

# Ion-Sense-Based Real-Time Combustion Sensing for Closed Loop Engine Control

Gerard Malaczynski, Gregory Roth and Donald Johnson  
Delphi Automotive Systems, LLC

## ABSTRACT

The cycle-to-cycle and cylinder-to-cylinder variations that occur in a spark ignited engine create the opportunity for monitoring combustion in real time to provide useful benefits for engine control. Reduction of variation and operation of the engine at closer-to-optimum conditions is possible if real time feedback of the combustion process is available.

An in-cylinder pressure sensor with pressure-based control algorithms is one method of monitoring the combustion process. However, such a solution presents new challenges of an additional cylinder penetration location, sensor packaging and added cost. A substitute for the in-cylinder pressure sensor is a device which measures the flame conductivity, commonly known as an ionization current sensor. It can be integrated with the spark plug in the case of SI engines, or with the glow plug in the case of compression ignition engines.

This paper presents a methodology of data acquisition and processing which leads to the extraction, in real time, of the following parameters critical for closed loop engine control: combustion phasing, knock detection and combustion stability. The algorithms utilize a combination of various methods including crank-angle-aligned data extraction, digital filtering of the ion sense signal and neural-network-based ion signal interpretation. A Delphi Ion Sense Development Controller (ISDC) is used for high-speed data acquisition and subsequent real time combustion parameter computation.

Our paper demonstrates key features and reports the performance of ionization-current-based combustion sensing using engine data. Key combustion parameters, generated by the ISDC on a combustion event basis, are sent to the engine controller via a Controller Area Network (CAN) for closed loop individual-cylinder combustion control.

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## INTRODUCTION

Current trends in internal combustion engine design defined by new stringent fuel economy and emission standards clearly indicate the necessity of expanding engine operating conditions into areas where risk of abnormal combustion is higher, and therefore precise monitoring of combustion and feedback control becomes paramount for safe, efficient engine operation. Cycle-to-cycle and cylinder-to-cylinder combustion variation due to the stochastic nature of the flame initiation and propagation process create an opportunity to improve engine control by monitoring the in-cylinder combustion in real time. Combustion systems employing high levels of boost and/or dilution are particularly benefitted by a combustion feedback system due to the additional dynamic range of operation. Operation closer to maximum brake torque (MBT), improved operation away from MBT (when desired), improved efficiency, and reduced emissions can be enabled by real-time combustion feedback.

An in-cylinder pressure sensor would create the best scenario when constructing pressure-based control algorithms. However, this solution has not been widely adopted since historically the available in-cylinder pressure sensors have been costly and have had limited demonstration of reliability for mass production. Also, the pressure sensor signal is traditionally processed by a Combustion Analysis System (CAS), a laboratory-grade instrument which is not conducive to integration with the vehicle engine control module (ECM).

A substantial change in the status quo of in-cylinder pressure sensor data processing techniques was introduced a few years ago with the release of the Delphi Cylinder Pressure Development Controller (CPDC) [1]. Despite the fact that a mass production engine delivers only limited resolution on crank angle position, the CPDC allowed cylinder pressure sensor analysis aligned with higher resolution of the engine crankshaft position by synthesizing a

0.1 degree sampling angle from the standard crankshaft-mounted target wheel.

A substitute for the in-cylinder pressure sensor in the meantime is a device which measures the flame conductivity, commonly known as an ionization current sensor. In fact, the ionization current signal (called commonly ion sense) is directly linked to the progress of the combustion as the flame temperature and pressure together with the chemistry of flame translate into the flame's electrical conductivity. This property is typically measured starting at the onset of combustion and concluding close to the end of the power stroke when the flame is extinguished (and the combustion products become effectively electrically non-conductive). The frame of reference, which is crank-angle-based, for conductivity monitoring is very similar to that used when monitoring in-cylinder pressure. Consequently, the CPDC can be software-tuned to be utilized for high-speed ionization current data acquisition and subsequent real time combustion parameter computation by ion sense-based combustion algorithms. In short, the CPDC controller was converted to an Ion Sense Development Controller (ISDC).

The ionization current sensor itself can be integrated with the spark plug in the case of SI engines, or with the glow plug in the case of compression ignition engines. The ion-sense-ready ignition coil circuit serving SI engines is sketched in Fig. 1 and 2, and the typical signal generated by the sensor's electronics used in the work described here is shown in Fig. 3.

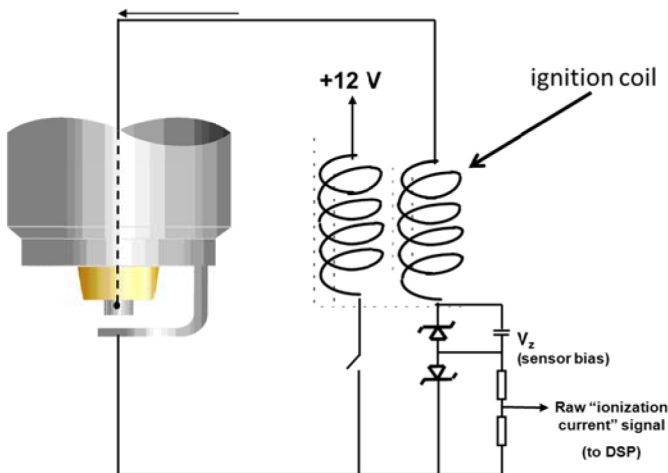


**Fig. 1. Bias voltage ( $V_z$ ) applied to the spark plug generates "ionization current" which is an indication of flame conductivity.**

The ionization current sensing technique has been researched for decades (see e.g. [2, 3, 4]) and suggested as a virtual pressure sensor in the context of pressure-based combustion engine control systems. So far, however, the approach was to demonstrate the ability of the ionization current signal to deliver some combustion-related parameters by extensive post-processing of the signal. As in the case of the pressure signal, the ability to extract the information is

closely related to the sampling resolution and was thus historically limited to laboratory or engine dynamometer experiments.

Reported combustion features extracted through various means from the ionization signal are: location of peak pressure (LPP) [5,6], misfire detection, knock detection [7], heat release/mass fraction of fuel burned phasing estimation [8], start of combustion [9], air-to-fuel ratio [10,11], and engine stability [12]. Since the ionization signal waveform data interpretation are of a statistical nature, except when detecting engine knock, the ion sense-based combustion diagnostic represents a data-based (stochastic) approach.

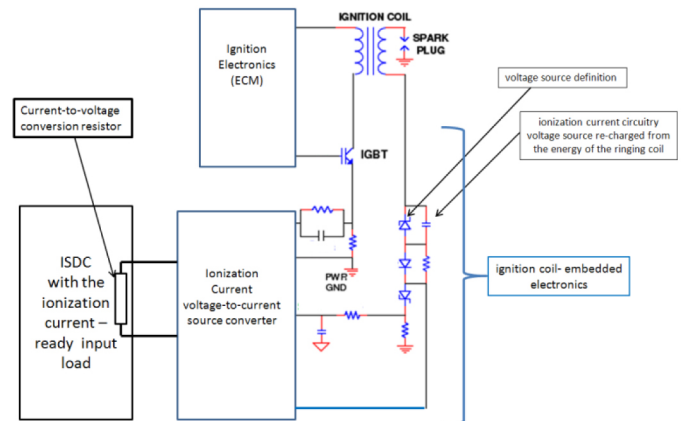


**Fig. 2. Simplified electronics of the ionization current sensor and its interface with the ISDC**

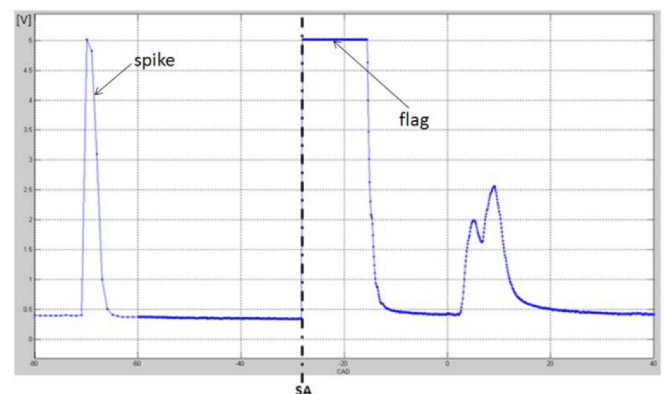


**Fig. 3. Example of an ionization current waveform. The flag preceding ionization current signal masks coil ringing. The spike before the flag represents parasitic noise acquired at the onset of ignition coil dwell, and rising slope of the flag coincides with the spark discharge, thus delivering information on spark advance (SA).**

## IONIZATION CURRENT INTEGRATED COILS

For development purposes, a custom ignition coil design was produced that supports ion sense integrated electronics

and features a high energy, high secondary current coil output to compliment operation of a highly boosted and dilute combustion system. The coil is capable of 100 mJ energy and over 200 mA of secondary current while delivering over 35 kV of available voltage. The coils were designed as a remote-mount style for ease of packaging on the development engine. Custom high-voltage ignition cables connected the remote-mount coils to the spark plugs. An integrated coil drive circuit using an insulated-gate bipolar transistor (IGBT) was included inside the coils for ease of spark control. A photo of the coil is shown in Fig. 4.



**Fig. 4. Remote mount, high energy, Ionization Current enabled ignition coil.**

The ion sense electronic circuit is incorporated into the top portion of the coil and is internally connected to the secondary output terminal. The design contains an application-specific integrated circuit (ASIC) that controls the ionization sensing function. It also delivers the ignition coil spark control. The ASIC and associated circuitry allows for adjustable bias voltage, ionization current signal gain, signal offset, adjustable ring-out timer and selectable flag functions. Available inter-coil flags provide the ability to multiplex the ion signal from several coils onto one signal line. The circuit also provides coil protection from over-dwell and over-current conditions. All listed features help to combat noise and assist with interpretation of the signal by the combustion analysis controller. One of the difficulties in interfacing the ionization current signal with a separate controller is ground shift and ground noise. The intention of the design was to minimize those effects. This is achieved by an electronic architecture which delivers a current source type output, thereby minimizing grounding effects. Consequently, a load resistor is required in the receiving controller (ISDC) to convert the current signal to a voltage for subsequent processing by the fast analog-to-digital (A/D) converters. If a variable (or selectable) load resistor is used in the receiving controller, a real time automatic gain control function can easily be implemented.

## COMBUSTION PARAMETER EXTRACTION ALGORITHMS

Ion sensing methods have been used previously for detection of misfire and knock in SI engines. Several new approaches to combustion parameter extraction algorithms were investigated and are presented in this paper. In particular, our efforts were focused on vehicle-realizable approaches to improved knock detection, determination of combustion phasing and estimation of combustion stability diagnostics. These approaches include the use of various digital signal processing techniques and the use of data-intensive artificial neural networks. The methods are described in more detail in the following sections.

### Improved Knock Detection Algorithm

An abnormal combustion reveals itself in many ways. Knock results from spontaneous ignition ahead of the propagating flame and signals itself as an acoustic noise transmitted through the engine structure while modulating both the pressure signal and the ion sense signal traces (see Fig. 5). The knock frequency depends on combustion chamber geometry and varies little with engine rotational speed.

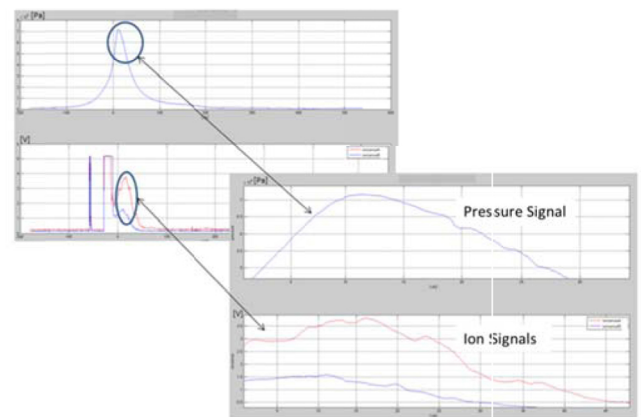


**Fig. 5. Knock-generated acoustic wave modulates pressure and two ionization current signals acquired from the same combustion cavity. The depicted case represents light knock.**

Previous ion sense knock algorithms utilized analog filters, whereas the techniques described in this paper utilize digital filters to provide additional flexibility. Since the CPDC/ISDC offers sampling rates which are constant in the angular domain, the time distance between consecutive samples acquired at constant angular distance varies with engine speed. Consequently it creates a challenge when designing a digital filter responsible for separating knock from either pressure or ionization current signal. In fact, the band-pass filter coefficients having central frequency equal to the knock frequency are not constant but must be engine speed dependent.

It is worthwhile to note that the sampling rate of 0.1 degree secures a sampling frequency which is higher than minimum required by the Nyquist Theorem to reconstruct (detect) the engine knock signal. Indeed at idling speed (600 rpm), sampling at 0.1 degree angular intervals translates to sampling frequency of 36 kHz, enough to detect knock of any typical automotive-sized engine (typically knock frequency is in the range of 4 to 16 kHz). The sampling frequency increases with engine speed and reaches 360 kHz at a typical maximum speed of 6000 rpm. Sampling at idle defines the upper limit of knock frequencies which can be detected when sampling at constant steps in angular domain. In addition, digital signal processing on the frequency scale requires anti-aliasing measures. To secure extraction of the knock signal either from pressure or ion sense signal, an anti-aliasing analog filter, with cut off frequency lower than 18 kHz would be required under assumption of sampling the signal with 0.1 degree steps.

The instrumentation-grade CAS system offers a knock detection feature utilizing a wide band-pass filter with a selectable cut-off frequency at the high end. It separates the near-DC component of the pressure signal from its high frequency knock-bearing component. In short, the knock signal separation feature is not engine-specific, and the filtering formula used assumes a low level of background (no-knock) related noise. Since the CPDC/ISDC requires engine-specific calibration, and the knock frequency of a specific type of engine can be measured or estimated, it is relatively easy to upgrade the above described knock detection filtering routine by employing narrow band-pass filter instead of a wide filter. This solution offers immunity to background noise and makes the algorithm mass-production worthy, but requires engine specific calibration.

As previously described, the CPDC/ISDC system operates in the crank-angle sampling domain. This complicates the digital filter design, which requires constant sampling rate in the time domain. The digital filter coefficients can be calculated for any single engine speed, which represents a constant sampling frequency in time domain. Then, a one-dimensional calibration table linking instantaneous engine speed to the set of coefficients representing a specific knock frequency can be generated and used in real time to fine-tune the filter coefficients in the response to varying engine speed [13]. The transfer function of the second order Butterworth band-pass filter is given as:

$$Y(z) = \frac{b(1)(1-z^{-2})}{1+a(2)z^{-1}+a(3)z^{-2}} X(z) \quad (1)$$

Note that the generic form of the transfer function has been modified in recognition of the following relationships:  $b(2)=0$ ,  $b(3)=-b(1)$ , and  $a(1)=1$ .

Since filter coefficients  $b(1)$ ,  $a(2)$ , and  $a(3)$  are engine speed dependent, the final form of the knock signal extraction algorithm may be represented using the model depicted in Fig. 6, and the calculated filter coefficients in the full range of engine speeds are shown in Fig. 7. Examples of the knock

signal extracted with the CPDC/ISDC-embedded algorithm together with the results delivered by a laboratory-grade CAS system are presented in Fig. 8.

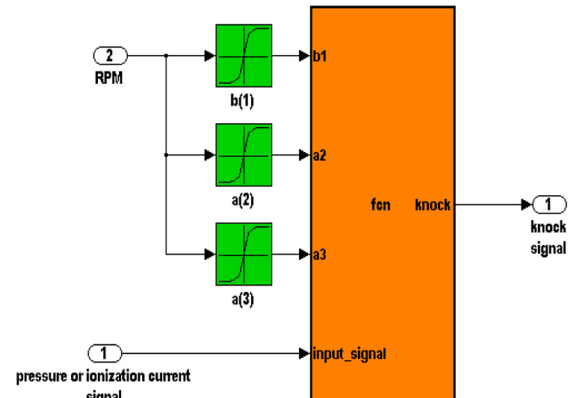


**Fig. 6. Simulink realization of knock extraction from either pressure or ionization current signal sampled at constant distance in the crank angle domain.**

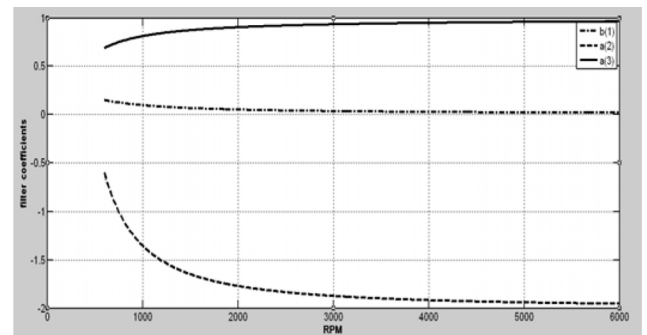


**Fig. 7. Dependence of 2<sup>nd</sup> order digital band-pass Butterworth filter coefficients on engine speed to match a sampling system operating with a constant rate in the crank angle domain.**

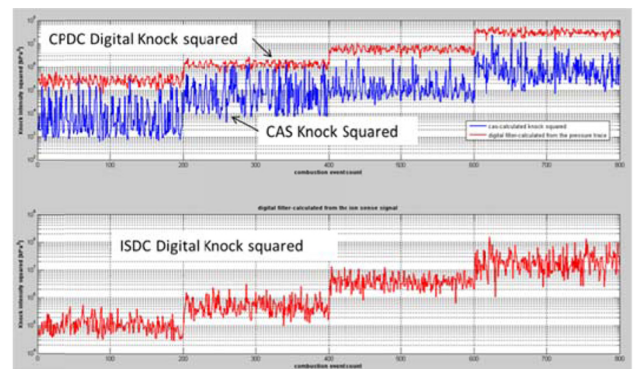


**Fig. 8. Engine knock level was raised in steps. The ion sense-based knock recording was scaled using a multiplier to convert the range of ion sense signal comparable units.**