

Virtual Combustion Phasing Target Correction in the Knock Region for Model-Based Control of Multi-Fuel SI Engines

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ABSTRACT

To improve fuel economy and reduce regulated emissions spark-ignition engines are equipped with a large number of control actuators, motivating the use of model-based ignition timing prediction strategies. Model-based ignition timing strategies require a target combustion phasing for proper calibration, generally defined by the crank angle location where fifty percent of the air/fuel mixture is burned (CA50). When fuel type is altered the target CA50 must be updated in the 'knock region' to avoid engine damage while maintaining the highest possible efficiency. This process is particularly important when switching between gasoline and E85 because they have vastly different octane ratings.

A semi-physical virtual octane sensor, based on an Arrhenius function combined with a quasi-dimensional turbulent flame entrainment combustion model, is described that identifies the size of the knock region for a given fuel. The combustion duration model is used to calculate cylinder pressure and temperature which are analyzed with an Arrhenius knock prediction model that accounts for the negative temperature coefficient and air/fuel ratio. An algorithm is developed to identify the "best achievable" combustion phasing and update the target desired combustion phasing accordingly. The algorithm operates off-line once the fuel octane number is observed to have changed, and then revised combustion phasing targets are calculated throughout the knock region. Experimental measurements and simulations are used to correlate and validate the algorithm with both gasoline and E85. Results are presented and conclusions are drawn.

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INTRODUCTION

Engine calibration with full factorial mapping methods, especially for ignition timing control, becomes cumbersome when the number of control degrees of freedom increases and/or a wide range of fuels are used in the engine. The calibration time will increase exponentially with each degree of freedom added. Thanks to the advanced and fully automated engine testing system, the automotive industry has successfully adopted model-based calibration and design of experiments (DoE) technology [1][2][3] to reduce the calibration time. Alternative approaches utilizing physical model based control methods are also widely studied, especially for future ultra-high degrees of freedom and multi-combustion mode/multi-fuel engines. Available Combustion models, based on fidelity, are from 0-D single-zone [4], quasi-dimensional multi-zone [5][6][7][8][9][10][11], and 3-D CFD multi-zone combustion models [12][13]. Model based control strategies are restricted by the computational power and fidelity of the models, however it appears to be a potential solution for highly flexible engines, and could significantly reduce calibration time.

Feed-forward model-based ignition timing control requires a target combustion phasing for proper calibration, generally based on CA50. The optimal CA50 location (MBT timing) is a balance between early combustion (high heat losses) and late combustion (high expansion losses). For combustion with low octane number fuel sources, the best CA50 location may also be limited by abnormal combustion (spark knock). Based on compression ratio or boost level, the desired combustion phasing will be determined by the calibrator for a particular engine with a known fuel source. When fuel type is altered (e.g. gasoline to E85) the engine can be subjected to a different octane number, requiring an updated CA50 target in the 'knock region' to avoid mechanical damage and still maintain high thermal efficiency.

Traditionally, knock feedback control utilizes a structure-mounted accelerometer as an observer [14], spark plug ionization signal [15], or in-cylinder pressure sensor [16]. The sensor will accumulate several knock events and constantly adjust spark advance using an adaptive map until knock is eliminated. The spark timing delivered to the engine

is the sum of the base ignition map, spark advance adjustment and the adaptive map. Drawbacks of such feedback approach are: 1) The engine will experience large amount of knock events until the adaptive map has been created; 2) The learning process is relatively slow because the algorithm requires input from all the possible operating conditions (speed/load points). In an example given by the Kiencke [14], the adaptation map required 50km of vehicle operation for 50:50 blending of 87 and 93 octane fuel sources.

To speed up this process a feed-forward knock prediction algorithm is desired in the multi-fuel adaptive engines because of the possible wide range of fuel source inputs. Spark knock is the consequence of auto-ignition in the unburned end-gas ahead of the propagating spark ignited flame front. The auto-ignition characteristic therefore is greatly related to the octane rating of the fuel source and governed by composite chemical reactions under the time history of temperature and pressure of the unburned end gas. Auto-ignition models [17,18,19,20] are available with a wide variety of fidelity options. Two other fuel properties are also of particular interest to knock control; 1) laminar flame speed that describes the potential mass burn rate which can reduce the time scale of the end-gas exposure prior to combustion, and 2) fuel heat of vaporization which alters charge cooling effects and unburned mixture temperatures.

This research aims to address the drawbacks of knock feedback control by developing a feed-forward prediction model for multi-fuel adaptive SI engines, and to generate a combustion phasing adjustment map in the knock region for model based ignition control. A semi-physical virtual octane sensor and laminar flame speed observer are used for fuel property feedback. A knock prediction model, based on an Arrhenius function combined with a quasi-dimensional turbulent flame entrainment combustion model, is described that identifies the limits of the knock region for a given fuel. The combustion duration model is used to calculate in-cylinder thermal conditions for a range of operating points in the knock region. Calculated in-cylinder thermal conditions are analyzed with a knock correlation that accounts for the negative temperature coefficient and air/fuel ratio. The model then calculates the “best achievable” combustion phasing at discrete points in the knock limited region and updates the target CA50 map accordingly. The routine operates off-line once the fuel octane number/fuel properties are observed to have changed and re-calculates desired combustion phasing targets. The method is shown to be capable of predicting desired combustion phasing for the entire knock region based on feedback from a single operating point. Experimental measurements are used to correlate and validate the routine using both gasoline and E85. Additionally, transient drive cycle simulations using GT-Power are used to evaluate the performance of the algorithm.

EXPERIMENTAL SETUP AND DATA COLLECTION

This research was carried out on a port fuel injected spark-ignited V-8 engine, as shown in Table 1. The engine was mounted to an AC dynamometer with each cylinder of one engine bank instrumented with passage-mounted AVL GH12D piezoelectric cylinder pressure sensors. The sensors were located in the cylinder head to maximize accuracy according to Patterson and Davis [21], and were equipped with flame guards to minimize thermal shock errors. Piezoresistive Kulite sensors were used for both intake and exhaust pressure measurements. Exhaust sensors are water cooled to minimize signal drift when exposed to high temperatures. Cylinder and manifold pressure measurements are recorded using an AVL-671 crank-angle resolved data acquisition system with a 0.5° CA resolution. AVL Concerto software is used to process the high volume of data acquired during each experiment. The test engine is controlled using an A&D Technology, Inc. ADX rapid-prototype ECU system that allows for complete adjustment of all actuators. Bosch lambda sensors, driven by Fuel Air Spark Technology (FAST) wide-band modules, are used to record air-to-fuel ratio for each cylinder.

Table 1. Engine specification

Engine:	GM Vortec V8 (LH6)
Displacement:	5328cc (325 ci)
Compression ratio:	9.95:1
Valve configuration:	overhead valves
Valves per cylinder:	2 (1-Intake, 1-Exhaust)
Aspiration	Naturally aspirated
Bore x stroke:	96.01 x 92mm
Fuel system:	sequential PFI
Horsepower:	235 kW @ 5200 RPM
Torque:	458Nm @ 4400 RPM
Block materials	Cast aluminum
Head materials	Cast aluminum
Piston:	Flat top

COMBUSTION PHASING TARGET ADJUSTMENT IN KNOCK REGION

A model based ignition control algorithm for multi-fuel adaptive engines has been developed by the authors, including a feed forward, spark timing prediction, utilizing a quasi-dimensional turbulent flame entrainment combustion model and two virtual fuel properties observers for sensing the laminar flame speed and octane number of fuel sources [22] [5]. The feed-forward spark timing prediction is determined based on the combustion duration prediction and a desired

combustion phasing (CA50). This desired combustion phasing is first determined by the calibration engineer for a particular engine taking into consideration combustion stability, emissions, performance, etc. Then the “best achievable” combustion phasing in the knock region will be updated, using the method presented in this paper, based on the current fuel source input. The illustration of the overall closed-loop algorithm is shown in Figure 1.

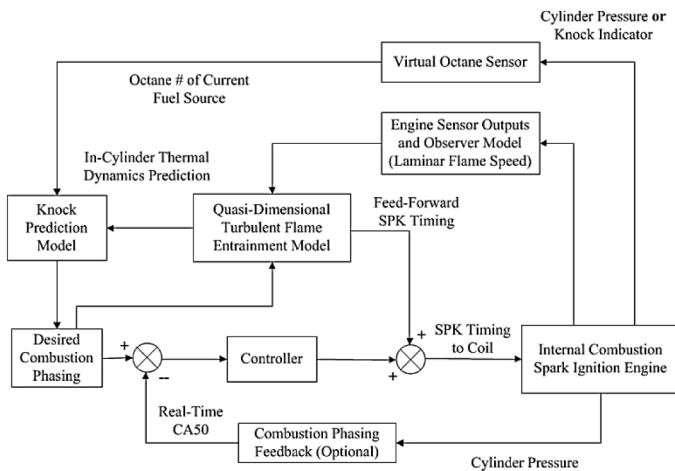


Figure 1. Desired combustion phasing (CA50) is used as a control reference in the model based spark timing control algorithm. A knock prediction model based on the octane number of the current fuel source and predicted in-cylinder thermal dynamics parameters calculates the “best achievable” CA50 in the knock limited region.

In order to calculate the “best achievable” combustion phasing target, knock limits must be realized for a particular engine with current fuel source. A wide range of bio-fuel sources might be blended together in future multi-fuel adaptive engines. Therefore, two virtual fuel behavior sensors are placed in the control algorithm to feedback octane number and laminar flame speed of the mixed fuel source. Octane number describes the ability of the fuel source to withstand compression before detonating. Laminar flame speed represents the fuel property that affects combustion burn rates. The quasi-dimensional turbulent flame entrainment model generates mass burned rates off-line for different combustion phasings at each engine operating condition (e.g. RPM, MAP). The first Law of Thermodynamics and heat release analysis is used to reconstruct cylinder pressure and unburned gas temperature profiles for each predicted combustion phasing. Then, the predicted in-cylinder thermodynamic conditions are used in the Livengood & Wu integral [18] to analyze if knock will occur at each particular combustion phasing. Finally the algorithm identifies the achievable combustion phasing closest to MBT timing and generates the updated CA50 target for model based spark timing control. The off-line “what if” algorithm for determining the “best achievable” combustion

phasing is shown in Figure 2. Each component of the described algorithm will be explained in the following sections.

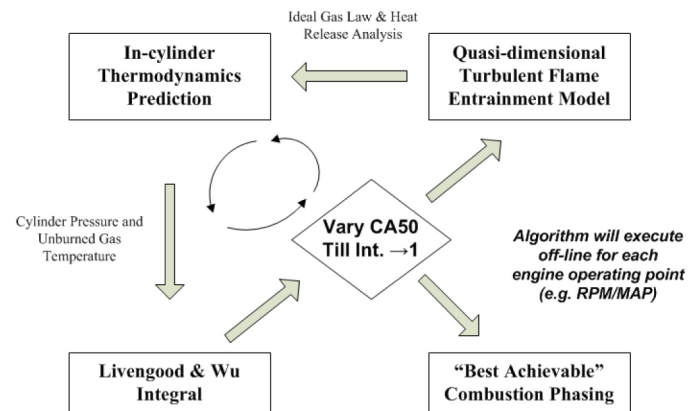


Figure 2. Off-line “what if” algorithm for determine the “Best achievable” combustion phasing in the knock region when the fuel source is altered.

Auto-Ignition Modeling and Prediction

Various levels of sophistication for auto-ignition characteristic modeling are available, from comprehensive chemical kinetic simulations [17], to a global single step Arrhenius function that describes all hydrocarbon oxidation reactions [18]. Reduced chemical kinetics descriptions are also available [19]. In the above methods, the single step Arrhenius function is recognized as the most practical way of predicting the ignition delay for control purposes because of its simplicity and relatively good physical representation [20]. It is widely studied based on experimental data for auto-ignition prediction in constant volume bombs, steady flow reactors, rapid compression machines and IC engines [23–24].

Phenomena for ignition delay is observed both experimentally, in rapid compression machines (RCM) [25] and in detailed chemical kinetics simulations [26]. Typical results for gasoline are shown in Figure 3. This figure demonstrates monotonic behaviors in the cool flame ignition delay region on the upper right, the intermediate region of negative temperature coefficient (NTC) behavior and the high temperature ignition region in the lower left hand corner [27]. Auto-ignition generally occurs when the unburned gas reaches around 900K to 1000K, where the NTC behavior is observed. Therefore, it is important for the knock prediction/ auto-ignition delay model to capture this phenomenon.