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ABSTRACT

Internal combustion engines are designed to maximize power subject to meeting exhaust emission requirements and minimizing fuel consumption. Maximizing engine power and fuel economy is limited by engine knock for a given air-to-fuel charge. Therefore, the ability to detect engine knock and run the engine at its knock limit is a key for the best power and fuel economy. This paper shows inaudible knock detection ability using in-cylinder ionization signals over the entire engine speed and load map. This is especially important at high engine speed and high EGR rates. The knock detection ability is compared between three sensors: production knock (accelerometer) sensor, in-cylinder pressure and ionization sensors. The test data shows that the ionization signals can be used to detect inaudible engine knock while the conventional knock sensor cannot under some engine operational conditions. Detection of inaudible knock is important since it will improve the existing knock control capability to allow the engine run at its inaudible knock limit.

Partial-burn detection using ionization is also shown in this paper. A comparison of both in-cylinder pressure and ionization sensor signals are used in this analysis. The test results show that some light partial-burn cases can only be detected by ionization signals. The partial-burn information appears to be difficult to observe under some conditions using the pressure trace directly.

INTRODUCTION

The performance of a spark ignition engine is often limited by engine knock. However, a controlled minor inaudible knock condition can increase engine combustion efficiency without harming the engine components. Ideally, when the MBT (minimum spark timing for the best torque) timing is limited by knock, it is desired to operate the engine as close as to its MBT timing with some inaudible knock.

The knock detection methodologies based on the use of in-cylinder pressure sensor are considered as the most accurate detection means identified so far ([1] and [2]). However, due to the expense of the pressure sensor, it is unlikely to be adopted for large-scale production.

A typical production knock control system works by monitoring the mechanical vibrations using a sensor(s) (accelerometer) mounted in a suitable location on the cylinder block and comparing the processed signal in the knock window with the one in a noise (background) window for each cylinder. When the ratio of the signal in the knock window and noise window is greater than a calibrated value, engine knock is declared and the spark timing is retarded by a sufficient amount to eliminate knock. If no knock is detected for a specific number of cycles, the spark will be advanced gradually in small increments toward MBT timing until the knock flag is active again. The background noise of the knock sensor affects the accuracy of engine knock detection tremendously. Often, the magnitude of the background noise increases rapidly as the engine speed goes up, which makes high-speed knock detection almost impossible. When noise happens to occur in the knock detection window, it may cause false detection. Due to the nature of the knock sensor (mechanical vibration detection), it requires tremendous efforts to properly locate the knock sensor and calibrate knock detection parameters ([3]).

Saab has been in production with a system utilizing an ionization current signal to detect engine knock since 1993. Subsequently, various papers have shown the benefits of using ionization signal to detect knock ([4],[5], and [6]). Since then, knock detection based upon the ionization current signal has been consented as an established methodology ([7]). However, ionization current based sensing has not been widely adopted in the automotive industry despite the clearly demonstrated benefits of full range misfire and knock detection, as well as enhanced engine combustion control. The reasons for the lag might be due to the mismatch of ignition system and ion detection system. This mismatch limits knock detection bandwidth. It could also be the "noisy" nature of the ion signal that was considered as an inferior signal to the in-cylinder pressure signal ([8]). The location of the spark plug also created some doubts about knock detection for engines equipped with center located spark plug ([9], [11], and [12]).

This paper is intended to show that with an improved ionization signal it can be used for detecting not only heavy (audible) knock but also light (inaudible) knock despite the central located spark plug. The testing results based on the use of an ionization signal were also compared to both an in-cylinder pressure signal and a regular accelerometer based knock sensor signal.

An ionization detection system uses a spark plug as a sensor to observe in-cylinder combustion process when a bias voltage is applied between the spark plug center and ground electrodes. Since the flame starts at the spark plug gap and gradually moves away, the ionization signal actually may have more detailed information about in-cylinder combustion than an in-cylinder pressure signal. In fact, when the engine load is high enough, the ionization signal can be used to locate in-cylinder pressure peak ([7]). Figure 1 shows a typical ionization signal for a two-liter four-cylinder engine operated at 1500 RPM with 2.62 Bar BMEP and the corresponding in-cylinder pressure signal. A typical ionization signal has two peaks. The first peak is due to the initial flame kernel development right after the spark. When the flame front leaves the spark plug, the magnitude of the ionization signal reduces. As the pressure in the cylinder increases rapidly, the combusted mixture around the spark plug gap is ionized again due to the high temperature resulted from the combustion, that generates the second peak.

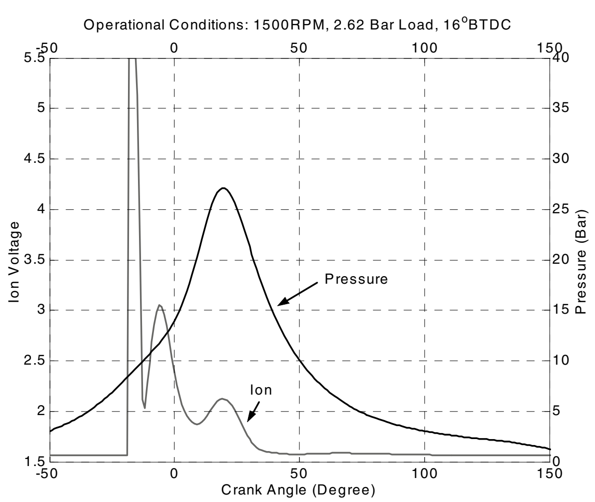

Figure 1 Typical ionization signal

The ionization signal provides a lot of information relative to engine combustion. It is well known that if there is no ionization signal after the spark event, the corresponding cylinder has misfired. Misfire detection is considered an easy task for ionization signal ([7]). Partial-burn detection capability using the ionization signal was described in [8]. It is important to detect partial-burn for combustion control during engine cold start to reduce emissions. This paper extends partial-burn detection capability using ionization signal to exhaust stroke. This is difficult even with in-cylinder pressure sensor.

EXPERIMENTAL SETUP

Engine tests were conducted using a two-liter four-cylinder engine. The dynamometer controller controls the four-cylinder engine except for engine ignition. All engine sensors are connected to the dynamometer controller. It controls the engine throttle position, EGR rate, and fuel injection. The dynamometer controller also controls the engine speed and load. A dSpace PX-10 expansion box was used for spark timing control. Kistler pressure sensors are installed in each cylinder for monitoring the in-cylinder combustion process.

The dSpace PX-10 expansion box consists of a main processor card, a digital waveform capture card, and a digital waveform output card. The digital waveform capture card generates the interrupt based upon the crankshaft encoder pulse that triggers calculation of current crank-angle position synchronized by the camshaft sensor. The current crank-angle information is used to generate the spark timing command for ignition coils and is updated every combustion event.

KNOCK DETECTION RESULTS

In this section knock detection capability using in-cylinder ionization signals is demonstrated for both audible and inaudible knock. The ionization knock signal is also compared with the in-cylinder pressure and conventional knock sensor signals to show the advantage of the ionization signal for knock detection.

Figure 2 shows a comparison of the ionization signal, in-cylinder pressure signal, and knock sensor signal when the engine is operated at 1500 RPM at Wide Open Throttle (WOT). The spark timing is set at 16 degree BTDC. The top graph is the original ionization signal and in-cylinder pressure signal, the middle graph is the conventional knock sensor (accelerometer) signal amplified 10 times, and the bottom graph shows conditioned ionization and in-cylinder pressure signals for showing their knock detection capability. They are the top signals filtered by a band pass filter to reduce the low frequency component so that the knock frequency can be observed easily. This is a relatively heavy knock and it is audible. It is obvious that in this case all three sensors, ionization, pressure, and knock sensors, indicate a knock condition is present in the engine.

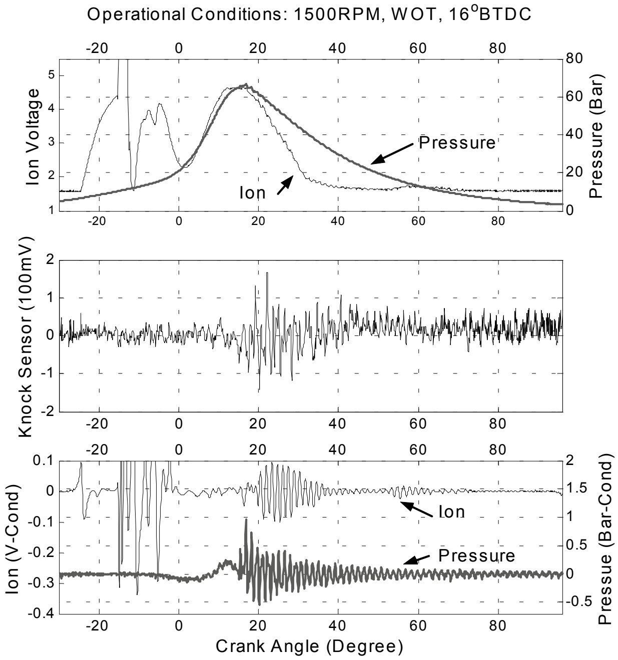

Figure 2 Knock signal comparison: ion & knock sensor

Figure 3 shows the magnitude of FFT (Fast Fourier Transformation) of the conventional knock sensor, conditioned ionization, and in-cylinder pressure sensor signals over the knock window. It is obvious that the first and the second order knock frequencies are the main components of the frequency response. The first order knock frequency is about 6.5 kHz, and the second order knock frequency is about 13 kHz. While for the knock sensor, the frequency response contains more frequency components than the other two sensors. This is mainly due to the fact that the knock sensor observes the knock signal filtered through the engine block and that signal includes other structural born disturbances.

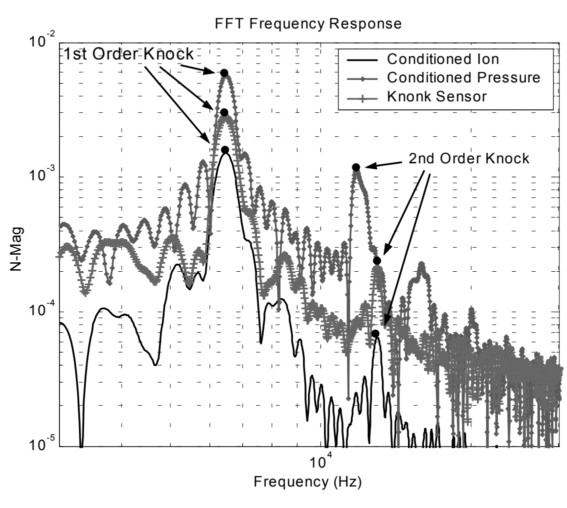

Figure 3 FFT of knock sensor signals

Figure 4 shows a light (inaudible) knock case when the engine is operated at 1500 RPM with WOT (Wide Open Throttle) condition. The spark timing is at 10 degree BTDC. Similar to Figure 2, the top graph is the original ionization signal and in-cylinder pressure signal, the middle graph is the conventional knock sensor (accelerometer) signal amplified 10 times, and the bottom graph shows both conditioned ionization and in-cylinder pressure signals for knock detection. This is a very light knock condition and it is inaudible. It is clear that the knock sensor is at its noise level, and cannot distinguish if the engine is knocking or not. However, the conditioned ionization and pressure signal show a clear knock frequency. In fact, for this case the ionization signal has a better signal to noise ratio than the pressure signal.

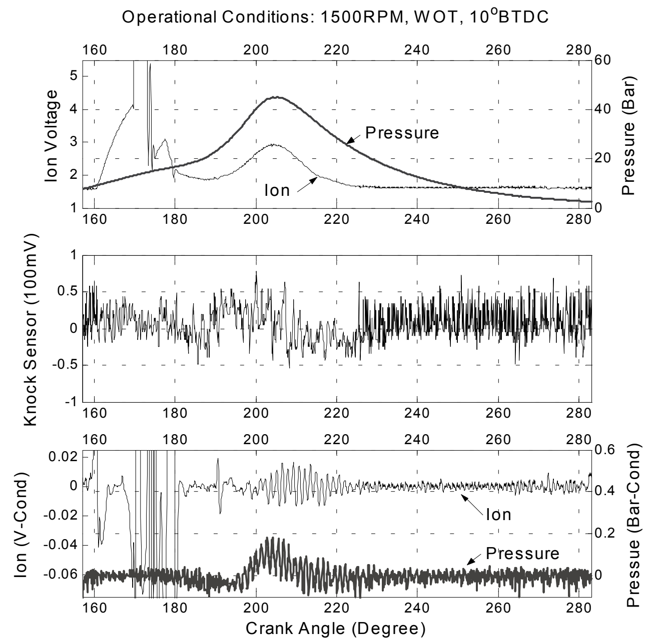

Figure 4 Light knock case

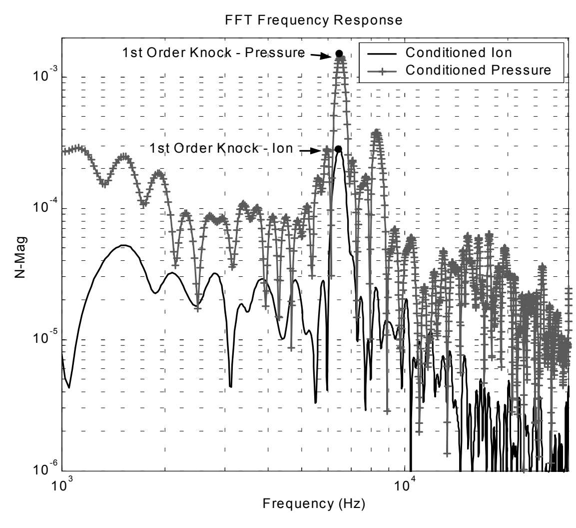

Figure 5 FFT of inaudible knock signal

Figure 5 shows an FFT result of the conditioned ionization and pressure signals shown in Figure 4. It is clear that the first order knock frequency is at around 6.5 kHz, but the second order knock is not as significant as the heavy knock case shown in Figure 3.

This demonstrates that the ionization signal can be used to detect not only heavy (audible) knock but also light (inaudible) knock. For the heavy knock case, the ionization signal contains not only the first order knock frequency but also the second order one.

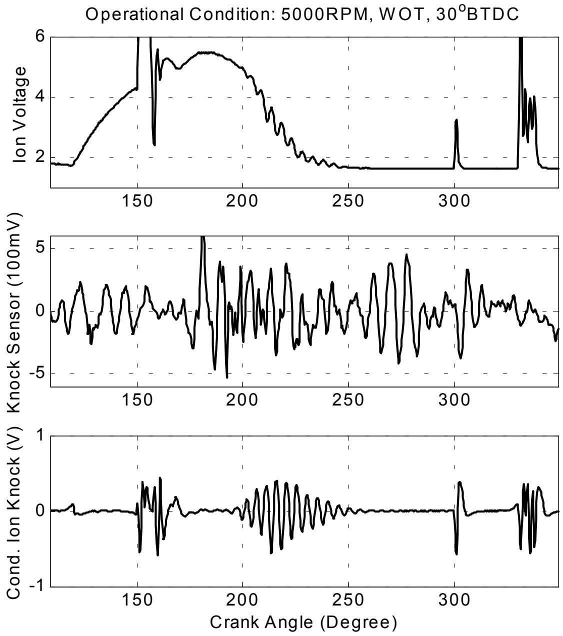

Figure 6 High-speed with knock

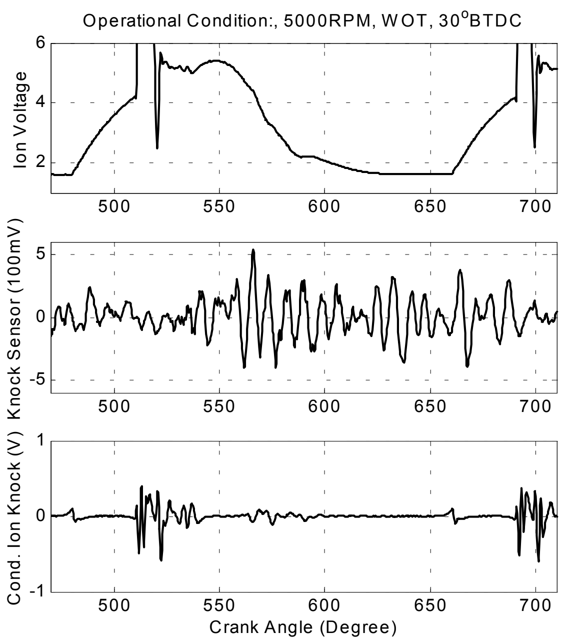

Figure 7 High-speed without knock

Next we study the case when the conventional knock sensor looses the knock detection capability at high engine speed. Figure 6 and Figure 7 show knock signals of different cycles when the engine is operated at 5000 RPM with WOT. The engine spark timing is 30 degree before TDC. Similar to Figure 2 and Figure 4, the top graph is the original ionization signal, the middle one is the knock sensor signal amplified by 10 times, and the bottom conditioned ionization signal for knock detection. It is clear that for Figure 6 the engine has audible knock and for Figure 7 the engine does not. However, the conventional engine knock sensor, the middle graphs of both Figure 6 and Figure 7, in both cases shows similar signatures. That is, at this speed, the conventional knock sensor fails to identify engine knock, while the ionization signal clearly identifies engine knock correctly at this high engine speed. The main reason for knock sensor detection to fail at high engine speed is the associated heavy mechanical vibration, which raises the knock sensor background noise level dramatically.

This demonstrates that the ionization signal provides engine knock detection capability at a much wider engine speed range.

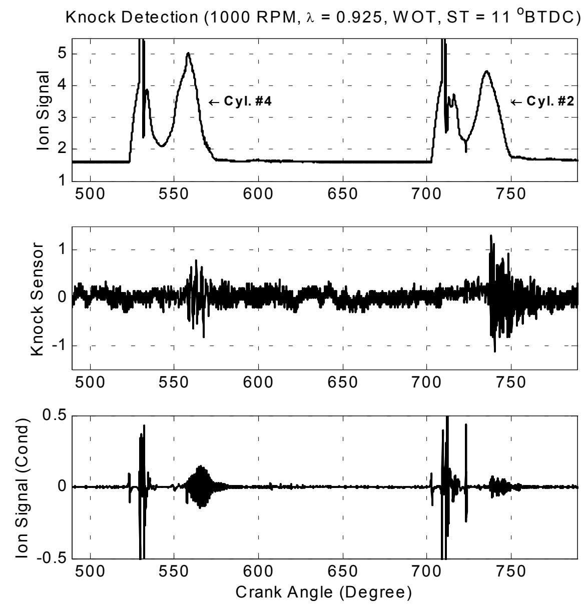

Figure 8 Knock Sensor observability

Another key factor for knock detection using a conventional knock sensor is that the sensor location has to be optimized to maximize the knock detection ability. Figure 8 shows two combustion events of a two-liter four-cylinder engine operated at 1000 RPM with WOT and A/F (air-to-fuel) ratio equal to 13.52. For this engine, the knock sensor is located at the engine block between cylinders two and three. Due to the sensor location, it is obvious that the knock sensor has better knock detection capability for cylinders two and three than cylinders one and four. To illustrate this, consider Figure 8, it shows that both cylinders four and two have knock using the ionization signal, where cylinder four has heavier knock than cylinder two. But for the knock sensor signal, cylinder four knock is almost undetectable, which indicated poor knock detection capability.

Figure 9 shows knock intensity plots of cylinder four for in-cylinder pressure, conventional knock sensor, and ionization signals. Note that each bar represents the knock intensity calculated for one combustion event. The data used for this calculation is from a two-liter four-cylinder engine running at 2000 RPM with WOT and 0% EGR. The engine spark timing was set to 26 degree BTDC.

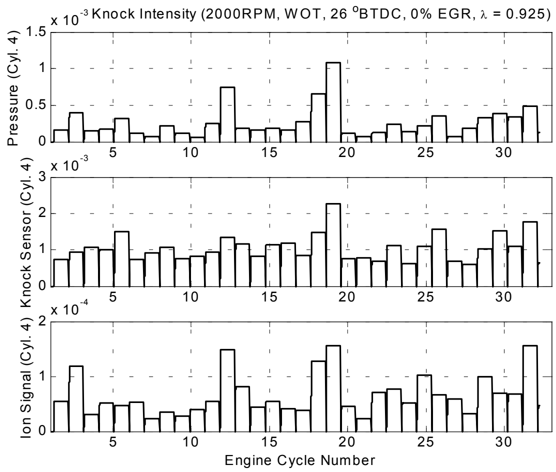

Figure 9 Knock intensity comparison

The knock intensity is calculated using the following steps:

[1] Filtering the input using a Butterworth band pass filter with cutoff frequencies at 3 kHz and 15 kHz,
[2] Computing the absolute value of the signal over the knock detection window, which is defined as a 25° duration starting 15°ATDC, and
[3] Integrating the absolute value of the signal over the knock window to obtain the knock intensity shown in Figure 9.

Table 1 Knock intensity correlations

	Pressure	Knock	Ion
Pressure	1.0000	0.8047	0.8341
Knock	0.8047	1.0000	0.7198
Ion	0.8341	0.7198	1.0000

The correlation matrix for the three intensity signals was calculated for the operating condition above and is shown in Table 1. It is clear that the knock intensities of the ionization and pressure signals have the highest correlation.

The knock intensity correlation matrix for the engine running at 4000 RPM with WOT and 0% EGR is shown in Table 2. The air-to-fuel ratio is 13.6 and spark timing is 30° BTDC. When the engine speed is increased to 4000 RPM, the correlation between the knock sensor and pressure reduces to 0.4868. This is due to the fact that vibration increases, as the engine speed gets higher, leading to high background noise.

Table 2 Knock intensity correlations

	Pressure	Knock	Ion
Pressure	1.0000	0.4868	0.8503
Knock	0.4868	1.0000	0.4194
Ion	0.8503	0.4194	1.0000

It is important to note that the correlation of knock intensity between pressure sensor and ionization sensors is independent of engine speed (0.8341 at 2000 RPM and 0.8504 at 4000RPM).

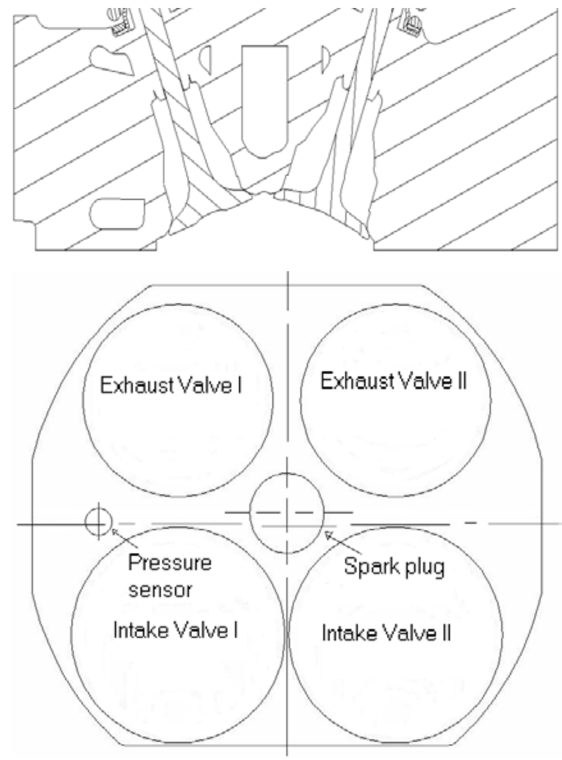

Figure 10 Test engine cylinder head drawing

There are references in the literature [11] and [12] that discuss the relationship between in-cylinder acoustic modes and sensitivity of knock detection to in-cylinder sensor location. One of the conclusions is that the center of the cylinder head is the worst location for any sensors to detect engine knock since the first acoustic mode is unobservable. The spark plug of our test engine is located close to the center of cylinder, which is the worst location for knock detection based upon [9], [11], and [12]. The in-cylinder pressure sensor is off center and located between exhaust and intake valves, see Figure 10. Therefore, the first knock mode should be relatively difficult for ionization sensor to detect since it uses a spark plug located close to the center of the cylinder head. But our test results show that first knock frequency can be easily observed, see Figure 3 and Figure 5, and the pressure sensor shows the same first order knock frequency as the ionization one. Also, from both Table 1 and Table 2 the calculated knock intensities from pressure and ionization sensors have high correlations, indicating similar knock detection quality for both sensors. Hence, the test results shows that even though the ionization sensor is located close to the center of the cylinder head, the knock detection capability using the ionization sensor is similar to that of pressure sensor located off center in the cylinder head. We believe that one reason for the mismatch between analysis and test results is that the analysis did not include the geometry of the cylinder head. The analysis in [11] and [12] assumes a flat cylinder head, indeed the first acoustic mode is unobservable at the center location of the cylinder head with this geometry, but if we include the geometry of the cylinder head, see Figure 10, the first acoustic mode should become observable because the geometry of the cylinder head is not symmetric with respect to the center of the cylinder head. Also, the spark plug is installed slightly off-centered due to the size difference between the intake and the exhaust valves.

PARTIAL-BURN DETECTION RESULTS

Partial-burn is between a normal combustion event, as shown in Figure 1, and misfire. Normally, when there is a partial-burn event, the combustion starts slowly after the spark event and may not be completed until the exhaust valve is open. To study this we divided the partial-burn into two cases: one case where there is no burn in exhaust stroke and the other where there is a major burn during exhaust stroke.

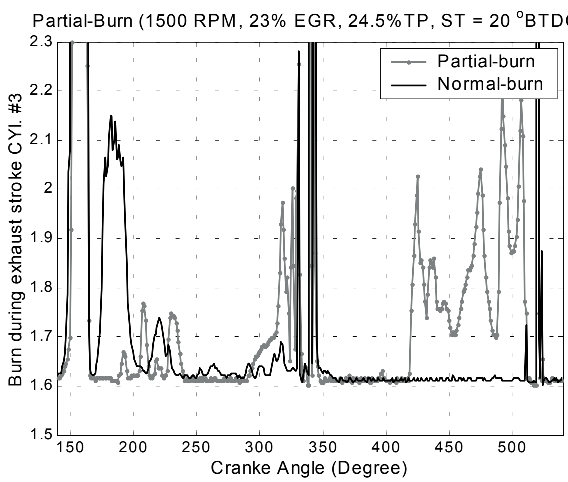

Figure 11 Partial-burn during exhaust stroke with EGR

Figure 11 shows two ionization signals from number three cylinder, sampled at one crank-degree resolution, when the engine is operating at 1500 RPM with 23% EGR and 24.5% throttle opening. The engine is running at an extremely high EGR rate to produce partial-burn. The solid line in Figure 11 is the ionization signal associated with normal combustion and the gray line with dot is the one with partial-burn. Note that the two peaks in the middle and end of graph, around 350 and 520 degrees, are the ground noise of the ignition event from other cylinders. Due to very high EGR rate, the lower flame temperature results in a relatively weak ionization signal.

The normal combustion ionization signal (solid trace shown in Figure 11) has two peaks similar to the typical ionization signal show in Figure 1, but the second peak of the ionization signal is almost invisible. This is mainly due to the low flame temperature caused by the high EGR rate. The gray line with dot partial-burn trace in Figure 11 shows that the majority of the combustion happens during the exhaust stroke. This is the case when the burn extends to the exhaust stroke.

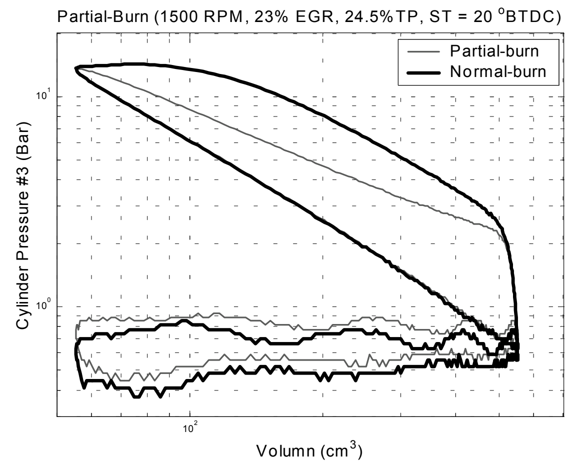

Figure 12 Partial-burn P-V diagram

Figure 12 shows the corresponding P-V (Pressure-Volume) diagrams of the normal and partial-burn combustion, where the solid curve is for the normal combustion and gray thin line for partial-burn. It is clear from the ionization signal that the majority of the combustion happens over the exhaust stroke, but it is difficult to observe this exhaust stroke partial-burn using the pressure signal, see Figure 12.

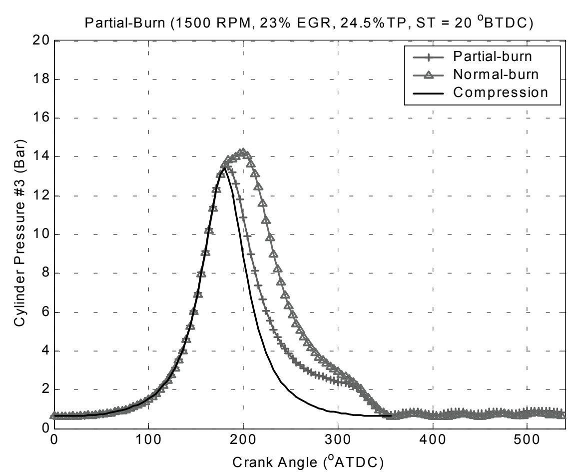

Figure 13 Comparison of partial-burn cylinder pressures

Figure 13 shows both normal and partial-burn pressure traces against the motoring pressure trace. The gray line with "▲" and the gray line with "+" are the pressure traces for normal and partial-burn cases at this operating point respectively, and the solid line is the motoring pressure trace. It is clear that even though there is not much combustion during the expansion stroke, the partial-burn in-cylinder pressure is higher than the motoring pressure during the expansion stroke, but below the normal combustion one. It is also clear from Figure 13 that exhaust stroke partial-burn can't be observed from pressure signal between 360 and 540 degree crank angle. Note that the pressure signal over this region is down nearly to its resolution level and as such it makes it almost impossible to reliably use the pressure signal over this region for detecting partial-burn over exhaust stroke.

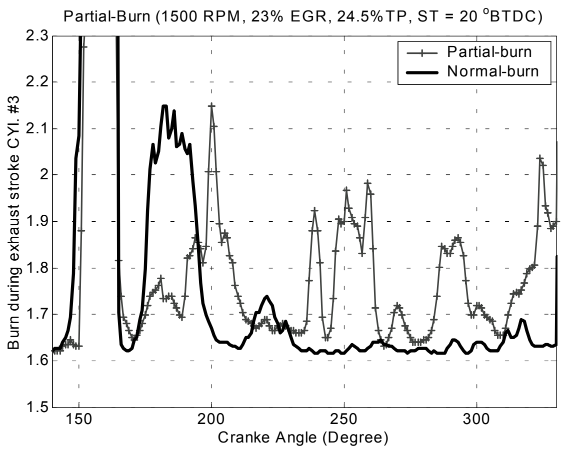

Figure 14 Partial-burn during expansion stroke

The case when the partial-burn event occurs during expansion stroke is shown in Figure 14. As before, the graph plots the partial-burn ionization signal against the normal combustion ionization signal. The partial-burn event mainly happens during the expansion stroke. The engine is operated at the same condition as the case shown in Figure 11. It is clear that the ionization signal is irregular and the ionization signal spread over the whole expansion stroke. The P-V diagram and the pressure traces are similar to the previous case, and are not shown in this paper.

It is very important to detect partial-burn from an emissions point of view. If misfire occurs engine HC (hydro-carbon) emissions increases dramatically. However, if the engine partial-burns, the HC emissions are much less than the misfire case. The conventional engine speed based misfire detection algorithm will report misfire since little work is being done during expansion stroke, leading to a large estimation error for HC emissions. Partial-burn detection capability of the ionization signal can reduce estimation error associated with HC emissions.

After examining engine partial-burn ionization signals with high EGR rate, it is interesting to look at the partial-burn ionization signal at light load case. Figure 15 shows both normal and partial-burn combustion ionization signals when the engine is operated at 800 RPM with no EGR and 1.0 Bar BMEP load. The spark timing is 40° BTDC. The solid trace is the normal combustion ionization signal, and the gray '+' trace is the partial-burn ionization signal.

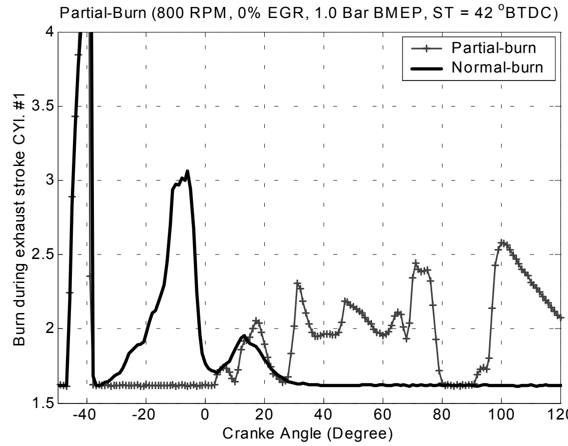

Figure 15 Partial-burn at idle condition

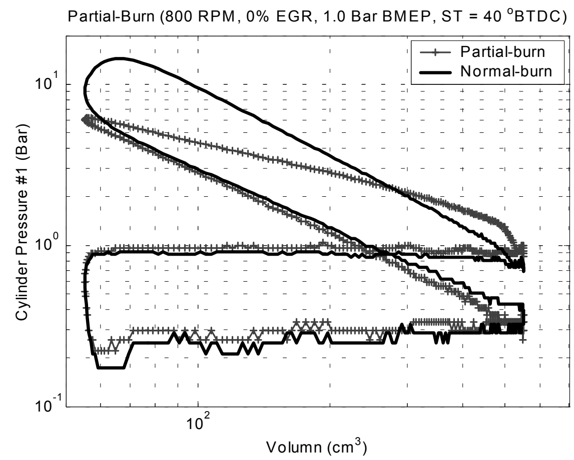

Figure 16 P-V diagram for idle partial-burn

It is clear that the normal combustion ionization signal has two peaks similar to the typical ionization signal shown in Figure 1. While the partial-burn ionization signal is spread over the whole expansion stroke. Similar to the high EGR partial burn case, the ionization signal for the partial-burn event is almost zero after the spark event indicating a very slow combustion after the spark event. Figure 16 shows the P-V diagram of both normal and partial-burn pressures. The solid trace is the normal combustion ionization signal, and gray line with "+" is the partial-burn ionization signal. One can clearly see that little work is being done during the partial-burn combustion.

The data demonstrates that the ionization signal provides enough information for partial-burn detection. The key is that partial-burn ionization signal shows a very slow initial combustion after the spark event. This characteristic can be used to distinguish a normal or partial-burn combustion.

As a summary of partial-burn combustion characteristics, the ionization signal provides enough information for detecting engine partial-burn for either case with EGR and without EGR.

CONCLUSIONS

This paper demonstrates that an ionization signal can be used to detect not only heavy (audible) knock but also light (inaudible) knock. For the heavy knock case, the ionization signal contains not only the first order knock frequency but also the second order one. This paper also demonstrates that the ionization signal provides engine knock detection capability at a much wider engine speed range when compared to conventional detection methods. This paper also shows that the correlation of knock intensity between pressure sensor and ionization sensors is independent of engine speed. The test results also show that even though the ionization sensor is located close to the center of the cylinder head, its knock detection ability is comparable to that of pressure sensor located off center of cylinder head.

The in-cylinder ionization signal also provides enough information for detection of engine partial-burn with EGR and without EGR. Two kinds of partial-burn can be observed: partial-burn combustion within the expansion stroke and partial-burn combustion extended to exhaust stroke.

ACKNOWLEDGMENTS

Kevin Moran and Bill Mammen of Visteon implemented Knock conditioning circuit and dSpace test software and made dynamometer engine tests possible.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

MBT:	Minimum spark advance for Best Torque
TDC:	Top Dead Center
°ATDC:	Degrees After Top Dead Center
°BTDC:	Degrees Before Top Dead Center
PRM:	Pressure Ratio Management
BMEP:	Brake specific Mean Effective Pressure
COV:	Coefficient Of Variation
IMEP:	Indicated Mean Effective Pressure
EGR:	Exhaust Gas Recirculation
P-V:	Pressure and Volume
WOT:	Wide Open Throttle
FFT:	Fast Fourier Transformation
kHz:	Kilohertz
A/F:	Air-to-Fuel
HC:	HydroCarbon