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Stochastic Limit Control and its Application to Spark Limit Control using Ionization Feedback

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***Abstract**:* Spark timing of an Internal Combustion (IC) engine is often limited by engine knock in advanced direction and by partial burn and misfire in retard direction. The ability to operate the engine at either its advanced (borderline knock) spark limit or its retard (partial-burn or misfire) spark limit is the key for improving emissions and fuel economy. Due to combustion cycle-to-cycle variations, IC engine combustion behaves similar to a random process. For example, the combustion stability metric COVariance of Indicated Mean Effective Pressure (IMEP) is calculated from in-cylinder pressure signals, assuming that IMEP is a random process. Presently, the spark limit control of IC engines is deterministic in nature. The controller does not utilize stochastic information associated with control variables such as knock intensity for advanced limit control and combustion stability for retard limit control. This paper proposes a stochastic limit control strategy to maintain engine operation in a normal region. It also presents a simple stochastic model for evaluating the proposed stochastic controller. The stochastic limit control is applied to both borderline knock limit control and combustion stability retard limit control on a 3.0L V6 engine.

I. INTRODUCTION

Internal Combustion (IC) engines are designed to maximize power subject to meeting exhaust emission requirements with minimal fuel consumption. Spark timing is used as one of the optimization parameters for the best fuel economy within the given emission requirements. For normal operation, engine spark timing is often optimized to provide Maximum Brake Torque (MBT). Traditionally, MBT spark timing is determined by conducting a spark sweep, but it can also be determined through closed loop spark timing control (see [1], [2], [3], [4], and [5]). On the other hand, engine combustion stability and knock avoidance requirements also constrain engine spark timing within a certain region, called feasible spark timing region. For certain operational conditions, it is desirable to operate the engine at the borderline of the feasible region continuously. For instance, under certain operational conditions engine MBT timing is located outside of the feasible spark-timing region due to the requirement to avoid engine knock. In order to obtain maximum brake torque, it is required to operate the engine at its knock limit or advanced limit of the feasible region. Similarly, in order to reduce cold start Hydro-Carbon (HC) emissions it is desired to locate the spark timing at the retard limit of the feasible region for fast catalyst light up while maintaining a certain level of combustion stability.

Due to the low signal-to-noise ratio of existing (accelerometer based) knock sensors, a dual-rate count-up/down scheme is used for engine knock limit control. Conventional approaches are based upon use of a single knock flag obtained by comparing the knock intensity signal of a knock sensor to a given threshold. The knock intensity signal is defined as the integrated value, over a given knock window, of the absolute value signal obtained by filtering the raw knock sensor signal using a band-pass filter. The disadvantage of this control scheme is that it continually takes the engine in and out of knock, rather than operating continually at the desired point. In addition at certain operating points knock observability can be severely compromised by engine mechanical noises such as valve closures and piston slap which may be picked up by the accelerometer. Such issues result in conservative ignition timing that leads to reduced engine performance.

The high quality of an in-cylinder ionization signal makes it possible to derive a linear knock intensity that is proportional the knock level (see [6], [7], and [8]). Further, the cycle-to-cycle variations in the combustion process results in an ionization knock intensity signal that is similar to a random process when the engine is operated at knock conditions. This makes it difficult to use an existing (deterministic) limit control scheme to find true knock borderline ignition timing and operate the engine at this corresponding timing smoothly.

As mentioned before, during cold start, it is desirable to operate the engine at its retard spark-timing limit for minimal HC emissions. The retard spark-timing limit is often constrained by an engine combustion stability metric such as COVariance of IMEP (Indicated Mean Effective Pressure). Due to unavailability of production ready in-cylinder pressure sensors, the retard spark-timing limit is obtained through engine mapping process, leading to

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conservative calibrations. The in-cylinder ionization signals can be processed to derive a metric for combustion quality similar to COV of IMEP and closeness of combustion to partial burn/misfire limit (see [9]), which can be used to provide a limiting value for the baseline ignition timing in the retard direction.

For both knock avoidance and catalyst fast light up during cold start, it is required to operate the engine at its borderline of the feasible ignition region continuously. Due to combustion cycle-to-cycle variations, the feedback signal (for example, knock intensity for advanced spark timing limit control) exhibits stochastic characteristics; the existing deterministic limit control strategies (such as count-up/count down strategy for knock control) are not able to smoothly operate the engine spark timing at the borderline of its region continuously. This paper presents a stochastic ignition limit control strategy utilizing the stochastic properties of the feedback signals, and demonstrates that the proposed control system is able to operate the engine at its spark limit despite the cycle-to-cycle combustion variability and inherent ionization signal variations owing to that stochastic nature.

The paper is organized as follows. In Section II we develop a simple nonlinear stochastic model suitable for spark timing limit control development. Section III proposes the stochastic limit controller architecture and evaluates the proposed stochastic controller, along with the conventional deterministic controllers, using the simple nonlinear stochastic model developed in Section II. The application of proposed stochastic limit controller to a 3.0L V6 engine to both knock (advanced) spark limit and cold start (retard) spark limit controls are described in both Sections IV and V respectively. Section VI adds some conclusions.

II. A Stochastic Plant Model

A typical ionization signal is shown in Figure 1. Following ignition phase it usually consists of two peaks. The first peak of the ionization signal represents the flame kernel growth and development, and the second peak is the re-ionization due to the in-cylinder temperature increase resulted from both pressure increase and flame development in the cylinder.

A combustion stability metric can be calculated as follows. The ionization signal is integrated over a user specified integration window; see Figure 1, and the crank angle at which the ionization integral reaches a calibratable percentage (for example, 90%) of the total integrated area is defined as the integration location, see [9] for details. This parameter has very high correlation to IMEP. The normalized ionization integral is also shown in Figure 1. Note that, 100% integration location is ideally reached when the ionization signal completely dies-out. A percentage close to 100 is used to approximately locate the crank location after which the ionization signal strength (combustion activity) is minimal.

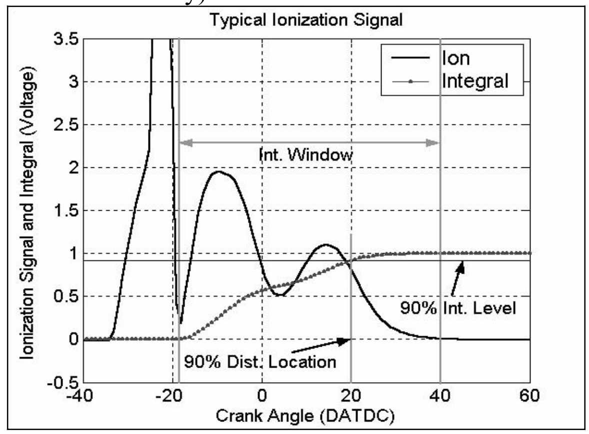

Figure 1: Ionization signal and integration location

Figure 2 shows the stochastic properties of the 90% integration location at spark timing -21 Degrees After Top Dead Center (DATDC). At each firing event, the ionization signal is processed to obtain the integration location number for that particular combustion. 300 cycles (number of consecutive firing events at the same spark timing) of data are used to create the PDF (Probability Density Function) or histogram of the integration location, where the solid line is the Gaussian fit of PDF.

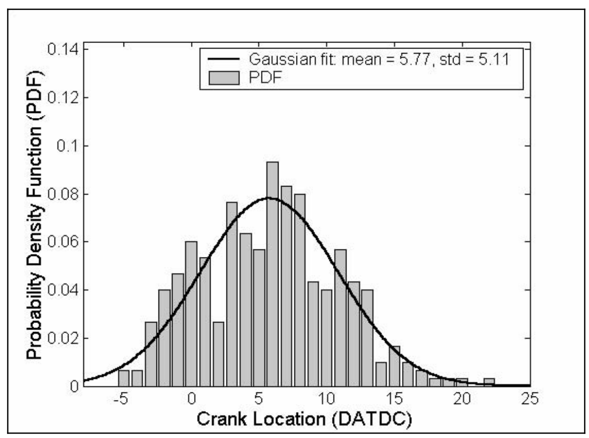

Figure 2: Ion integration location PDF

Based on the PDF shown in Figure 2, the combustion cycle-to-cycle variations and statistics of the ionization integration locations seem to match a Gaussian random process. As the spark timing gets retarded, PDF of integration location starts skewing towards the retard direction, see [9] for details. But more importantly, at the spark timing with a desired combustion stability level, the PDFs can be approximated by a Gaussian random process. That is the motivation to generate a stochastic model of integration location for control design purposes.

The stochastic properties of the ionization integration locations during a spark sweep at 1500 RPM and 2.62 bar BMEP (Brake specific Mean Effective Pressure) are shown in Figure 3, where stars represent the test data and the solid lines are fitted curves using polynomials. A 3.0L V6 engine was used to generate data shown in Figure 3. Assuming that for a given spark timing, the PDF can be approximated by a Gaussian random process, integration location can be modeled as the following:

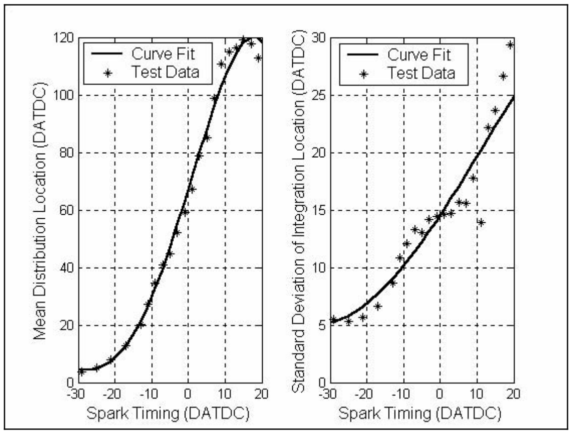

Figure 3: Mean and standard deviation of integration locations

$$\begin{aligned} x_{ST}(k+1) &= a(N)x_{ST}(k)+[1-a(N)]u_{ST}(k) \\ x_{ET}(k+1) &= b(N)x_{ET}(k)+[1-b(N)]u_{ET}(k) \\ x_{ID}(k) &= x_{ST}(k)+x_{ET}(k) \\ y_{ID}(k) &= PM_{ID}[x_{ID}(k)]+PS_{ID}[x_{ST}(k)]w(k) \end{aligned} \quad (1)$$

where u_{ST} and u_{ET} are engine spark timing and engine coolant temperature, *a(N)* and *b(N)* are first order dynamic coefficients as a function of engine speed *N*, states x_{ST} and x_{ET} are corrected spark timings corresponding to u_{ST} and u_{ET} respectively, x_{ID} is effective engine spark timing, projections PM_{ID} and PS_{ID} (defined in Figure 3) map the effective spark timing to corresponding mean value and standard deviation of the integration locations respectively, *w* is a zero-mean unit-standard-deviation Gaussian process and finally, y_{ID} is the modeled integration location output. The model described in Equation (1) has been implemented in Simulink and simulation results show that the modeled integration location is a Gaussian random process with its mean and standard deviation defined in Figure 3.

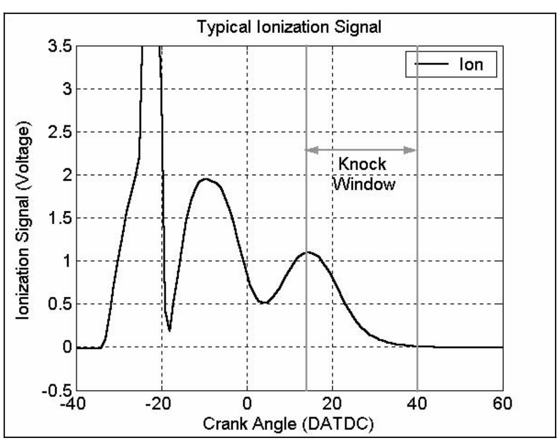

Figure 4: Knock detection window

Under conditions that result in knock, an IC engine knock intensity signal can be obtained using in-cylinder ionization signals (see [6], [7], and [8]). Knock intensity is defined as an integrated value, over a given knock window (defined in Figure 4), of the absolute value signal obtained by filtering the raw ionization sensor signal using a band-pass filter. Figure 5 shows a PDF of knock intensity signal obtained from ionization signal. The engine is operated at 1000 RPM with WOT (Wide Open Throttle). The spark timing is at -18 DATDC. Comparing the PDF drawings of Figure 2 and Figure 5, the knock intensity PDF histogram is not symmetric and it is obvious that a Gaussian random process cannot approximate it.

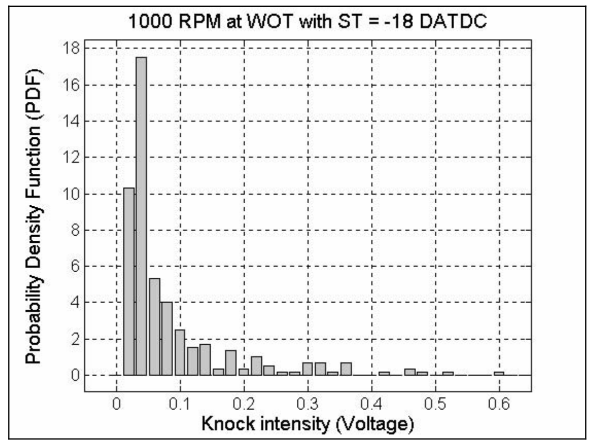

Figure 5: Knock intensity PDF

In order to be able to use the Gaussian random process to model the knock PDF, consider the nonlinear map described in Figure 6. This nonlinear map translates the symmetric Gaussian PDF into the knock PDF shown in Figure 5 by compressing the left axis of the Gaussian PDF. With the help of the nonlinear mapping described in Figure 6, the knock intensity signal can be modeled using the following dynamic model:

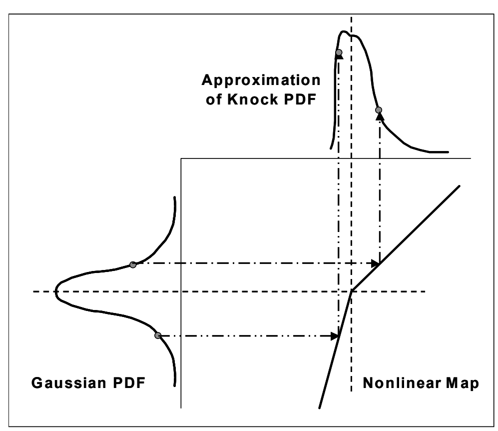

Figure 6: Mapping from Gaussian to knock PDF

$$
\begin{aligned}
x_{ST}(k+1) &= a(N)x_{ST}(k)+[1-a(N)]u_{ST}(k) \\
x_{ET}(k+1) &= b(N)x_{ET}(k)+[1-b(N)]u_{ET}(k) \\
x_{KI}(k) &= x_{ST}(k)+x_{ET}(k) \\
y_{KI}(k) &= PM_{KI}[x_{KI}(k)]+PS_{KI}[x_{ST}(k)]\cdot P_{KI}[w(k)]
\end{aligned} \tag{2}
$$

where u_{ST}, u_{ET}, $a(N)$, $b(N)$, N, x_{ST}, x_{ET} and w have the same definition as Equation (1), x_{KI} is effective engine spark timing, PM_{KI} and PS_{KI} are nonlinear mapping defined by knock intensity mean and standard deviation shown in Figure 7, P_{KI} is the nonlinear map defined in Figure 6 and finally, y_{KI} is the modeled knock intensity output.

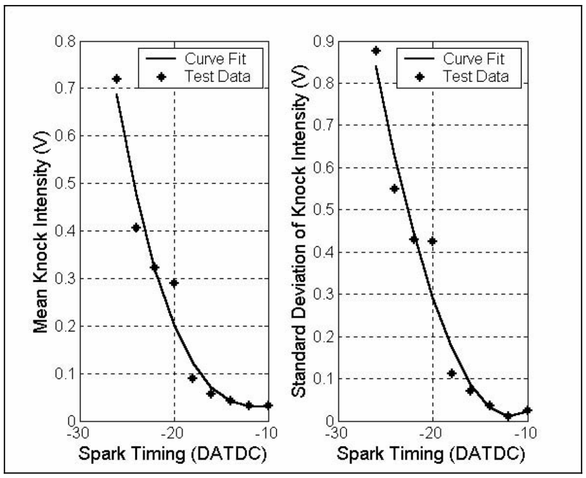

Figure 7: Mean and standard deviation of knock intensity

Figure 8 shows the knock intensity signal and its PDF simulated by the model defined in Equation (2). The simulated operational condition is 1500 RPM at WOT with ignition timing at -20 DATDC. Although the PDF shape shown in Figure 8 does not match with the one in Figure 5 exactly, we believe it is close enough for evaluating closed loop knock controllers. The nonlinear map defined in Figure 6 can be further improved to make the simulated PDF close to the actual one shown in Figure 5, which is not the subject of this paper.

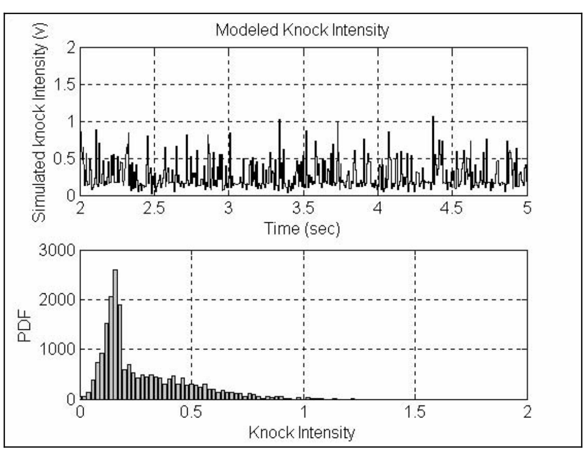

Figure 8: Modeled knock intensity and its PDF

III. Stochastic Limit Control

As described in the Introduction section, a conventional knock controller uses count-up/down logic, which can be described in the following equation. The purpose of knock control is to hold engine knock intensity below the desired level.

$$
\begin{aligned}
e_{KI}(k) &= y_{DESIRED}(k)-y_{KI}(k) \\
u_{ST}(k+1) &= \begin{cases} u_{ST}(k)+gn_{UP}, & if\ e_{KI}(k)\geq 0 \\ u_{ST}(k)+gn_{DOWN}, & if\ e_{KI}(k)<0 \end{cases}
\end{aligned} \tag{3}
$$

where $y_{DESIRED}$ and y_{KI} are desired knock intensity level and feedback knock intensity level respectively, u_{ST} is the control command (spark timing) and gn_{UP} and gn_{DOWN} are count-up/down gains. For this simulation, gn_{UP} and gn_{DOWN} are -0.1 and +3 respectively. That is, if the actual knock intensity is below the desired level, advance the ignition timing at 0.1 crank degree increment rate and if the actual knock intensity is beyond desired level, retard the ignition timing at the 3 degrees decrement rate.

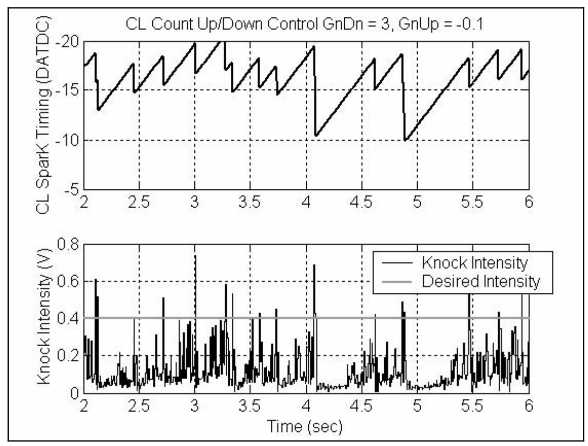

Figure 9: Count-up/down control results

Figure 9 shows the simulation results using count-up/down controller specified in Equation (3). It is obvious that the count-up/down control is not able to keep the actual knock intensity below the desired level and as a byproduct the engine ignition timing varies between -10 to -20 DATDC, leading to large variation of engine torque output. The nominal variation is about 5 degrees, a value typically observed in practice. After studying the simulation results, it may be concluded that any deterministic controller, without utilizing the stochastic information of the feedback signals (such as knock intensity and combustion stability metric) is not able to operate the engine smoothly at the borderline of its feasible spark region. This leads to the proposed stochastic limit control strategy discussed next.

The architecture of the proposed stochastic limit management system is shown in Figure 10. The ionization feedback signals of all cylinders are fed into the signal conditioning circuit, and signals are merged. The conditioning signal is then sampled and processed to determine a stochastic limit feedback parameter. The further details of the set-up can also be found in [4], [5], and [8].

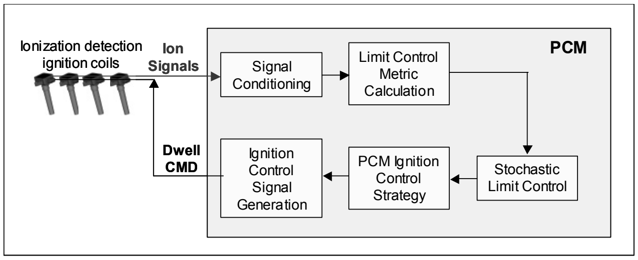

Figure 10: CL Stochastic limit control system architecture

Figure 11 shows the architecture of the proposed closed-loop stochastic limit controller. It's a part of an overall spark controller, which manages the spark timing for best fuel economy, power and emissions by employing a closed loop MBT timing strategy [8]. For the ionization feedback system, the ionization signal from each cylinder is sampled and saved in a buffer at each combustion event. The overall spark control is triggered at every firing event and stochastic limit control processes the ionization signal from the most recent combustion event to generate feedback parameters (such as knock intensity and combustion stability metric) for the stochastic limit control. The objective of stochastic limit controller is to provide a spark timing limit for the overall spark controller to avoid engine knock or to assure combustion stability.

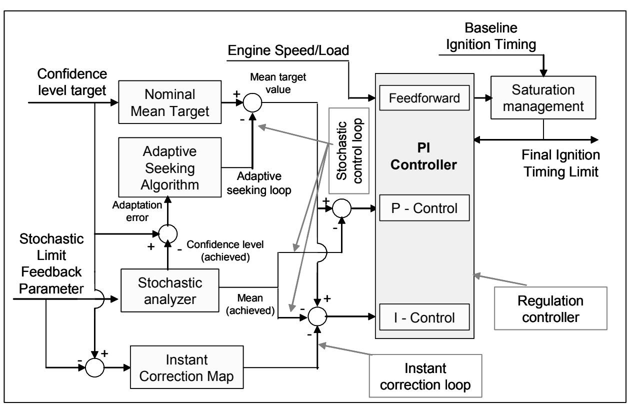

Figure 11: Closed-loop stochastic limit controller

The key part of the proposed limit controller is the stochastic analyzer block. The derived stochastic ionization feedback parameters obtained from each firing cycle are computed from a buffer of a user-selected size. Basically, the mean, standard deviation and PDF of data are constantly updated at the end of each combustion event. Using the PDF, an achieved user-specified percentage *confidence level* number is also computed. For the knock intensity feedback signal, this number is defined as follows: saying 90% confidence level for knock intensity is 0.4 volt means that for the 90% of the combustion events in the buffer, the measured knock intensity is below 0.4 volt. In case of combustion stability measure the definition can be found in [9].

Three main feedback actions are proposed in the stochastic limit controller. Their functionalities are listed below:

***Regulation controller for stochastic feedback*:** The regulation loop is used to regulate the mean value of the stochastic limit feedback parameter to a mean target value. The regulation controller is structured as a PI controller with a feed-forward term based on engine operating conditions. Despite the variability of the stochastic limit feedback, its mean value is a well-behaved signal for regulation purposes. The regulation controller is tuned to provide the desired settling time and steady-state accuracy for the response.

Adaptive seeking feedback: The purpose of this loop is two-fold: reducing the calibration conservativeness by providing the engine with its "TRUE" ignition timing limit target and improving robustness of stochastic limit controller when the engine operates under different conditions. This is accomplished by using an error signal between the desired confidence level target and the achieved one. Note that the confidence level is a second-order property of PDF like variance. The adaptive seeking algorithm reduces the mean target for the regulation controller if the confidence number is greater than the specified; otherwise, increase the mean target value.

Instant correction feedback: This block calculates an instant correction signal to be fed into the integration portion of PI controller. When the error between confidence level target and stochastic limit feedback parameter is greater than zero, the output is zero. That is, no correction is required, and when the error is less than zero, the error is fed into a one dimensional lookup table that outputs an instant correction for the integration portion of the PI controller.

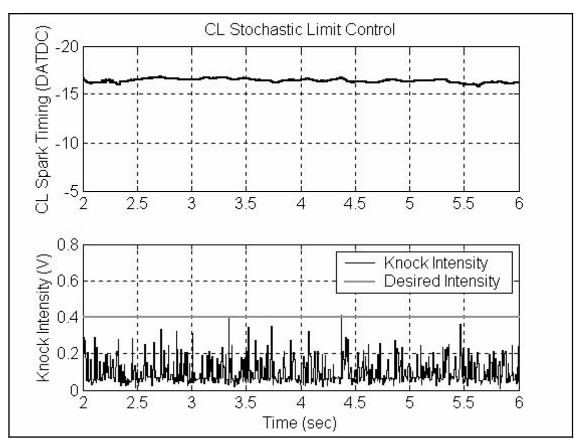

Figure 12: Stochastic limit control results

The interaction of the stochastic knock limit controller with the overall spark controller is as follows: If the baseline spark is more retarded than the current knock (advanced) limit, then the baseline spark is used as it is. In that case, the knock limit controller pushes the limit in the maximum advanced direction by itself. This is due to the fact that the integration keeps integrating till the maximum advanced allowed is reached (an anti-windup scheme is used) as it was designed. If the baseline spark controller pushes the ignition timing to a level at which the feedback signals generate corrections, the advanced limit moves from its maximum limit to a new level as a variable saturation limit on the baseline spark. On the other hand, if the baseline controller still tends to push the spark in the advanced direction, the seeking and instant correction actions of the advanced controller will adjust the advanced limit online.

Figure 12 shows simulation results of closed loop knock limit control using the proposed stochastic limit control strategy shown in Figure 11. It is clear that the knock intensity stays below the desired knock intensity level, and the spark timing limit stays close to constant level instead of varying at certain range.

IV. Application to Retard Limit Control

During engine start-up operations, rapid catalyst light-off control strategy is required and it is often achieved by maximally delaying the combustion as long as misfire and partial-burn are avoided. This strategy reduces cold-start HC emissions by reducing the time required for the catalyst to reach its light-off temperature. The closed loop nature of the system provides maximum usage of the possible spark timing range in the retard direction at any given operating condition.

Using an engine ignition control system, the benefits to cold start HC emissions are two-fold. During normal operating conditions, if the baseline ignition strategy tends to push the spark timing to a level where the combustion variability is not acceptable, the ignition can be limited in the retard direction for satisfactory combustion stability level. Secondly, the retard limit is continually adjusted by monitoring the combustion stability level through the in-cylinder ionization signals, and this allows future online spark timing optimization to eliminate a one-fits-all value or map.

During engine warm-up process, the stochastic retard limit manager seeks the maximum retard spark timing possible while assuring that misfire and partial-burn are avoided with the objective of increasing the catalyst temperature rapidly. Delaying the combustion through high values of spark retard can shorten the time that it takes the catalyst to reach its light-off temperature. Therefore, the conventional three-way catalyst becomes effective much sooner in reducing tail-pipe emissions ([10], [11], and [12]). However, if the ignition retard is too much, engine-out HC emissions become excessive due to incomplete combustion (partial-burn) as well as misfire. An open loop retard calibration needs to provide enough margin to avoid misfire under all conditions and with all fuels. It therefore is inherently conservative. On the other hand, a real time retard limit indicator as part of a closed loop strategy alleviates this conservatism by further being able to push the spark timing in the retard direction if things are favorable. That way, the catalyst light-off time is minimized and the tail-pipe emissions can be reduced.

The ideal action of the stochastic retard limit controller can be explained as follows: suppose that we want to make sure that the integration location will not go beyond 90 DATDC. This location is then the desired confidence level target. Using the standard deviation of the measured data, one can back-calculate a nominal target for the regulation controller by subtracting a certain multiple of the standard deviation of the measured data in the buffer. That initial mean target is then increased by the adaptive seeking loop slowly if the resulting, say 90%, confidence level number computed from the measured data is less than desired confidence level target of 90 DATDC. That way, if the initial mean target was too conservative; i.e., the worst-case integration location is well below 90 DATDC, then the mean target will be increased. On the other hand, the instant correction feedback acts as a safety since whenever the feedback goes beyond 90 DATDC it will instantaneously advance the retard limit. Then the seeking will start again to push the retard limit as long as the things are favorable. Since the mean and stochastic properties are used as feedback signals, the controller will not react aggressively to each combustion variation, which would be the case if the feedback signal from each cycle were used directly.

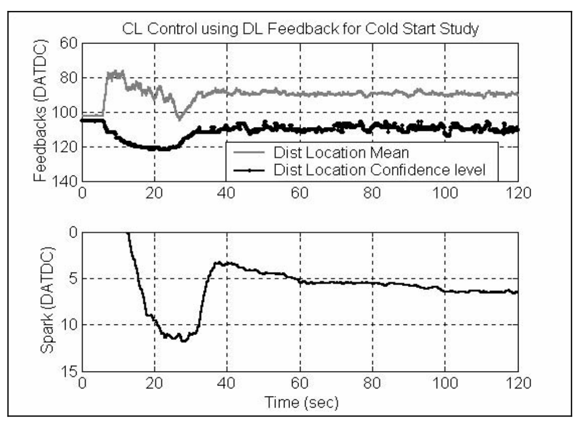

Figure 13: Control for cold start run-up

To illustrate the performance of the retard limit controller, some preliminary dyno test results have been included in Figure 13 and Figure 14. The stochastic analyzer block and the regulation/adaptive seeking loops were tested at several fixed operating points. The main emphasis so far was given to the evaluation of the control features rather than demonstrating its projected benefits. A 3.0L, V6 engine equipped with ionization feedback coils was used for these experiments.

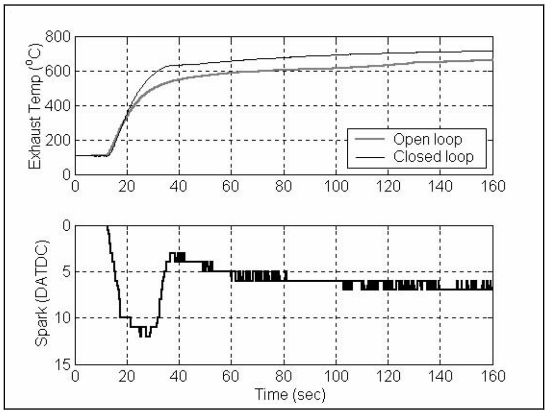

Figure 14: Temperature versus controlled ignition retard

Figure 13 and Figure 14 show responses from a cold-start run. For this case, the ionization integration location parameter was used as the feedback signal and the control was activated with all features. The confidence level was also included in Figure 13 as a performance measure. Note that it was kept around 110 DATDC at the steady state and did not exceed 124 DATDC, which was the exhaust valve opening timing for the particular engine tested. Therefore, combustion was over before the exhaust valves were opened and the controlled high retard timing was safe in terms of HC emissions. Figure 14 demonstrates the corresponding fast exhaust temperature rise-up during the run. An open loop temperature profile was also included in Figure 14 to show the improved temperature rise-time with the proposed control. For the open loop case, the ignition timing was held at TDC (Top Dead Center), which was the initial ignition timing for the closed loop controller. Based on Figure 14, the time that takes the exhaust temperature to reach 500 ^oC was reduced to 12 seconds from 18 seconds with the closed loop controller.

V. Application to Knock Limit Control

Before discussing closed loop control of knock limit, knock controllability, using ionization knock intensity feedback, is studied. As described in Section III, the stochastic limit control strategy utilizes the mean and standard deviation information of the ionization knock intensity signal as well as the evolution of its stochastic distribution. Due to the high-resolution knock intensity signal obtained from in-cylinder ionization signals, both mean and standard deviation of the knock intensity signal show high correlation to engine spark timing, see Figure 15. When the engine spark timing varies from –10 DATDC to –26 DATDC, both mean and standard deviation increase. This demonstrates good controllability using the knock intensity obtained from ionization signals. The mean and standard deviation data was obtained from a 3.0L V6 engine operated at 1000 RPM with WOT. The mean and standard deviation data is processed using 300 cycle ionization data. Similar results are obtained over the whole speed and load range of the engine.

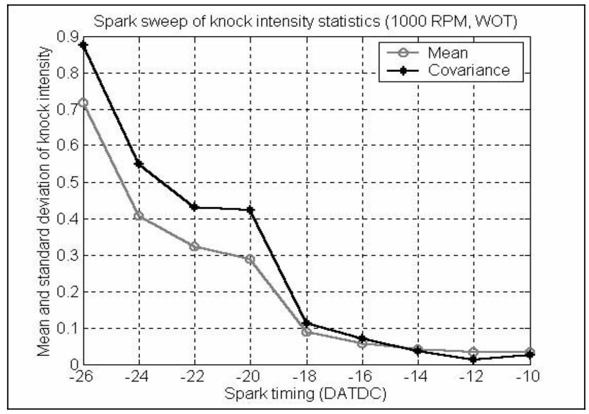

Figure 15: Knock intensity statistics

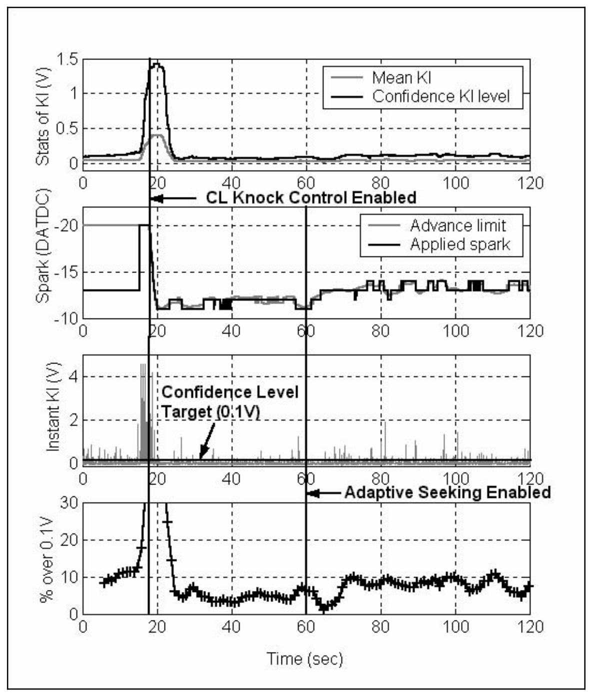

Figure 16: CL knock limit control

The architecture of the knock limit control is similar to the retard case. The closed loop control results of Knock Intensity (KI) distribution control, using the proposed stochastic limit control, are shown in Figure 16, where the top plot shows both actual mean knock intensity and confidence level knock intensity; the second plot from top shows spark advance limit and actual spark timing; the third shows the instantaneous knock intensity signal and the target confidence level knock intensity at 0.1 volt; and the bottom plot shows the percentage of KI over the 0.1 volt threshold. During the first 18 seconds, the closed loop knock limit control is not active, baseline spark timing starts at around –13 DATDC and the knock intensity mean is relatively low (around 0.1 volt). At the 16^{th} second, the baseline spark timing is manually advanced to –20 DATDC and mean and confidence level knock intensity increases to over 0.40 volt and 1.4 volt respectively right before the closed loop knock limit control is activated. After the knock limit control is enabled at 18th second, knock intensity is reduced to desired knock intensity level and the advanced limit, generated by the closed loop knock limit controller, moves back to –13 DATDC. Note that the advanced spark is digitized from the advanced limit with one-degree resolution due to the control hardware limitations. Between the 18th and 60th second, the bottom plot shows that there is about 5% of the actual knock intensity staying beyond 0.1volt confidence level target. At the 60th second, the adaptive seeking algorithm is enabled with a 90% actual confidence level target, and the KI percentage over 0.1 volt target increases to around 10% (or 90% confidence level). The spark timing is further advanced to between –14 and -13 DATDC.

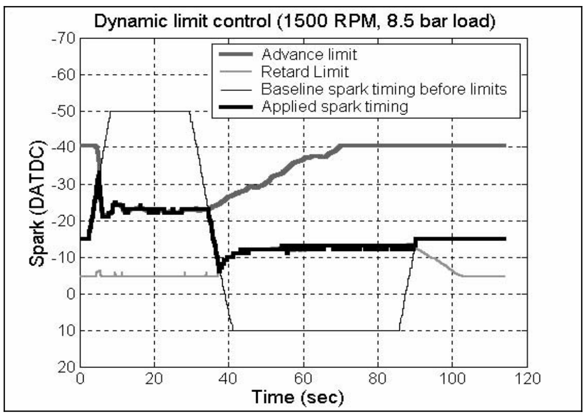

Figure 17: CL advanced and retard limit control

Figure 17 shows the test results of the combined advance and retard limit control. The thin dark line is the engine baseline spark timing starting at –15 DATDC. Since the engine is neither knock limited nor retard limited, both advance (heavy gray) and retard (thin gray) limit stay at their maximum levels (-40 DATDC for advanced limit and -5 DATDC for retard limit). When the baseline spark timing moves at the advanced direction and causes engine knocking, the advanced limit reduces due to the closed loop knock limit control, the baseline spark timing is limited to about –23 DATDC and the retard spark limit stays at its maximum retard limit (-5 DATDC). At 30th second, the baseline spark timing starts moving in the retard direction. At about 38th second, the retard limit control moves the retard limit in the advanced direction due to reduced the combustion stability and the retard spark timing stabilizes at about –12 DATDC while the knock limit controller moves the advanced limit to its maximum at –40 DATDC. This plot demonstrates both steady state and transitional control utilizing both knock advanced limit control and combustion stability retard limit control.

VI. Conclusion

A stochastic closed loop spark timing limit management system is proposed in this paper. A simple nonlinear dynamic model was developed to study stochastic nature of the spark limit control feedback signals: knock intensity and combustion stability. Simulation results show that the conventional deterministic spark limit control techniques are not able to operate an IC engine at its spark limit smoothly. With the proposed stochastic spark limit control strategy, utilizing stochastic information of the feedback signals, the control can seek, maintain and limit the spark timing at a desired user-specified level of knock intensity or combustion quality using the feedback signal derived from in-cylinder ionization signals. The proposed limit control system also utilizes an adaptive control architecture. The stochastic limit control strategy is successfully applied to both closed loop knock (advanced) limit and combustion stability (retard) limit control using in-cylinder ionization feedback signals. The system is currently being evaluated in terms of its projected benefits on combustion quality, cold start emission reductions, and knock control quality.

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