

Threshold Optimization and Performance Evaluation of a Classical Knock Controller

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ABSTRACT

A new knock threshold optimization method is presented based on minimization of the total misclassification error of knocking / non-knocking engine operating conditions. The procedure can be used in conjunction with any knock-event-based controller, but is illustrated on a classical knock control strategy. Initial simulations suggest that the method delivers significant performance improvements with no changes other than a retuning of the controller. However, it is not possible rigorously to evaluate controller performance based on any individual experiment or simulation time history due to the random nature of the knock process. A recently developed stochastic simulation technique is therefore used to compute and compare the statistical properties of the closed loop steady state and transient response characteristics. The results demonstrate that optimization of the knock threshold can significantly reduce the dispersion of closed loop spark angle, while also improving the ensemble mean transient performance of the controller.

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1. INTRODUCTION

Under knock limited conditions, the aim of a knock controller is to advance the spark as far as possible while limiting the knock intensity below levels which could cause engine damage or driver annoyance, [1, 2, 3]. To a good first approximation, however, cyclic variations in knock intensity behave as an independent random process whose values, since they are random, cannot be controlled directly, [4, 5]. The near-universal strategy is therefore to apply a threshold in order to identify potentially damaging high-intensity cycles, and to manipulate the spark so as to control the rate or probability of these 'knock events'. Although a variety of different control strategies have been proposed, [6, 7, 8, 9, 10, 11, 12, 13], the performance of these controllers is very dependent on the thresholds that define the knock-event feedback signal. Optimization of this threshold therefore offers potential benefits for the whole class of 'event-based' knock controllers.

Knock thresholds are typically set such that only a small fraction of high intensity knocking cycles classify as knock events under BorderLine (BL) knock spark advance conditions. Recent work, however, suggests that lowering the knock threshold and controlling to a higher 'weak knock' rate target provides more informative feedback on differences in the underlying knock intensity distribution and results in improved closed loop knock control, [14]. However, in this prior work, a rather ad-hoc method was used to optimize the thresholds. In this paper a more rigorous approach is adopted which seeks to place the threshold so as to minimize the misclassification error of knocking / non-knocking engine operating conditions. This procedure is applicable to all knock event-based controllers, but is illustrated on a classical slow-advance, fast-retard knock controller.

A second, and equally important contribution of the paper, concerns the performance evaluation of the resulting control strategy. Two aspects are of particular concern: First, the steady state closed loop spark distribution is important because of its close relation to fuel economy, and for reasons of cyclic stability. Second, the transient response of the controller to disturbances from the desired steady state BL condition is important in order to ensure that the engine rapidly recovers from any damaging knock condition or from overly retarded conditions that carry a heavy fuel economy penalty. Evaluation of these performance characteristics is difficult due to the random nature of knock events. Typical time domain simulations, or indeed physical experiments, are highly dependent on the particular instance of knock events that happened to occur, and very different responses may be observed if the simulation or experiment is repeated. Any attempt to calibrate or quantify the performance of the controller based on such single instances is likely to be biased, and the results cannot be extended to the more general case with any degree of confidence.

To address this issue, a new stochastic simulation technique has recently been developed which enables the evolution of the *distribution* of closed loop spark advance (for all possible instances) to be computed as a function of time or cycle number, in response to some initial disturbance, [15]. In this paper, stochastic simulation techniques are therefore applied to provide a rigorous evaluation and comparison of the new threshold-optimized knock controller with a typical 1% threshold knock controller. In particular steady state closed loop spark distributions are computed, as well as the mean closed loop spark transient response to over-advanced and over-retarded spark disturbances.

2. KNOCK CONTROL AND OBJECTIVES

As outlined in the introduction, the knock threshold is typically set such that only a small (eg. 1%) fraction of cycles classify as knocking when operating at the BL audible knock limit - where this limit is identified by an expert calibration engineer. As the spark is advanced relative to BL, the knock probability increases rapidly, while if the spark is retarded the knock probability tapers towards zero (Fig. 1, solid line). The immediate task of the controller is therefore to regulate the knock rate to the 1% BL knock condition, and to return to this condition as rapidly as possible when perturbed by some disturbance.

A classical knock controller, for example, achieves this goal by advancing the spark angle, $\theta(n)$, gradually by an amount K_{adv} on each non-knocking cycle, and retarding by a larger amount K_{ret} on each knock event:

$$\theta(n) = \begin{cases} \theta(n-1) - K_{ret} & \text{if knocking} \\ \theta(n-1) + K_{adv} & \text{otherwise} \end{cases} \quad (1)$$

This results in a sawtooth-like waveform for the closed loop spark advance (Fig. 2), where the downward steps correspond to the arrival of knock events. Since advances must on average balance retards, then assuming the system is stable, the two must equate according to,

$$K_{ret} p = K_{adv} (1 - p) \quad (2)$$

The resultant closed loop knock probability p is then obtained by rearrangement of (2) as,

$$p = \frac{K_{adv}}{K_{ret} + K_{adv}} \quad (3)$$

The strategy therefore successfully regulates the closed loop knock probability, on *average*, but it should be noted that the controller does not settle to a constant condition and the strategy results in an undesirably wide cyclic dispersion of the closed loop spark advance, (Figs. 2,3). Indeed, inspection of the Fig. 3 shows that the majority of cycles operate at some overly retarded condition, rather than at the desired BL knock condition.

Although the classical control strategy (1) is simple and intuitive, a deeper examination of the knock control problem shows that knock intensity values belong to a probability distribution. The shape of this distribution, characterized by its probability density function (pdf), changes as the spark is advanced, with a shift (as expected) towards higher intensity values as the engine moves further into knocking conditions, (Fig. 4). In a more general sense, therefore, the control objective is to adjust the spark so as to select the desired BL distribution from this continuum of possible knock distributions.

In this context, the knock event probability (Fig. 1) corresponds to the portion of the pdf curves lying to the right of the threshold line (shown dotted in Fig. 4), and can therefore be regarded as one (of

many) possible measures of this distribution. Other measures could also be used, including the knock event rate defined using some other knock threshold, [14].

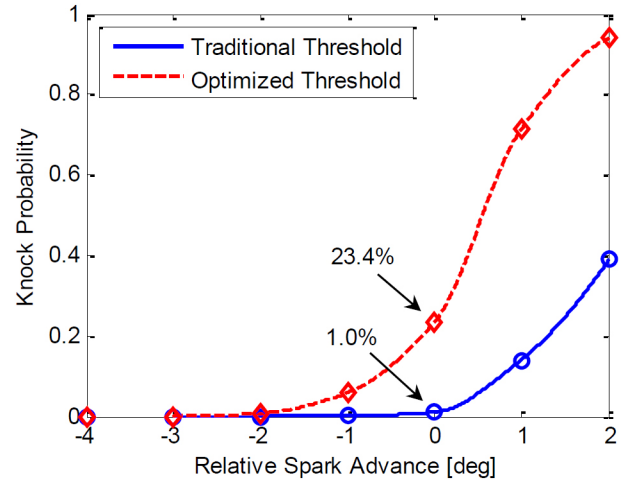


Figure 1. Knock probability as a function of spark advance for two different knock intensity thresholds.

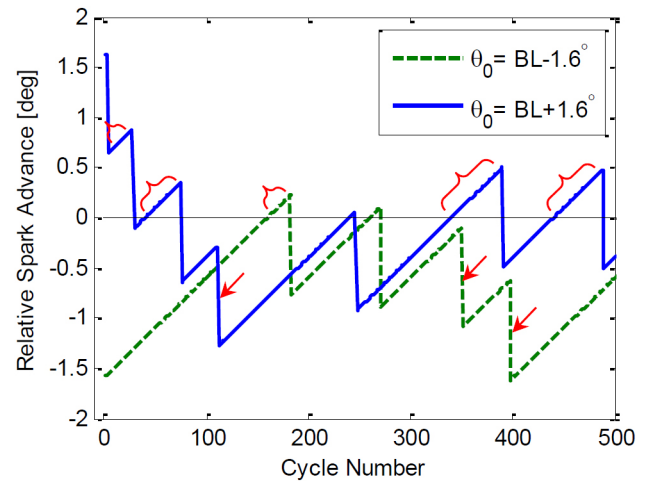


Figure 2. Closed loop transient response for different initial conditions. Arrows and braces indicate instances of 'incorrect' control actions where the spark is being adjusted away from the desired BL condition.

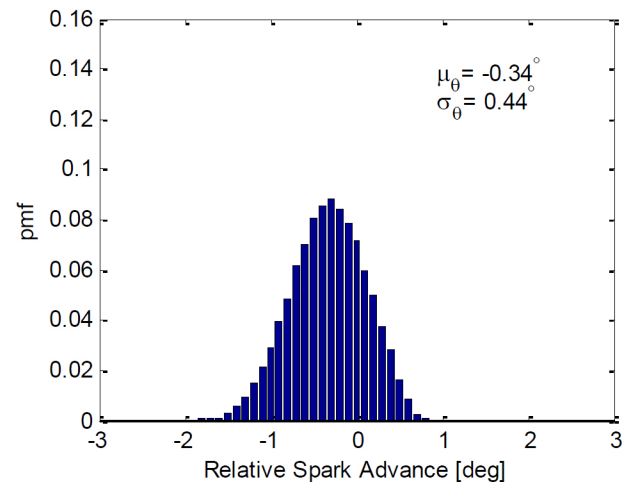


Figure 3. Probability mass function (pmf) of the discrete distribution, of the closed loop spark advance time-averaged over 10,000 cycles.

Lowering the threshold, for example, will increase the apparent knock rate (since more knock intensities classify as knocking) and result in a different knock probability characteristic, as shown dotted in Fig. 1. Note that controlling this new ‘weak’ knock rate still controls the distribution as a whole, and hence also the normal ‘hard’ knock rate that is associated with the tail of the distribution.

Recent work has therefore proposed optimizing the threshold so as to maximize the sensitivity of the observed knock rate to changes in engine operating condition, [14]. As observed in Fig. 1, changing the knock threshold changes the steepness of the knock probability characteristic with respect to the spark timing, and a sensitivity criterion, s , was therefore defined in terms of the discrete gradient of this characteristic at the desired BL operating condition,

$$s = \frac{1}{\left(0.1 + \sqrt{p(\theta_{BL})(1 - p(\theta_{BL}))}\right)} \frac{p(\theta_{BL+1}) - p(\theta_{BL-1})}{2} \quad (4)$$

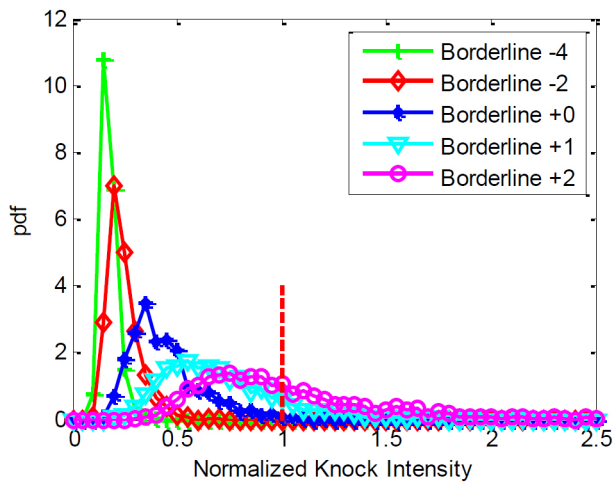


Figure 4. Knock intensity pdf's at different spark advances.

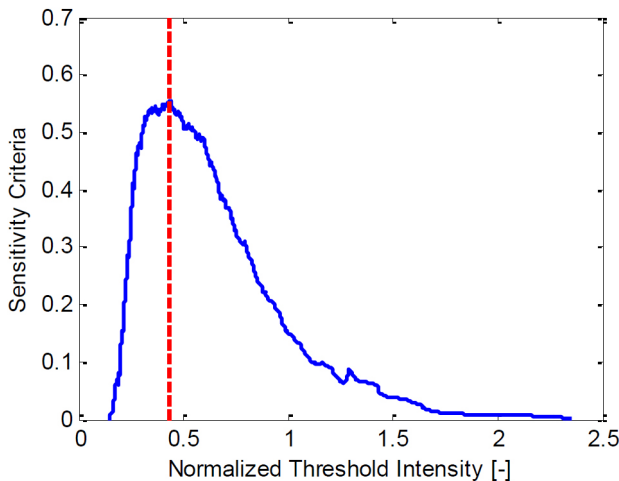


Figure 5. Sensitivity criterion as a function of knock threshold level.

The first factor is included to normalize the result according to the standard deviation of knock events in any fixed number of cycles, and the constant 0.1 was inserted to make the expression more robust in cases where the knock probability is very low. The sensitivity can

plotted as a function of the knock intensity threshold, as shown in Fig. 5, and the optimum threshold is then easily identified as the value that maximizes the sensitivity. This approach was shown to be very promising for its impact on the closed loop control performance [14], but the sensitivity function (4) is somewhat ad hoc. A new threshold optimization strategy is therefore developed below.

3. MINIMIZING MISCLASSIFICATION ERRORS

Although the use of a knock threshold provides a very quick and effective way to classify knock intensity values into ‘knocking’ and ‘non-knocking’ cycles, it is important to distinguish between knocking or non-knocking *events* or *cycles*, and nominally ‘knocking’ or ‘non-knocking’ engine *conditions*. The former relates to a particular sample of the random knock process, while the latter defines a particular distribution among those illustrated in Fig. 4 and is ultimately what we wish to control. Note that many non-knocking engine cycles can be observed even when operating at some undesirably advanced ‘knocking condition’ where the probability of knock events is quite high. Likewise, occasional knocking cycles are still to be expected even when operating at an overly retarded ‘non-knocking’ condition.

In this sense, the knock *event* status sometimes gives a misdiagnosis of the engine *condition* as illustrated in Fig. 6, and this can result in an inappropriate controller response. A classical knock controller, for example, always reacts to a non-knocking event by advancing the spark, even if this actually pushes the engine further into the knock region (see for example the portions of the response annotated with braces in Fig. 2). Likewise, a knock event always causes the controller to retard the spark even if the engine is already operating in a retarded state (see for example cycles 111, 397 and 350, indicated with arrows, in Fig. 2). In all these cases, the controller actually moves the spark angle away from, rather than towards the desired condition as a result of misdiagnosing the true engine condition. It is therefore important to choose the knock threshold so as to minimize these misdiagnosis errors.

		Engine Operating Condition	
		Knocking	Non-knocking
Knock Event Status	Knocking	Correct ☺	Type I Error False positive
	Non-knocking	Type II Error False negative	Correct ☺

Figure 6. Classification categories and Type I and Type II errors.

Statistically, such errors are called Type I, or Type II errors with respect to some null hypothesis. In this case the null hypothesis, denoted H_0 , is that the engine is operating at the desired BL knock condition, with the knock intensity distribution illustrated in Fig. 7. The alternate hypothesis, denoted H_A , is that the engine is operating at some other condition, corresponding (in the illustration of Fig. 7), to a BL+2° knocking condition with an overly advanced spark advance. Applying a knock threshold x_T , as illustrated by the dashed line in the figure, defines the knock probability at each of these engine operating conditions as previously discussed in the context of