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MICROPHONES AND KNOCK SENSORS FOR FEEDBACK CONTROL OF HCCI ENGINES

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ABSTRACT

Homogeneous charge compression ignition (HCCI) engines lack direct in-cylinder mechanisms, such as spark plugs or direct fuel injection, for controlling the combustion timing. Many indirect methods have been used to control the combustion timing in an HCCI engine. With any indirect method, it is important to have a measure of the combustion timing so the control inputs can be adjusted for the next cycle.

In this paper, it is shown that microphones and knock sensors can be used to detect combustion in HCCI engines. The output from various microphones and a knock sensor on an HCCI engine are measured at light and high loads. The combustion timing data obtained from the sensors are compared to the combustion timing data obtained from a piezoelectric cylinder pressure transducer. One of these sensors is selected and used for closed-loop control of the combustion timing in a single cylinder HCCI engine.

NOMENCLATURE

ACF autocorrelation function
ARMA(p,q) p-order auto-regressive, q-order moving average model
C degrees Celsius
CA50 engine crank position in CAD at 50% heat release
CAD crank angle degrees
HCCI homogeneous charge compression ignition
$\hat{\mu}$ sample mean
∇ differencing operator, $\nabla Y_t = Y_t - Y_{t-1}$
P_t predicted (at engine position t) value of a series
ϕ fuel-air equivalence ratio
PID proportional-integral-derivative control law
RPM revolutions per minute
SI spark-ignited
TDC top-dead-center of the compression stroke
V voltage
Y_t time t values of data series
WN(μ,σ^2) normally-distributed white noise process with mean μ and variance σ^2
Z_t white noise, normally-distributed series

INTRODUCTION

The Homogeneous Charge Compression Ignition (HCCI) engine has received renewed interest in recent years. In the past decade, several hundred papers have been published, largely in the literature of the Society of Automotive Engineers. A recent publication by Zhao (2003) reviews much of this literature [1]. HCCI engines have features of both spark ignited (SI) and Diesel

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engines. Like SI engines, HCCI engines are generally premixed and operate lean ($\phi < 0.5$) thus they produce very low oxides of nitrogen (NOx) and particulate emissions (PM). Yet, HCCI engines typically have high compression ratios and thus high efficiencies, similar to those found in Diesel engines. In a SI engine, the combustion event is initiated by a spark and the spark timing is routinely adjusted. Similarly, the combustion event in a Diesel engine is initiated by injection of the Diesel fuel. The injection time and duration is variable. The HCCI engine does not have direct in-cylinder mechanisms, such as spark plugs or direct fuel injection, for controlling the combustion timing.

Many indirect methods have been used to control the combustion timing in an HCCI engine [1]. These include intake air heating, variable valve timing, and intake or exhaust throttling. With any indirect method, it is important to have a measure of the combustion timing so the control inputs can be adjusted for the next cycle. In a research environment, piezoelectric pressure transducers provide cylinder pressure data which are used to calculate [2, 8] the combustion timing. The transducers are expensive, however, prohibiting their use in practical implementations.

Some of the methods used for detecting knock in SI engines might be used for detecting the combustion timing in an HCCI engine. Wavelet transforms have been used with knock sensors to detect knock in SI engines [3]. A combination of cylinder pressure, engine block vibration, and sound pressure has been used to detect knock in SI engines [4]. The speed and acceleration of the crankshaft has been used to estimate the cylinder pressure [5]. Recently, an ion signal has been detected and used as a measure of combustion timing for an HCCI engine [6, 7].

In this paper, it is shown that microphones and knock sensors can be used to detect combustion in HCCI engines. The output from various microphones and a knock sensor on an HCCI engine are measured at light and high loads. Time series techniques are used to analyze the data. The combustion timing data obtained from the sensors are compared to the data obtained from a piezoelectric cylinder pressure transducer. One of the sensors with a high signal-to-noise ratio is selected and used for closed-loop control of the combustion timing in a single cylinder HCCI engine.

Table 1. CATERPILLAR 3401 SPECIFICATIONS.

Configuration	single cylinder
Displacement (L)	2.44
Compression ratio	16.25
Bore (mm)	137.185
Stroke (mm)	165.108
Connecting rod length (mm)	261.62

Table 2. MICROPHONE AND KNOCK SENSOR SPECIFICATIONS.

Ref. No.	Sensor Specifications	Sensor Mounting
A	Panasonic WM61A omni-directional electret condenser microphone	recessed in hole
B	Panasonic WM55D103 noise-canceling electret condenser microphone	recessed in hole
C	Panasonic WM55A103 unidirectional electret condenser microphone	recessed in hole
D	Panasonic WM55D103 noise-canceling electret condenser microphone	top of cyl. head
E	Panasonic WM55A103 unidirectional electret condenser microphone	top of cyl. head
F	Bosch, spark-ignition engine knock sensor	bolted to head

EXPERIMENTAL TEST SETUP

The experiments are performed on a single cylinder Caterpillar 3401. The engine specifications are given in Tab. 1. A variety of microphones and a knock sensor are installed on the engine. Table 2 gives the specifications for the microphones and knock sensor. Some of the microphones are recessed in unused bolt holes in the side of the cylinder head, while others are epoxyed directly to the top of the head. The knock sensor is bolted to the side of the cylinder head. Figure 1 shows the installation of the microphones on the engine.

The output from the microphones is fed to a signal conditioning circuit and then to a laboratory-grade preamplifier. The knock sensor output is fed directly to the data acquisition equipment. Cylinder pressure data is obtained from an AVL piezoelectric pressure transducer. The cylinder pressure and the corresponding sensor (from Tab. 2) signal are gathered simultaneously at 0.1 CAD intervals. The engine speed is fixed at 1800 RPM, and pump-grade gasoline (87 octane) is used as the fuel. The intake air is preheated to 110C, and the fuel flow rate is varied to give equivalence ratios of $\phi = 0.26$, $\phi = 0.29$, and $\phi = 0.32$. The intake air pressure is fixed at 1.7 bar. Injectors introduce the fuel to the intake air 1 meter upstream of the engine to insure adequate fuel-air mixing.

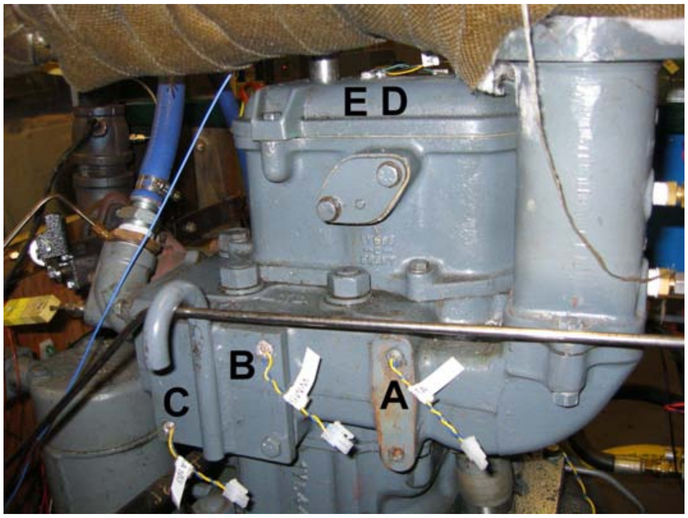

Figure 1. THE MICROPHONES ON THE CATERPILLAR 3401.

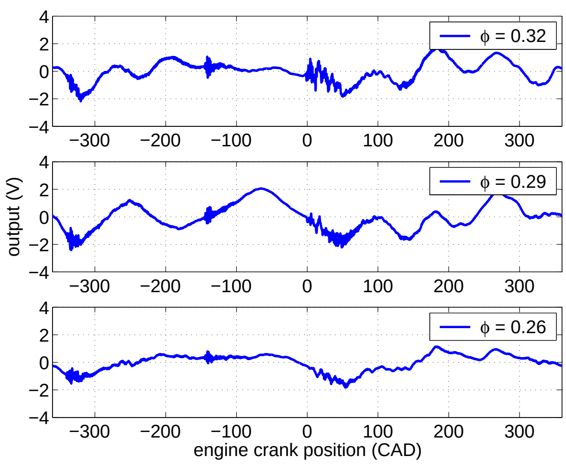

Figure 2. SENSOR A OUTPUT.

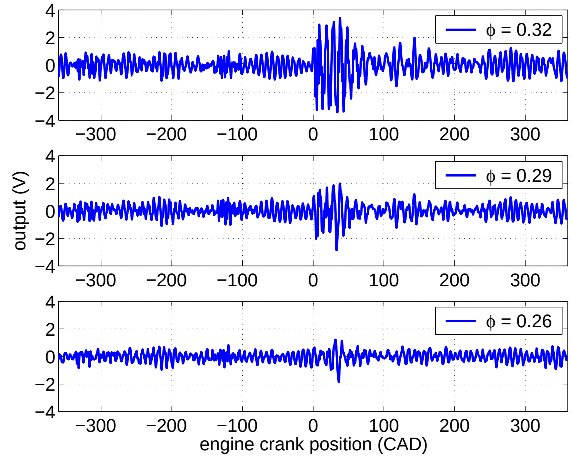

Figure 3. SENSOR B OUTPUT.

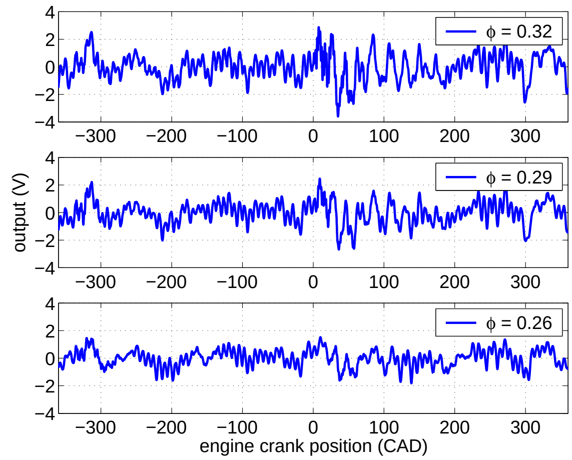

Figure 4. SENSOR C OUTPUT.

SENSOR DATA

The 50 cycle-averaged data for the various sensors are shown in Figs. 2- 7. The 50 cycle-averaged cylinder pressure data (collected simultaneously with the sensor A data) are shown in Fig. 8. The cylinder pressure data collected simultaneously with the other sensors are similar and not included here. The individual cycle data show similar trends, though averaging does remove some noise. The combustion timing (CA50), calculated from cylinder pressure data, was held constant at approximately 0 CAD for these experiments.

All of the sensors yield combustion timing information. There is a significant change in the sensor output signal around 0 CAD, or top-dead center of the compression stroke (TDC), when combustion occurs. The combustion timing is more evident at the higher equivalence ratios. At these higher equivalence ratios, the in-cylinder explosion produces an extremely rapid pressure rise which can be detected using microphones or knock sensors. At lower equivalence ratios where the load is reduced, the combustion event signal in the microphone and knock sensor signals is reduced. The maximum rates of pressure rise for the $\phi = 0.32$, $\phi = 0.29$, and $\phi = 0.26$ experiments are approximately 8.5, 6.5, and 2.5 bar/CAD, respectively. Below $\phi = 0.26$ (2.5 bar/CAD), the signal from the microphones and knock sensors is faint.

Comparing the sensor B and sensor D output, or the sensor C and sensor E output, it is clear that the sensors mounted on top of the cylinder head exhibit a higher signal-to-noise ratio than those mounted in recessed holes on the cylinder head.

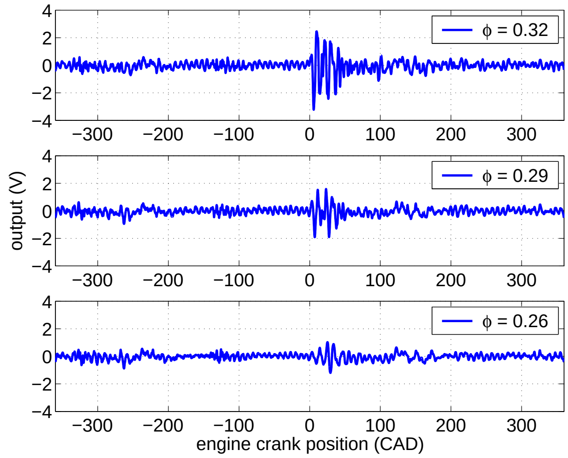

Figure 5. SENSOR D OUTPUT.

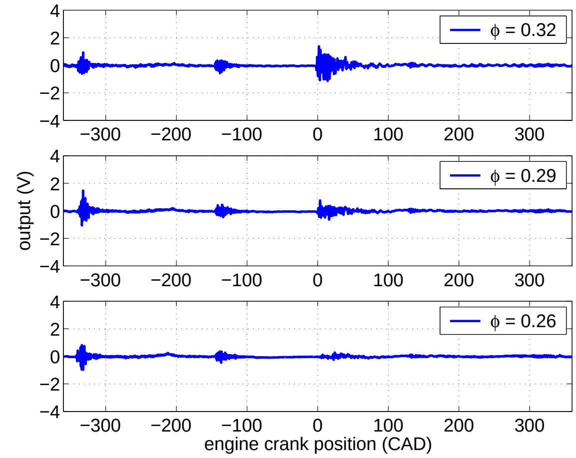

Figure 7. SENSOR F OUTPUT.

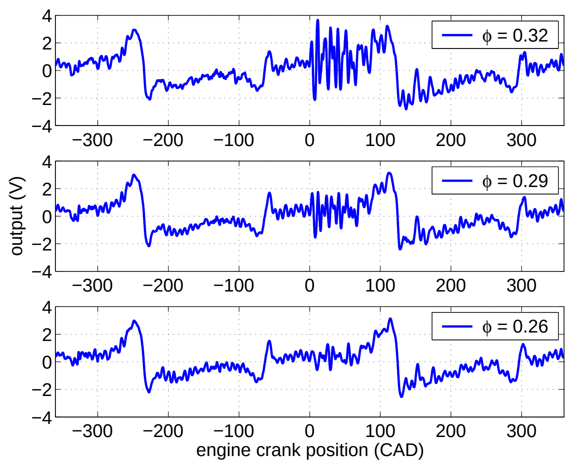

Figure 6. SENSOR E OUTPUT.

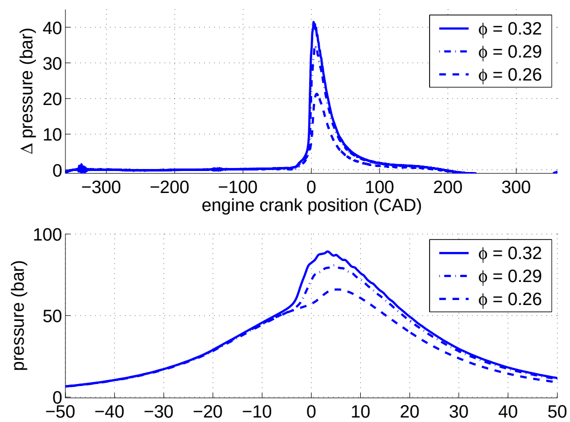

Figure 8. Δ CYLINDER PRESSURE = CYLINDER - MOTORING PRESSURE; EXPLODED VIEW OF CYLINDER PRESSURE NEAR TDC.

Before the microphone or knock sensor output can be used in a feedback control system, the combustion timing information must be understood. A procedure is demonstrated for sensor A when the intake air temperature is fixed at $T = 110C$ and $\phi = 0.32$. The 50 cycle-averaged data for this operating condition is shown in Fig. 2. A similar approach can be used for sensors B-F.

ISOLATING THE PRE-COMBUSTION DATA

The search for combustion timing information should be performed over a narrow region around TDC. However, before defining this region, it is important to quantify any signal delays between the reference combustion timing obtained from cylinder pressure transducers and the combustion timing obtained from the microphones and knock sensor. The region used here is a conservative 45 CAD before TDC to 45 CAD after TDC. Figure 9 shows the narrow region from sensor A for a single cycle.

The method used for detecting combustion timing information involves fitting a model to the pre-combustion data. The reference combustion timing, calculated from the cylinder pressure data, is used to determine the pre-combustion region. The model is used along with confidence bounds to determine the time at which combustion occurs. The combustion timing is estimated as the engine crank position t when Y_t exceeds the 1-step confidence bounds established for $P_{t-1}Y_t$, where Y_t is the measured sensor output at time t and $P_{t-1}Y_t$ is the 1-step prediction of Y_t.

The cycle-averaged data is not used for the model development. Averaging data tends to remove noise. A realistic estimate of the noise variance is needed to establish the model confidence bounds. If the crank position averaged data is used, the noise

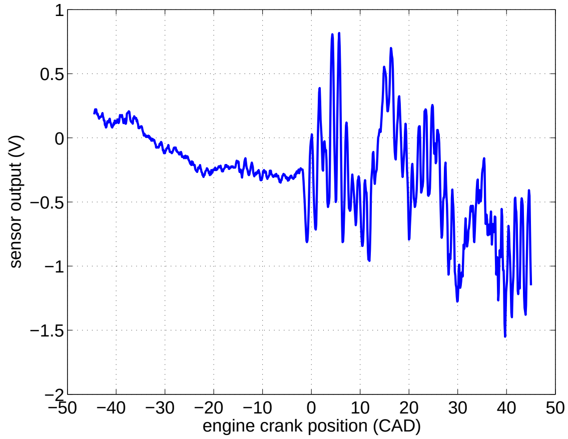

Figure 9. NARROW REGION AT TDC, SENSOR A, SINGLE CYCLE.

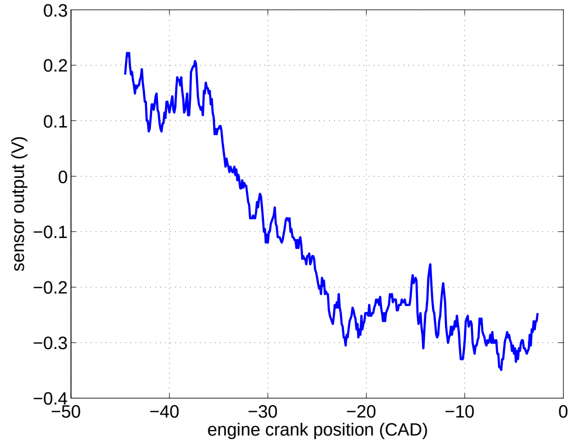

Figure 11. PRE-COMBUSTION DATA Y_t, SENSOR A, SINGLE CYCLE.

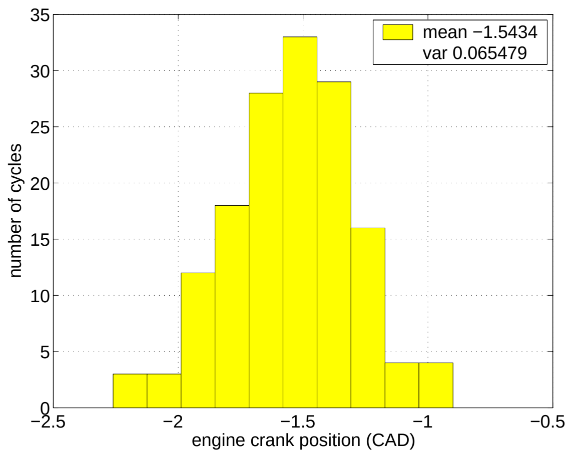

Figure 10. REFERENCE COMBUSTION TIMING (CA50) CALCULATED USING CYLINDER PRESSURE DATA, 150 CYCLES.

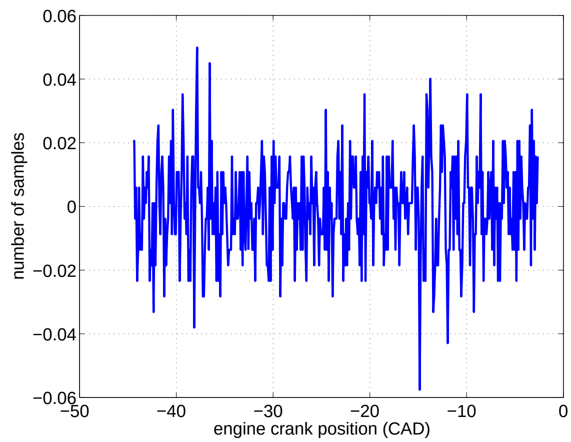

Figure 12. PRE-COMBUSTION STATIONARY SERIES $\nabla Y_t - \hat{\mu}$, SENSOR A, SINGLE CYCLE.

variance will decrease, the model confidence will increase, and the number of false-positive combustion triggers will increase.

A heat-release analysis is performed on the cylinder pressure data [2, 8]. The reference combustion timing is defined as the engine crank position when 50% of the heat is released (CA50). A histogram of the reference combustion timing for 150 cycles is shown in Fig. 10. The data appears to be from a normally-distributed process.

Estimating the combustion timing as normal provides a method for separating the pre-combustion data. Sensor delays can complicate the separation of the post-combustion data, however, since there may be a delay between when the combustion occurs and when it is detected and recorded by the microphones and knock sensor.

Using the histogram shown in Fig. 10, the normal parameters are estimated as $\hat{\mu} = -1.5434$ CAD, $\hat{\sigma} = 0.2559$ CAD. Using these estimates, the reference combustion timing falls in the interval (-2.54, 45.0] CAD with 99.99% certainty. Figure 11 shows the estimated pre-combustion data on the interval [-45, -2.54] CAD for a single experiment with sensor A.

The series in Fig. 11 is not stationary. The data shows a slight linear trend. Differencing the series and subtracting the mean results in the zero-mean, stationary series shown in Fig. 12.

MODELING THE PRE-COMBUSTION SERIES

A histogram of 50 cycles of pre-combustion data is shown in Fig. 13. The data appears to be normally-distributed. A simple model for the pre-combustion data is to treat it as normally-

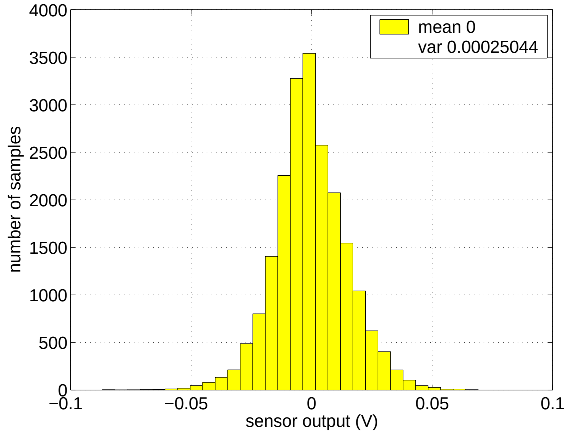

Figure 13. PRE-COMBUSTION STATIONARY SERIES $\nabla Y_t - \hat{\mu}$, SENSOR A, 50 CYCLES.

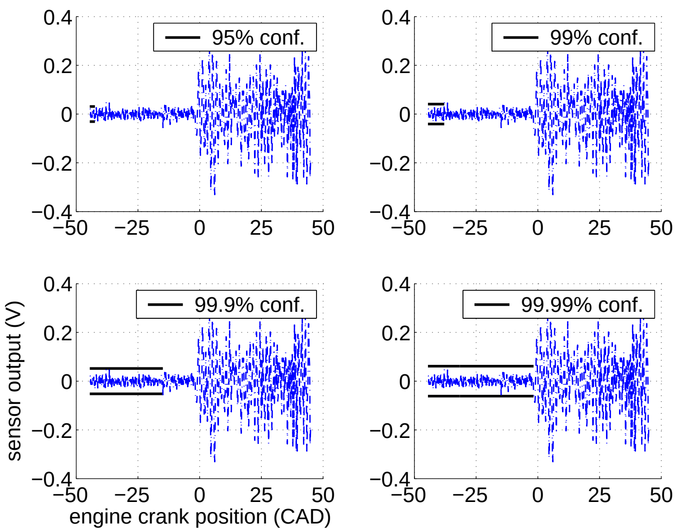

Figure 14. $\nabla Y_t - \hat{\mu}$ WITH CONFIDENCE BOUNDS, SENSOR A.

distributed white noise, as in Eqn. 1 [9].

$$Y_t = Z_t, \quad Z_t \sim WN(0, \sigma^2) \tag{1}$$

The simple model in Eqn. 1 is used along with confidence bounds to estimate the combustion timing. The combustion timing is estimated as the point at which the sensor output exceeds the confidence bounds established for a 1-step predictor; i.e. combustion occurs when the pre-combustion model is no longer valid. The confidence bounds are calculated using the normal cumulative distribution function [10]. For the simple model in Eqn. 1, the confidence bounds are constant. Figure 14 shows the differenced, zero-mean sensor output for a single cycle and various confidence bounds.

As expected, increasing the confidence bounds results in an improved estimate of the combustion timing by avoiding false triggers. However, if the confidence bounds are increased too far, the combustion timing will be estimated too late. To select the most appropriate confidence bound, the combustion timing is predicted for 50 cycles of data using various confidence bounds. The variance of the estimates is then calculated. The confidence bound yielding the minimum variance in the estimated combustion timings is chosen.

The confidence bounds provide useful information that can be incorporated into the control process. For example, at a sampling rate of 0.1 CAD, there are approximately 400 samples in the pre-combustion data for 1 cycle. If one of these 400 pre-combustion samples lies outside the chosen confidence bounds, a false trigger will occur and the combustion timing estimate will be too early. If a 1% false-triggering rate is acceptable, then only $\frac{1}{100(400)}$ samples should lie outside the confidence bounds. This implies the confidence bounds should be chosen as $1 - \frac{1}{100(400)}$, or 99.9975%.

MODEL VALIDATION

A new set of 50 cycles is obtained from sensor A under similar operating conditions. The combustion timing is estimated from the sensor A data using the model in Eqn. 1. Histograms of the reference combustion timing calculated from cylinder pressure data and the combustion timing calculated from sensor A data are shown in Figs. 15 and 16, respectively.

The combustion timing predicted using the sensor A output is roughly 0.7 CAD later than the reference combustion timing. If desired, this error can be easily corrected with an offset term. It should be noted that the distribution of the estimated combustion timing is not normal. If confidence bounds on these combustion estimates are desired, it will be necessary to estimate the distribution shown in Fig. 16.

USING A MORE DETAILED MODEL

Although only the simple model in Eqn. 1 is used for the current research, a more detailed model can be used. The pre-combustion data is normally-distributed, but does not appear to be from a white noise process. The microphone is likely picking up background and other cyclic engine sounds. The autocorrelation function (ACF) of the residuals (the difference between the series and the model) shows a substantial number of points outside the $1.96/\sqrt{n}$ lines, where n is the number of samples. If the model were accurate, approximately 95% of the residuals should lie within these bounds [10]. The substantial number of residuals outside the $1.96/\sqrt{n}$ lines suggests fitting a more appropriate p-order autoregressive, q-order moving-average (ARMA(p,q))

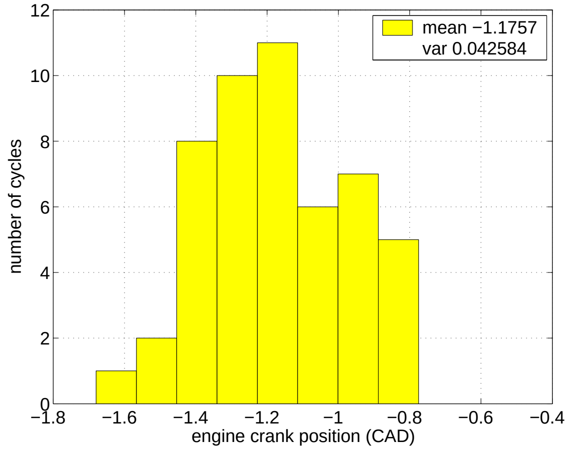

Figure 15. REFERENCE COMBUSTION TIMING FROM CYLINDER PRESSURE DATA, 50 CYCLES, MODEL VALIDATION DATA.

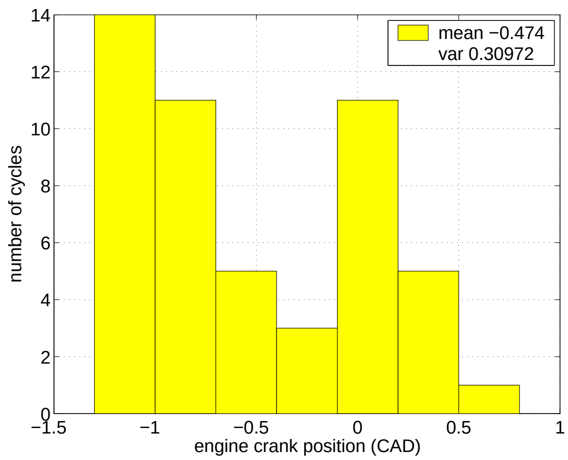

Figure 16. ESTIMATED COMBUSTION TIMING, SENSOR A, 50 CYCLES, MODEL VALIDATION DATA.

model to the differenced series. An ARMA(2,4) model has been used successfully with knock sensor data. This model was not used for the current research, thus the model and results are not included here.

However, the size of the model used should be weighed against its accuracy and usefulness in a feedback control system. The simple normally-distributed white noise model in Eqn. 1 provides reasonable results and is easy to implement.

USING THE SIGNAL FOR FEEDBACK CONTROL

The techniques discussed earlier are applied to the sensor D data. The simple model in Eqn. 1 is used, and appropriate confi-

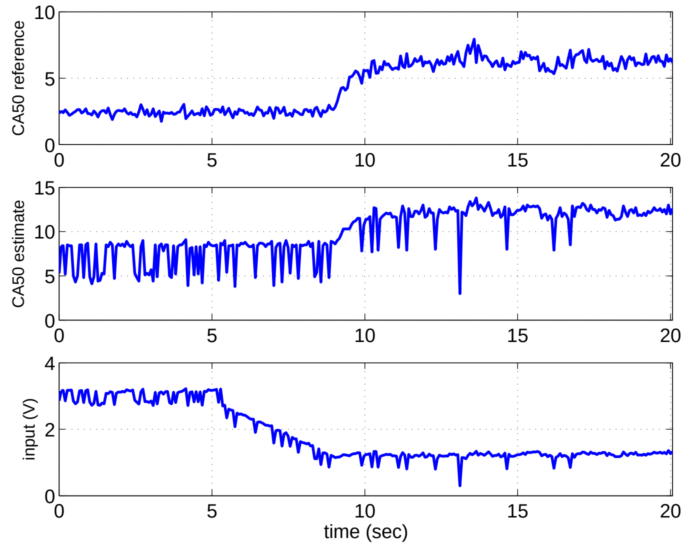

Figure 17. CLOSED LOOP CONTROL OF COMBUSTION TIMING USING SENSOR D OUTPUT.

dence bounds are selected. The intake air is preheated to 160C, and the equivalence ratio is fixed at $\phi = 0.28$. The engine speed is fixed at 1800 RPM. A pneumatically-actuated exhaust throttle is used to control the combustion timing. Closing the throttle increases the in-cylinder residual gases and thus the temperature at the intake valve closing, resulting in advanced combustion timing.

The engine controller is based on the Mathworks' xPC Target platform. Custom device drivers provide engine synchronization, high-speed cylinder pressure and microphone signal data acquisition, and fuel pulse generation. An experimentally-tuned PID controller is used to control the exhaust throttle.

Figure 17 shows the estimated combustion timing, the "true" reference combustion timing calculated from cylinder pressure data, and the control input (the voltage to the exhaust throttle). At time t = 5 seconds, the desired combustion timing is changed from 7 to 12 CAD. There is a noticeable delay before the combustion timing changes, which is due to the nonlinear response of the pneumatic exhaust throttle. The estimated combustion timing tracks the reference combustion timing and the microphone output provides a sufficient signal for use in the closed-loop controller. An offset of approximately 5 CAD exists between the reference and estimated combustion timings.

It is important to note that detecting the combustion event using the microphone data is much more difficult at lower equivalence ratios where the engine load decreases. The diminished signals are not suitable for control since it is difficult to obtain an accurate estimate of the combustion timing.

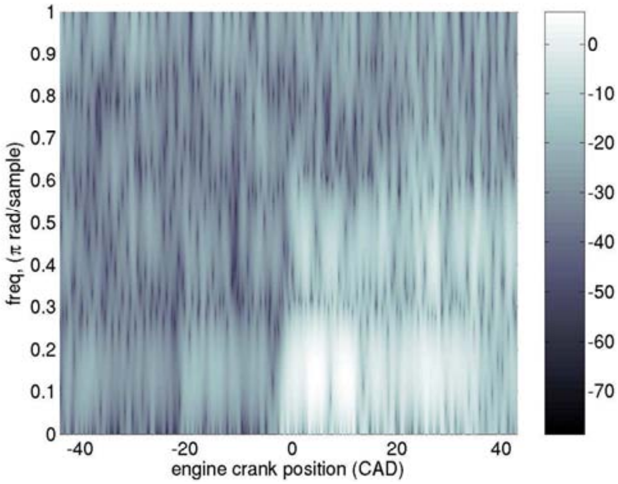

Figure 18. DYNAMIC SPECTRUM ESTIMATE FOR $\nabla Y_t - \hat{\mu}$, SENSOR A, SINGLE CYCLE.

ALTERNATE FREQUENCY-BASED METHODS

In the time domain, either the simple model in Eqn. 1 or a more detailed ARMA(p,q) model can be used to model the pre-combustion data and estimate the combustion timing. Figure 18 shows a dynamic spectrum estimate for the zero-mean differenced sensor A data. It is clear there is an increase in high-frequency components when combustion occurs. These results could be used to build a frequency-based combustion timing detection method.

Initial investigations suggest that a wavelet transform analysis may be a suitable method for detecting combustion timing from the microphone and knock sensor signals. Wavelet transforms have been used successfully for detecting knock in SI engines [3, 4], so a similar analysis may work for an HCCI engine.

CONCLUSIONS

Data were collected from various microphones and a knock sensor. Some of the microphones were mounted on the top of the cylinder head, while others were recessed in unused bolt holes on the cylinder head.

Using the output from sensor A, a procedure for determining the combustion timing was demonstrated. The pre-combustion data was isolated and differenced to produce a stationary time series. A simple model was fit to the pre-combustion data series and confidence bounds were established. The combustion timing was estimated as the time t when the measured data exceeded the confidence bounds established for the pre-combustion series; i.e. combustion occurs when the pre-combustion model is no longer valid. The model was validated using a fresh data set, and closed-loop control was demonstrated using the sensor D output.

The main results can be summarized as follows:

1. All of the sensors exhibited combustion timing information at the specified intake air temperatures and equivalence ratios.
2. The microphones mounted on top of the cylinder head yielded better combustion timing information than those recessed in holes in the head.
3. The combustion timing information contained in the sensor output deteriorated as the engine load decreased.
4. A simple normally-distributed white noise model was successfully used to estimate the combustion timing.
5. The microphone and knock sensor output can be used for closed-loop control of the combustion timing in an HCCI engine at high to medium engine loads.

ACKNOWLEDGMENT

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