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Closed loop statistical performance analysis of *N-K* knock controllers

James C. Peyton Jones [a,*], Saeed Shayestehmanesh [a], Jesse Frey [b]

[a] *Electrical and Computer Engineering, Center for Nonlinear Dynamics and Control, Villanova University, USA*
[b] *Mathematics and Statistics, Villanova University, USA*

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ABSTRACT

The closed loop performance of engine knock controllers cannot be rigorously assessed from single experiments or simulations because knock behaves as a random process and therefore the response belongs to a random distribution also. In this work a new method is proposed for computing the distributions and expected values of the closed loop response, both in steady state and in response to disturbances. The method takes as its input the control law, and the knock propensity characteristic of the engine which is mapped from open loop steady state tests. The method is applicable to the '*n-k*' class of knock controllers in which the control action is a function only of the number of cycles n since the last control move, and the number k of knock events that have occurred in this time. A Cumulative Summation (CumSum) based controller falls within this category, and the method is used to investigate the performance of the controller in a deeper and more rigorous way than has previously been possible. The results are validated using onerous Monte Carlo simulations, which confirm both the validity of the method and its high computational efficiency.

1. Introduction

One of the factors that has hindered the development of improved engine knock controllers is the lack of rigorous performance metrics for these systems. A variety of different knock controllers have been proposed in the literature [1–9], but it is not immediately apparent how to quantify or compare their steady state and transient performance. Perhaps for this reason the tuning and calibration of these systems remains something of a 'black art'. Typical studies present plots of the closed loop spark advance and/or knock intensity, either in steady state or in response to some imposed spark timing disturbance, but quantitative measures of these traces are often lacking. More fundamentally, however, such plots do not give repeatable results: To a good first approximation, knock behaves as a cyclically independent random process [10]. In any given test, the controller response therefore reflects a particular instance of this process. If the experiment is repeated, even under otherwise perfectly identical operating conditions, a different result will be obtained since the controller will be reacting to a different sequence of knock events. The 'single-instance' time history traces presented in much of the literature are therefore only indicative, and do not constitute a rigorous assessment of closed loop behavior.

One way to address these issues is to perform hundreds or possibly thousands of repeated experiments, and then to determine the empirical distribution of all the closed loop responses that are obtained. However, this is difficult and costly

* Corresponding author.
E-mail address: james.peyton-jones@villanova.edu (J.C. Peyton Jones).

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to perform in practice, and (as shown in Section 4) even in simulation it is computationally burdensome. A different approach is to derive *expressions* for the statistics of the closed loop response based on the knock characteristics of the engine and the control law that is applied. The engine knock characteristics are readily obtained from open loop, steady state spark sweep tests as described in Section 2. It is then possible to compute, for example, the transient evolution of the expected closed loop spark angle, the expected response times of the system, or even the expected closed loop knock intensity distribution when subject to a specific control law [11,12]. To date, however, such results have only been obtained for a traditional slow-advance, fast-retard knock controller. The aim of this paper is to extend the approach to a Cumulative-Summation (CumSum)-based knock controller [8]. Initial work in this direction was presented in [13], but this paper presents a new and more elegant derivation of the expression for the closed loop spark angle distribution. Expressions for the expected response times of the system subject to the CumSum control law are also derived for the first time.

The paper is organized as follows: In Section 2 a brief summary is given of the way in which the knock characteristics of the engine are defined for the purposes of this work. In Section 3, the CumSum knock control strategy is briefly reviewed and its performance illustrated using single-instance time history simulations. As discussed above, such results are indicative but not rigorous or repeatable because they depend on the particular sequence of knock events experienced in this one case. Methods to compute the transient and steady state *distribution* of the closed loop spark angle are therefore presented in Section 4. The method is actually applicable to any knock controller in which the control strategy is a function only of the number, n, of cycles since the last spark adjustment and the number of knock events, k, that have occurred in that same time. The CumSum strategy is one example of this 'n-k' class of control strategies, and is used as the primary exemplar. Also in Section 4, a first-step analysis is used to obtain the expected response times of the system, and the expected number of knock events during the transient, as a function of the initial condition or magnitude of the spark perturbation. Finally, brief conclusions are provided in Section 5.

2. Engine knock characterization

The ability to predict or analyze the closed loop response of a knock control system depends fundamentally on having some statistical model for the knock characteristics of the engine. Various physics-based models exist for exploring knock combustion chemistry [14–16], but such models are generally deterministic (as well as being highly computationally intensive), and are therefore inappropriate for this work. Most control-oriented knock models take a more empirical approach, and characterize recorded knock intensity data as a random process [10,17–21]. Different systems may use different knock sensors and detection metrics [20,22–24], but what matters under this approach is accurate statistical characterization of the knock feedback metric (however this is defined) that is seen by the Engine Control Unit (ECU). In this work, for example, a knock signal is obtained from an accelerometer mounted on the engine block of a Ford 5.4 liter V8 gasoline engine [10]; the signal is windowed, bandpass filtered, rectified and averaged in order to obtain a knock intensity value. Providing this data is cyclically independent, it is completely characterized by its probability density function (pdf) or cumulative distribution function (cdf). Estimates of the pdf of this data taken from cylinder #1, at 1000 rpm Wide Open Throttle (WOT), are therefore shown in Fig. 1, for different spark advance values relative to the angle of BorderLine (BL) knock onset, where the latter is identified by an experienced calibration engineer. These curves can be encapsulated as lookup tables and used in simulation to generate data statistically similar to the original according to the prevailing spark advance, and engine operating

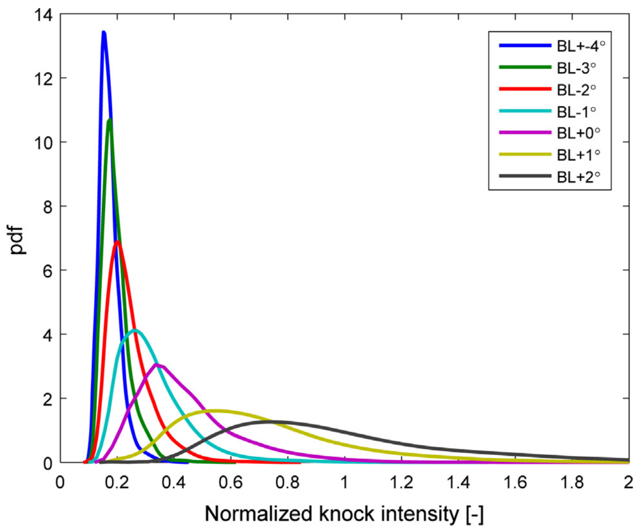

Fig. 1. Open loop knock intensity distributions for different spark advances (1000 rpm, WOT).