynamic model of the automotive powertrain system focused on the dynamics and kinematics of a four-stroke spark-ignition gasoline engine considering a vehicle with automatic transmission. At the end of the decade, Rizzoni [11] developed a robust submodel considering the dynamic of the IC engine, where the cylinder pressure is viewed as the input of the system (IC engine) and the output corresponds to the crankshaft angular acceleration and the crankshaft torque, in this work the cylinder pressure was deterministically related to the net engine torque through the geometry and dynamics of the reciprocating assembly. In Rizzoni [12], the author proposed a stochastic model for the cylinder pressure process, in this work the author tied together deterministic and stochastic models in a Kalman's Filter (KF), where the KF is proposed for the rotational dynamics of the engine, the author validated his work with experimental results.

In the 90s different works were developed in order to design and implement control strategies in the IC engines [13–15] or to increase the exactitude of the IC engines models. On one hand, Ramli and Morris [13], developed an IC engine model for control purposes, this work was based on a previous research developed by Dobner [5], the model allows the direct incorporation of the nonlinear characteristics of the IC engine such that it was possible to represent the engine performance in a wide operating range. In order to use the main transient effect in a traction control system Crossley and Cook [14] developed a nonlinear model for a four-cylinder spark-ignition engine. In order to design control strategies, Chang et al. [15] developed a discrete nonlinear fuel-injected SI (Spark Ignition) engine model, focused on the air-fuel ratio (AFR) control, in this work, the control law was implemented in a fuel-injected single-cylinder engine laboratory port, the fuel mass was defined by the equations developed in [7]. On the other hand, in order to propose an overall and exact engine model, different authors developed mathematical models over the decade. In [16–18] authors presented a mathematically compact model that can be easily configured for different engines, the engine model comprises three subsystems: fuel injection, air intake and engine speed. The model uses the fuel injection system presented in [7], the dynamics of the engine speed and the air dynamics. In [19], the inertia moment of mass was considered variable and authors used the Newtonian and Lagrangian methods to derive the nonlinear governing equations of the internal combustion engine kinematics and its dynamics forces. The tests results showed the accuracy of the model in a wide operating range. In [20] a simple model in discrete time for the IC engine was proposed, the model combines stochastic and deterministic nonlinear elements to provide an overall description of combustion. The result is a nonlinear model for the combustion cycle variation in the spark-ignition engine.

At the beginning of this century in [21] authors made a complete model of the internal combustion engine. To model the IC engine, authors considered the following subsystems: air mass flow dynamics, combustion dynamics and moving parts dynamics. In this work, the authors developed empirical equations to estimate different parameters such as volumetric and thermodynamic performance, intake pressure, among others. Authors concluded that the fraction of liquid fuel is a function of the throttle valve angle only for the central injection engines, but that dependence is negligible in multi-point systems. One year later, Yoon and Sunwoo [22] developed a nonlinear SI model focused on the controllers' design, the model was composed of three subsystems: intake manifold dynamics, film fuel dynamics, and the rotational dynamics of the engine. Authors made the model mathematically compact in order to facilitate its real-time implementation, this model was experimentally validated with an engine-dynamometer.

Some important parts of the IC engines modeling are related to the exhaust emission and motion; Chiavola [23] presented a study for the unsteady gas flow in both, intake and exhaust, systems of internal combustion engines. In this study the author proposed an one-dimensional model that considers the ducts phenomena with a lumped parameter scheme to describe the cylinder volume behavior, the author coupled both systems with a 3D model in order to describe the flow behavior in a complex geometry. The author presented the simulation results of a multi-cylinder exhaust system. Related to the motion modeling, in [24] authors developed an IC engine model that involves the equations of motion for the major components in an internal combustion engine using a recursive formulation. The modeled components were the engine block, pistons, connecting rods, crankshaft, balance shafts, main bearings, and engine mounts. Authors compare their results with the Adams model; they include a discussion of the obtained results with a linear and nonlinear bearing models. Moreover, in [25] a torque-based engine and powertrain model for control purposes was proposed, the model is based on physical principles and experimental data, the model incorporates the throttle inlet, intake manifold intake, cylinder inlet, engine rotation dynamics and vehicle dynamics. For the throttle inlet, authors used the model presented in [26], where three elements were considered, the position of throttle, the pressure before and after the throttle and the temperature of the suction air. Authors used the approach presented in [27] for the intake manifold and cylinder filling dynamics based on the mass conservation and the ideal gas law. The engine torque model was based on the torque structure engine control, proposed in [28,29].

In the last years, the IC engine modeling has been reoriented due to the increment of the use of biofuels, the relation and compromise between biofuels, engine performance and exhaust gas emission. In that sense several experimental and numerical works have been developed for the IC engine fuelled by pure compounds (gasoline, ethanol, methanol, natural gas, hydrogen) or different compounds, mainly alcohol blends. In this context, the control theory has been adapted to this trend (biofuels), moreover, the control AFR algorithms have been optimized for the existent gasoline engines.

Authors in [30] presented the fundamentals of gasoline engine dynamics, in this work a mathematical model based on thermodynamic and ideal gases laws as well as some issues related to the IC engine control were presented. Concerning to the model, the exhaust path dynamics, the behavior of the residual gas and the influence of the composition of the air-fuel mixture gas to the combustion process were not considered. Authors consider that implementing advanced control theory in the automotive engineering is an area of opportunity. Related to the modeling of the IC engine fuelled by pure compounds in [31], authors developed a thermodynamic model in order to estimate the performance and emission characteristics of a SI engine fuelled by gasoline and natural gas.

Exhaust Gas Recirculation (EGR) is an efficient method for NO_x control [32]. EGR remove oxygen in the intake air by exhaust gas recirculated to the combustion chamber. According to the authors in [32] the advantage of the EGR methods is that the exhaust gases decrease the oxygen concentration in the combustion chamber, and increase the specific heat of the intake air mixture, which causes lower flame temperatures. Likewise, the author reported that by using this method the thermal efficiency is slightly increased and Break Specific Fuel