

Ionization Signal Response during Combustion Knock and Comparison to Cylinder Pressure for SI Engines

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ABSTRACT

In-cylinder ion sensing is a subject of interest due to its application in spark-ignited (SI) engines for feedback control and diagnostics including: combustion knock detection, rate and phasing of combustion, and mis-fire On Board Diagnostics (OBD). Further advancement and application is likely to continue as the result of the availability of ignition coils with integrated ion sensing circuitry making ion sensing more versatile and cost effective.

In SI engines, combustion knock is controlled through closed loop feedback from sensor metrics to maintain knock near the borderline, below engine damage and NVH thresholds. Combustion knock is one of the critical applications for ion sensing in SI engines and improvement in knock detection offers the potential for increased thermal efficiency.

This work analyzes and characterizes the ionization signal in reference to the cylinder pressure signal under knocking and non-knocking conditions. Combustion data including cylinder pressure and ionization signals from a 2.0L I4 and a 5.4L V8 engine are collected at varying operating conditions. The ion and pressure signals are characterized and compared through the use of frequency analysis, correlation, and coherence. The results show that the correlation and coherence are low as a result of both the ion and pressure signals being point measurements and the stochastic aspects of combustion knock and characteristics of the in-cylinder pressure waves. Using additional statistical analysis however, the results show a high correlation of knock levels between the ion and cylinder pressure measurements.

INTRODUCTION

Pre-ignition and combustion knock are major factors limiting SI engine thermodynamic efficiency and power plant performance. Although a number of techniques exist for detection and control of combustion knock, it remains a major challenge in current engine management systems. In-cylinder pressure monitoring of each cylinder using piezoelectric instrument grade

pressure sensors is commonly practiced in the laboratory and has generally a good signal to-noise ratio and is often used as a reference signal for comparison to other measurement techniques. However, in-cylinder pressure measurement is not typically a viable option for production engines due to the high costs of the sensors and the requirement that each cylinder has its own sensor. A widely applied method in production uses engine mounted accelerometers, remote from the cylinders with typically one or two sensors used to determine knock on all the cylinders. The accelerometer detects the vibrations transmitted through multiple transmission paths in the engine to diagnose knock in the combustion chamber. The main disadvantage associated with the use of accelerometers is the influence of other vibrating sources on the signal, which becomes more troublesome at higher engine speeds. The deterioration of the signal is especially evident for V8 and other high cylinder count engines [1]. An alternate sensing method for knock detection is through the use of individual cylinder ion current measurement. Ion current provides a more direct measure of the combustion process similar to that of cylinder pressure. The ion measurement as typically applied in an SI engine is made by measuring the ion current using the spark plug as a sensor [2, 3]. The technique involves applying a DC bias to the spark plug and the measure of the current that flows through the circuit after the ignition current has subsided. The current obtained is rich in information regarding the combustion inside the cylinder. The ionization current comprises three characteristic phases which are (i) the ignition, (ii) flame front and (iii) post flame. The ion current has a very high amplitude during the ignition phase, with reverse polarity [2]. In the flame front phase, a high level of ions produces one or more characteristic peaks. The recombination rate varies for the ions in the flame front, some recombine quickly to stable ions, while others take more time. Thus, the high initial peak flattens gradually as the ions become stable. In the post-flame phase, the ion signal follows the cylinder pressure/temperature due to their respective effects on ion concentration. In this phase, ions are created both due to the measurement voltage and the high temperatures of the burned gases [4].

The ionization current is affected by various engine parameters including cylinder temperature, A/F ratio, EGR, type of fuel and load, among others [5]. In past studies and applications, the ion sensing technique has been applied to examine and characterize a number of aspects of combustion behavior. The ion signal has been used for misfire detection, combustion knock detection and control, partial burn detection, and determination of mass fraction burn [5 - 7]. Adrenaline Research [8] and Wayne State University's researchers have also applied the ionization method to estimate the A/F ratio [6]. Researchers at Mitsubishi Electric Corp. [4] applied the ion signal in an Engine Management System [EMS] to yield information to discriminate between misfires and normal combustion over a wide range of engine operation. Also in this study, it was shown that in-cylinder knock data can be extracted from the signal, and the spark angle retarded to eliminate knock through feedback control in the EMS.

In another study conducted at the University of Bologna-Italy and Ferrari Auto [9], researchers outlined an algorithm for closed loop spark advance control through the application of an ionization system. Various knocking index definitions were defined and compared with pressure-based knocking indexes. The maximum amplitude of the absolute value of the filtered pressure signal was compared to the maximum amplitude of the absolute value of the filtered ion signal and the ion signal integrated over a frequency band and a crank angle window. It was concluded in the study that the ion-signal-based processing algorithm is the most appropriate for use in a real time closed loop spark advance control [9]. A similar conclusion is put forward by the studies conducted at Linköping University, Sweden [2, 5, 10]. In this work, extensive research on ion signal interpretation was also conducted and closed loop ignition control achieved [2].

This is in comparison to mechanical accelerometer sensors which are the predominate means of knock detection in current engine management systems. Daniels et al. [4] contend that conventional knock sensor is sometimes incapable to detect inaudible knock. In addition, a conventional knock sensor is highly location-dependent [11]. According to Daniels et al., the ion signal detects not only heavy knock, which was also picked up by a mechanical sensor, but also inaudible knock.

In this study, characterization of the ion signal was performed through frequency analysis and through correlation, coherence, and statistical analysis compared to the in-cylinder pressure signal for knock detection. First, frequency analysis of the ionization and pressure signals were performed and the knock modes observed in each was compared. Then ionization signal-based knock intensity was correlated to the same intensity metric computed from the cylinder pressure signal. Utilizing linear regression analysis, this correlation was quantified through the Coefficient of Determination (COD). This is followed by spectrogram and coherence analysis that further provided insights into various characteristics of the ion signal and differences to the pressure signal. The results in these analysis showed

generally poor cycle-to-cycle correlation of the ion and pressure signals due to the stochastic nature of combustion knock and due to the fact that both the ion signal and pressure signal result from local measurement in the cylinder, which has a space-dependent response because of differing mode shapes and amplitudes. To further examine the responses of each of these combustion knock metrics, a statistical comparison was performed which showed that the two sensing methods (ion and pressure) have a well-correlated response in the characteristic distributions as affected by the ignition timing.

EXPERIMENTAL SETUP

Test data was collected from both a 2 L inline 4 cylinder and a 5.4 L V8 engine. The I4 engine was equipped with electronic throttle control, cylinder independent electronic spark timing control, and a port fuel injection system. The I4 engine also has twin independent variable cam timing enabling independent intake and exhaust valve timings. However, in this study, the cam positions were kept at fully advanced positions. The V8 engine was similarly equipped. Specifications for the two engines are shown in Tables 1 and 2.

Table 1: Specifications for the I4 engine.

Type:	4-Stroke, PFI, SI
Cylinders/Arrangement:	4, Inline
Displacement (cm ³):	1999
Bore x Stroke (mm):	87.5 x 83.1
Compression Ratio:	10

Table 2: Specifications for the V8 engine.

Type:	4-Stroke, PFI, SI
Cylinders/Arrangement:	8, V
Displacement (cm ³):	5400
Bore x Stroke (mm):	90.1 x 105.9
Compression Ratio:	9.80

The data from the I4 engine was collected at engine speeds varying from 1500-2500 rpm, manifold air pressure varying from 55-85 kPa and spark advances of 10-36°. Each data set of a test consisted of between 200 to 300 combustion events.

Test data for the V8 was collected at engine speeds of 1000-5000 rpm at wide open throttle (WOT) and spark advances varying from borderline (BL) – 4° to Borderline (BL) + 3. Borderline conditions were set based on a real-time combustion analysis tool used in the dynamometer laboratory and verified in the post processed results. For each test condition, three data sets of 333 combustion events were collected.

The ignition coils on both engines had integrated ion control, voltage biasing, and sensing. In these coils, the ion current is created through the spark plug gap by applying a DC bias. The current is amplified by the coils and acquired as a voltage signal through a shunt.

For the I4 engine, the pressure signals were acquired from four Kistler 6125B pressure transducers. The transducers were flush-mounted in the cylinder head approximately 35mm from the centrally located plug.

For the V8 engine the pressure signals were also acquired utilizing Kistler 6125B pressure transducers. The transducers were flush-mounted approximately 25mm from the centrally located plug.

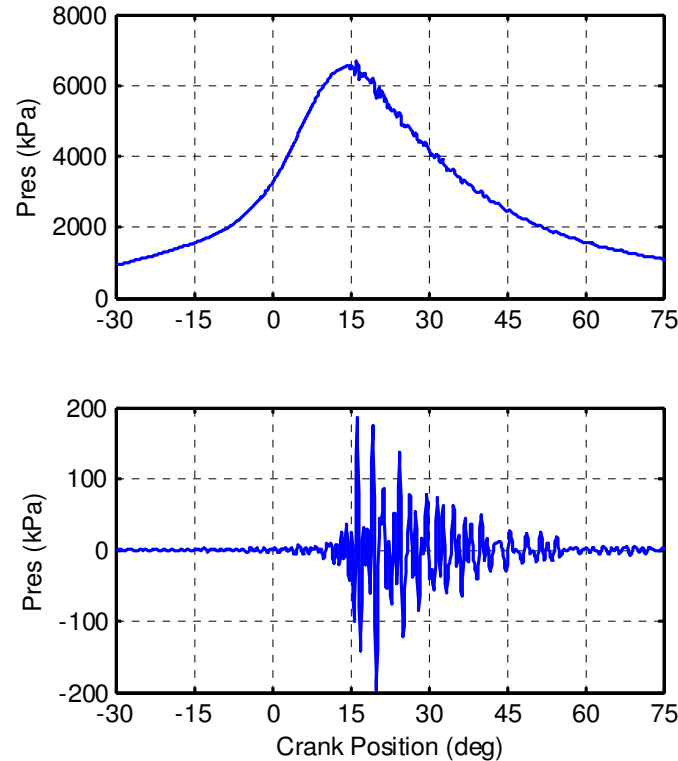


Figure 1: Cylinder pressure signal, raw and band pass filtered for a knocking event (V8, 3000 rpm, WOT, Cyl. 1, BL+3 Spark Timing).

The signals acquired for the analysis included the in-cylinder pressure and ion signals for each cylinder and one or two accelerometer signals along with an engine position signal and additional engine and dynamometer data.

Figure 1 shows the in-cylinder pressure trace for the V8 engine for a knocking cycle at 3000 rpm and BL+3 ignition timing. The top plot shows the normal trace and the bottom plot shows the cylinder pressure after a 6450 to 18500 hz band-pass filter was applied to it. As is well known the knock event causes multiple in-cylinder pressure waves at different modes and amplitudes [1, 16] (see Appendix A) and the measured amplitudes of those modes are dependent upon the sensor placement and mounting [11]. The bottom plot in figure 1 shows the response of the cumulative modes at the location of the pressure transducer. The high frequency components correlating to combustion knock start just prior to 15° ATDC at high amplitude and decay in time (angle) through to 60° ATDC. Figure 2 shows the ionization trace for the V8 engine for the same knocking cycle as figure 1. Again the top plot shows the normal trace and the bottom plot shows the ion signal after a 6450 to

18500 hz band-pass filter has been applied. Before applying the band-pass filter in the case of the ion signal, a cosine-tapered window with a taper parameter of 0.5 was applied from -5 to 60° ATDC. This effectively removed discontinuities in the signal that result from the effects of the ignition at -15° ATDC.

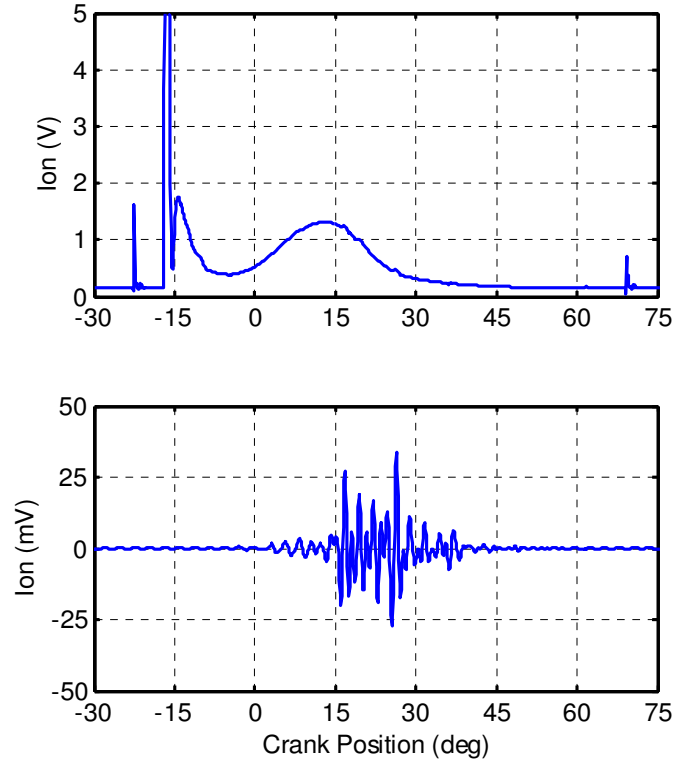


Figure 2: Ionization signal, raw and band pass filtered for a knocking event (V8, 3000 rpm, WOT, Cyl. 1, BL+3 Spark Timing).

In figures 1 and 2, during the post flame period between 0 and 60° ATDC we see a peak that aligns with the peak in cylinder pressure. Examining the lower plot that is band-passed filtered, we see a high frequency contents that starts at 15° ATDC. However, in this case, for the ion signal the time (angle) response is different than that observed in the pressure trace. This is a result of the strong dependence of the ion signal on temperature [5]. Further, as we will see in the frequency analysis, because of the location differences of the pressure and ion measurements, the combustion knock modes and mode amplitudes that are detected differ between these two signals.

Figures 3 and 4 show the same pressure and ionization signals for V8 engine for the same test condition (3000 rpm, WOT, BL+3 spark) for 333 consecutive cycles. Again, the top plot in each shows the unfiltered signals and the lower plot shows the band-pass filtered signals. As shown, each combustion event produces different signal content in terms of amplitude and phasing indicating the stochastic nature of combustion knock. In general, however, the combustion knock impulses are high frequency components in the crank angle range of 0 to

60° ATDC. In addition, the aggregate response differs between the cylinder pressure and ion signals as detailed for the single cycle results shown in figures 1 and 2.

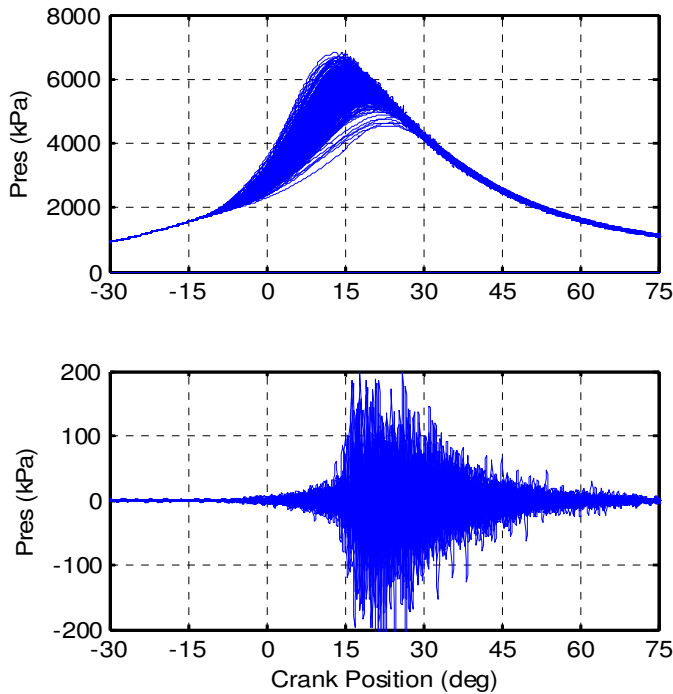


Figure 3: Cylinder pressure signal, raw and band pass filtered for 333 consecutive cycles (V8, 3000 rpm, WOT, Cyl. 1, BL+3 Spark Timing).

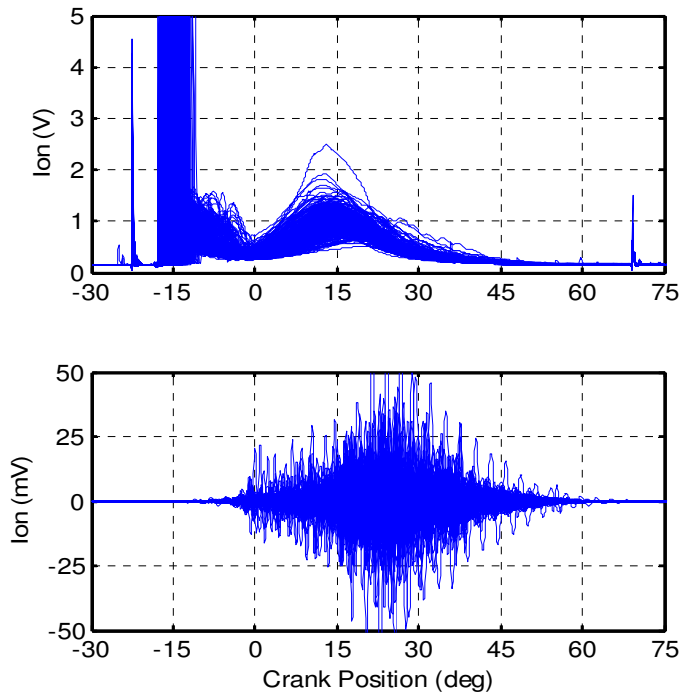


Figure 4: Ionization signal, raw and band pass filtered for 333 consecutive cycles (V8, 3000 rpm, WOT, Cyl. 1, BL+3 Spark Timing).

KNOCK INTENSITY METRICS

For the correlation and other analysis, the digitized signal acquired from the cylinder pressure transducer was used as a reference to quantitatively determine the knock level and for comparison to the ion signal (see Correlation section below). This method is commonly used for quantitative analysis of accelerometer sensors to select sensor locations and optimized signal processing [1].

Following from [1], the knock intensity metric (PI) for the cylinder pressure is:

$$PI(N) = \frac{1}{t_2 - t_1} \int_{t_1=t(\theta_1)}^{t_2=t(\theta_2)} |p_f(t)| dt = \frac{1}{n} \sum_{i=1}^n |p_f(i)|, \quad (1)$$

and similarly the knock intensity metric (II) for the ion signal is:

$$II(N) = \frac{1}{t_2 - t_1} \int_{t_1=t(\theta_1)}^{t_2=t(\theta_2)} |ion_f(t)| dt = \frac{1}{n} \sum_{i=1}^n |ion_f(i)|. \quad (2)$$

In equations (1) and (2), p_f and ion_f are the band-passed filtered pressure and ion signals respectively, and PI and II are computed for every combustion cycle N . These knock intensity metrics are the average rectified amplitude of the filtered signals during the crank period θ_1 to θ_2 .

In addition to the integrated knock metrics, the peak value of the absolute band-passed pressure signal (PP) in a window around the expected knock timing was used to quantify the knock level for each cycle. This was used in the statistical analysis to quantify the responses of the knock metrics to changes in the knock level.

FREQUENCY ANALYSIS AND COMPARISONS

To compare the frequency response of the pressure and ion signals, a frequency analysis was performed by computing the Discrete Fourier Transform (DFT) over a specific period of each cycle during which knock occurred or would be expected to occur. To compute the DFT, again a cosine-tapered window with a 0.5 ratio of taper to constant sections was utilized. However, in this case, the window started 0.75 ms prior to rapid increase of the signal to 1.5 ms after the increase. This window has shown to capture the initial burst of energy without including significant noise that can occur for longer window periods. In addition, the taper at the start and end of the window ensured that end points had zero amplitude and zero derivatives, minimizing leakage in the DFT. Before passing either the pressure or ion signal through the DFT processing, a high pass filter of 4 kHz was used to remove DC components due to the pumping and combustion processes not related to combustion knock. In this method, a DFT (frequency dependent amplitudes and phases) was obtained for each combustion event.

The frequency dependent amplitudes of the DFT were then averaged over select cycles of the 333 combustion events in differing ranges of *PI* knock-intensities. For example, the 0–5th percentile representing those combustion cycles where no or very low knock was occurring, and the 95–100th percentile representing those cycles where the strongest knock was occurring. Furthermore the cycle average amplitudes were normalized by the 95–100th peak amplitude in the pressure and ion DFT respectively.

Figures 5 and 6 show the cycle averaged DFT amplitudes for the pressure and ion signals where the cycle averages were based upon the *PI* knock-intensities as discussed. These cycle-averaged DFTs are from the data shown in Figures 3 and 4 for the V8 engine (3000 rpm, WOT, Cyl.1, BL+3 spark).

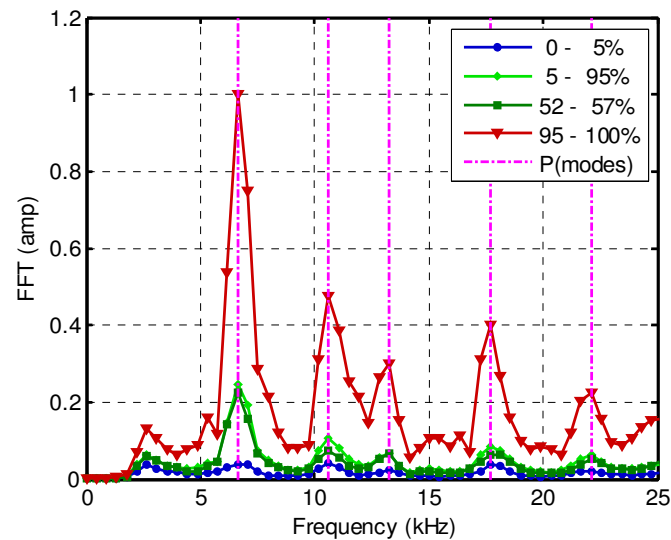


Figure 5: Knock intensity cycle averaged DFTs for the in-cylinder pressure signal (V8, 3000 rpm, WOT, Cyl.1, BL+3 Spark).

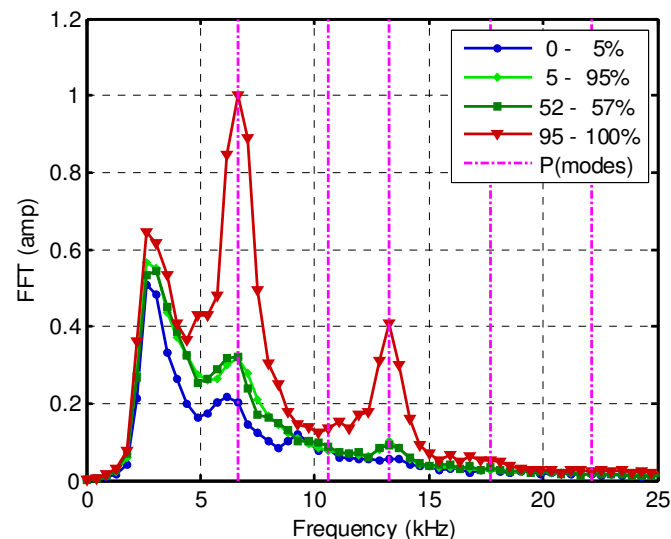


Figure 6: Knock intensity cycle-averaged DFTs for the ion signal (V8, 3000 rpm, WOT, Cyl.1, BL+3 Spark).

The cycle-averaged DFT for the cylinder pressure as shown in Figure 5 shows five distinct peaks in the DFT amplitudes from 5 to 25 kHz. These peaks occur at: 6.6, 10.6, 13.3, 17.7, 22.1 and 25.6 kHz. To identify these peaks in both the pressure and ion DFT plots (Figures 5 and 6), vertical dash-dot lines have been placed. Comparing the observed frequencies with the theoretical frequencies from mode analysis (see Appendix A) selecting the first circumferential mode (1, 0) with a base frequency of 6.6, the other modes correlate well. That is, the other mode frequencies at 10.6 and 13.3 are in good agreement with the estimated frequencies 10.9 and 13.8 at modes (2, 0) and (0, 1).

In further discussions, the modes will be labeled (I, II, III, IV, and V) in terms of increasing frequency (e.g., mode I correspond to the peak in frequency observed near 6.6 kHz).

Examining the knock-intensity-dependent cycle-averaged DFTs for the cylinder pressure as shown in figure 5, we see the expected trend in reduced amplitude in all modes as the knock intensity average interval decreases. In comparison, the 0–5th percentile peaks are all well below (less than 0.05) the mode I peak for the 95–100th percentile. The mid range (52–57th and 5–95th) percentile peaks are slightly higher with a Mode I peak of 0.22.

Comparing the relative amplitudes in the cylinder pressure averaged DFT of the peaks for the 95–100th percentile, we see that mode I has the highest amplitude with the other mode peaks (II–V) in the range of 0.2 to 0.5 of that of mode I. In particular, examining Mode III we see that it is at 0.3 of the amplitude of Mode I.

Examining figure 6 for the knock intensity cycle-averaged DFTs of the ion signal, a number of significant differences are observed. First, only two distinct peaks corresponding to mode I and mode III are observed even for the highest knock levels (95–100th percentile). For these two modes (I and III) for this cylinder and test conditions, the mode frequencies are well-aligned. Considering the other modes, we conclude, for this particular setup and test conditions, that there is little or no observable signal for the ion for modes II, IV or V (see further discussion in the Coherence section).

Further, as we examine the amplitudes in Figure 6 and specifically compare the relative amplitudes of mode III to mode I, we see it is slightly higher at 0.4 in comparison to the pressure mode III (which was 0.3). Another important characteristic in the amplitude shown in Figure 6 is in comparing the baseline between the knock modes and for the combustion events where little or no knock was present (i.e., 0–5th percentile). We see a steady increase in the background amplitude at lower frequencies, such as that between 4.5 to 5.5 kHz where we see a background signal level in the 0–5th percentile of nearly 0.2. This will be further discussed in examination of Spectrograms, but it indicates increasing signal content, likely not correlated with combustion knock, in these lower frequencies.