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Stochastic Simulation of a CumSum Knock Controller

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Abstract: Single time-history simulations of knock control strategies cannot provide repeatable measures of closed loop performance because such responses are strongly dependent on the random arrival of knock events during the specific simulation or experiment. Stochastic simulation algorithms address this issue by computing the probability distribution of the closed loop response as a function of time from any given initial distribution. In this paper, a new algorithm is presented for stochastic simulation of a Cumulative Summation-based knock control strategy. The stochastic simulator is then used to assess the performance of this strategy in a scenario in which feedback sensitivity is also enhanced through the use of an optimized knock threshold. The results are compared to those for a traditional knock controller operating using a more conventional knock threshold level.

Keywords: Automotive control, Stochastic control, Spark advance control, knock.

1. INTRODUCTION

The ability to simulate and quantify the closed loop behaviour of a control system design is essential to the design process. Step response tests, or tests from some disturbed system state are often used to assess the transient response of the system. The steady state error, once these transients have decayed, is also used to quantify the stationary response. In the case of knock control systems, however, such simple measures of closed loop performance are often lacking. Although it is relatively straightforward to record the closed loop response in any given experiment or system simulation, the results are often strongly dependent on the particular instance of the random knock process that was experienced during the test. Re-running the experiment may therefore give results that differ significantly from those obtained in the first instance, making it hard to quantify the performance characteristics of the controller in any rigorous repeatable way.

Recent work has attempted to address this issue through the use of Markov-like stochastic simulation techniques [1]. Instead of simulating just a single, specific time history of the response, the stochastic simulator predicts the *distribution* of the controller state, and its transient evolution with time. This provides a complete characterization of the response to all possible instances of the knock process, and it is therefore possible to derive a variety of other statistics of interest as required. It is straightforward, for example, to compute the closed loop spark advance distribution, expected response times, and even the expected closed loop knock intensity distribution, [2].

Although the general approach is applicable to many different knock control strategies, the particular stochastic simulation strategy is specific to the controller, and to-date the technique has only been applied to a classical knock control strategy, [3]. While such controllers, or simple variants thereof, are still widely used in production, there has also been renewed interest in developing more advanced knock controllers designed from explicitly stochastic principles, [4–9]. Although the new controllers appear promising, it is hard to assess their performance relative to each other, or to the classical knock controller baseline, without improved performance metrics. The aim of this paper is therefore to develop a stochastic simulation strategy for a CumSum-based knock control strategy, several variants of which have been proposed in recent years [8,10,11].

The paper is organized as follows: The characterization and simulation of knock events based on the knock probability curve of the engine, is described in Section 2. The closed loop behaviour of this system when subject to a traditional knock control law is then briefly reviewed in Section 3, using both deterministic and stochastic simulation techniques. The CumSum controller, and its optimization with respect to the knock threshold, is described in Section 4, and its operation illustrated by means of a single-instance time history simulation. The new stochastic simulation technique for the CumSum controller is developed in Section 5, and it is shown how this provides a much more complete description of its closed loop performance. Finally, brief conclusions are provided in Section 6.

2. CHARATERIZATION OF THE KNOCK PROCESS

A pre-requisite for any closed loop knock control simulation is some form of open loop model or characterization of the knock process. A detailed study of knock properties derived from a large database of knock experiments was presented in reference [12]. This study concluded that knock closely approximates an independent random process, and that it is therefore completely described by its probability density

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function (pdf), or cumulative distribution function (cdf), at any given operating condition. Most controllers, however, respond to the occurrence of knock events, i.e. undesirably high knock intensity cycles which exceed some threshold. Although it is possible to model the knock intensity distributions, and then simulate knock intensity values, and then determine whether these values classify as knock events, it is actually simpler and arguably more accurate to simulate knock events directly. In particular, the binary classification of cycles as 'knocking' or 'non-knocking' means that knock events are, by definition, binomially distributed and are completely characterized by the knock event probability, $p(\theta)$. The variation of knock probability with spark angle θ is easily identified by recording knock intensity data at each spark condition, applying a threshold and then evaluating the knock event rate in each case. A plot of the resulting knock probability curve from one such test sweep performed at 1000 rpm on a Ford V6 engine is shown in Fig. 1. The circled points correspond to experimental measurements, and the stepped nature of the curve reflects the resolution of the spark angle actuation (0.1 degrees) used in this work. Spark advance is measured relative to BorderLine (BL) knock as identified by a calibration engineer. Further experimental details can be found in reference [12].

The knock probability curves, such as those shown in Fig. 1, define the model of the knock process that forms the basis of both the conventional and stochastic simulators used in this work. In the first case, the curves are used to simulate knock events that are statistically similar to the original data: At each cycle, a uniformly distributed random number is generated, and if this number exceeds the non-knocking probability, $(1 - p(\theta))$, then a knock event is indicated. This technique has been used in several previous studies to simulate the closed loop response of the engine to the spark timing commanded by the controller, and it is also used as the basis for the time-history results presented in Sections 3 and 4 of this paper. In the second case, the knock probability curves are used to populate the transition matrix **M** or transition expressions used by the stochastic simulator to propagate the closed loop distribution from one cycle to the next. This, more general, stochastic simulation approach is described in Section 3.1 (for the traditional controller), and in Section 5 (for the CumSum controller).

3. TRADITIONAL KNOCK CONTROL STRATEGIES AND THEIR SIMULATION

Both the traditional knock controller, and the CumSum controller regulate the knock event rate, where knock events are defined as cycles in which the knock intensity exceeds some threshold value. Typically, this threshold is set at a relatively high level in order to identify potentially damaging knocking cycles. In this work, for example, the threshold level was calibrated (initially) such that only 1% of cycles classify as knocking under BorderLine (BL) audible knocking conditions. The control objective is to manipulate the spark timing in response to observed knock events so that closed loop operation is maintained as close as possible to a 1% knock rate target and BL operation.

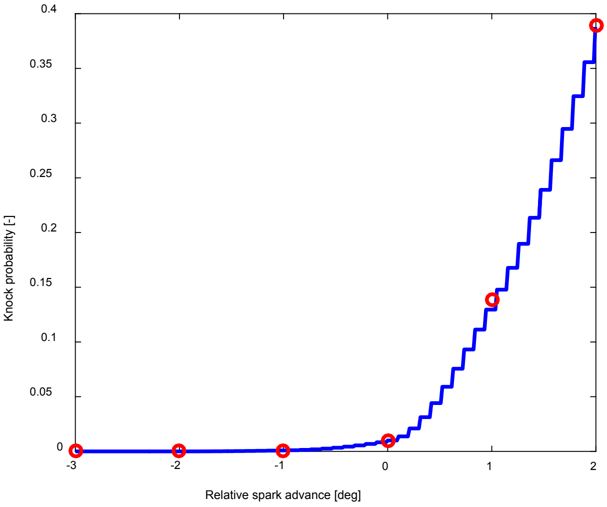

Fig. 1. Knock probability characteristic.

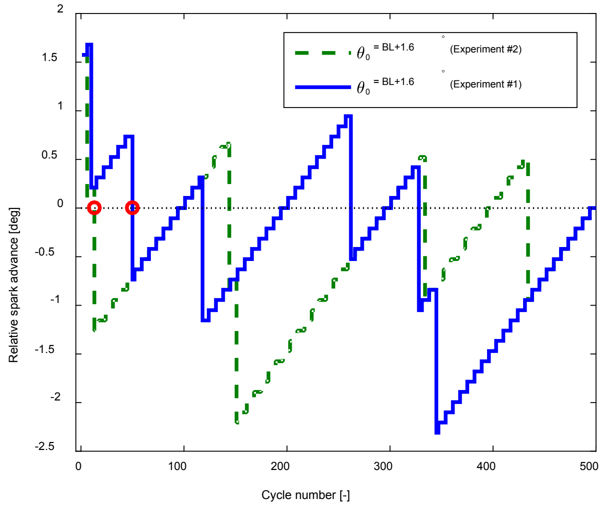

Fig. 2. Two instances of the closed loop spark angle response to an initial 1.6° disturbance offset.

A conventional knock control strategy achieves this objective by advancing the spark gradually every cycle until a knock event occurs, at which point the spark is retarded rapidly to a more safe region of operation. The control law may therefore be expressed as,

$$i_{n+1} = \begin{cases} i_n - m_2' & \textit{if knocking} \quad m_2' = \min(m_2, i_n) \\ i_n + m_1' & \textit{otherwise} \quad m_1' = \min(m_1, [i_{\max} - i_n]) \end{cases} \tag{1}$$

where $i \in \{1..i_{max}\}$ denotes the system state which corresponds directly to the applied spark angle θ_i. Symbols m_1', m_2', denote the spark advance (positive) or retard (negative) control moves that are taken according to the knocking status of the current cycle. As indicated in (1), these moves are constrained so that the controller cannot advance beyond the state $i_{\max}$, which (when the engine is not knock-limited) corresponds to the optimum MBT spark timing.

Implementation of (1) gives rise to the classic sawtooth waveform shown in Fig. 2, where the controller cycles in, and