

Understanding Knock Metric for Controlled Auto-Ignition Engines

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ABSTRACT

The knock metric for controlled auto-ignition (CAI) engines is assessed by considering the physical processes that establish the pressure wave that contributes to the acoustic radiation of the engine, and by analyzing pressure data from a CAI engine. Data sets from the engine operating with port fuel injection, early direct injection and late direct injection are used to monitor the effect of mixture composition stratification. Thermodynamic analysis shows that the local pressure rise produced by heat release has to be discounted by the work spent in acoustic expansion against the ambient pressure to properly predict the pressure wave amplitude. Based on this analysis, a modified correlation between the pressure wave amplitude and the maximum pressure rise rate (MPRR) is developed by introducing an MPRR offset to account for the expansion work.

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INTRODUCTION

Severe pressure oscillation, often referred to as knock, constrains the high load limit of controlled auto-ignition (CAI) engines. The metric for knock, however, is not well defined. Although the subjective measure is the audible knock, an objective metric based on pressure measurement is preferred for consistency of results. The maximum pressure rise rate (MPRR) [1] or the ringing index (RI) introduced by Eng [2] is often used. The knock thresholds based on these metrics, however, are often inconsistent, especially under turbocharged and stratified conditions. This paper addresses these inconsistencies by relating the heat release to the acoustic wave excitation process. Then engine data is used to support the analysis and to develop a correlation for the pressure oscillation amplitude.

Acoustic Wave and Knock Metrics

The combustion rate in CAI engines is not constrained by heat and mass transfer, and near-simultaneous ignition of the entire mixture can occur. Heat release reactions could complete on the order of 0.1 ms, which is very short when compared to the time scale of the order of 10's of ms with flame propagation.

This fast heat release rate results in pressure wave formation in the combustion chamber: the pressure waves form when the acoustic expansion rate of the igniting parcel cannot accommodate the thermal expansion rate produced by the chemical heat release [1, 3]. As a result, the local pressure of the igniting parcel must increase above the chamber pressure. The non-uniform pressure distribution in the chamber results in the formation of pressure waves at the resonant frequencies of the chamber. As the energy flux of the pressure waves increases, severe noise and vibration can occur, which is referred to as engine knock.

A criterion for the onset of pressure oscillation based on the acoustic pressure accommodation requirement as described in the above is [1, 3]

$$\dot{q} \geq \left(\frac{\gamma}{\gamma - 1} \right) \frac{P}{L/a} \quad (1)$$

where $\dot{q}$ is the volumetric heat release rate, L is the size of the heat release region, γ is the specific heat ratio, and a the sonic velocity. (See end of paper for definition of symbols.) By design, combustion in CAI engines involves a fast heat release rate ($\dot{q}$) in regions of substantial size (L). Therefore according to Eq. (1), the presence of pressure oscillation is

the norm rather than exception. Of concern is whether these oscillations are objectionable to the engine noise and vibration. Since the oscillation is excited by $\dot{q}$, and for a locally constant volume combustion (i.e., before the acoustic expansion takes effect), $\dot{q}$ is proportional to the pressure rise rate. As a result, MPRR is often used as a metric for gauging the magnitude of the oscillation. (The correspondence is not strictly correct since $\dot{q}$ is proportional to the local pressure rise rate, and MPRR is obtained from the global cylinder pressure measurement. The assumption is that there is a correlation between the two.)

A more precise metric is proposed by Eng [2] based on the acoustic energy flux I (watt/m²) carried by a plane pressure wave. For wave amplitude ΔP (i.e. $P(x,t)=\text{Re} [\Delta P e^{i(\omega t-kx)}]$), I is given by

$$I = \frac{a(\Delta P)^2}{2\gamma P} \quad (2)$$

Using $P_{\max}$ for P and the corresponding $T_{\max}$ (temperature at the maximum pressure) for the calculation of the sonic speed, a metric for I is the knock intensity (KI) defined by

$$KI = \frac{1}{2\gamma} \frac{(\Delta P)^2}{P_{\max}} \sqrt{\gamma R_u T_{\max}} \quad (3)$$

Note that all the quantities in Eq.(3) are obtainable experimentally with high frequency pressure measurement (with T calculated from P). However in computer modeling of CAI combustion, ΔP cannot easily be obtained without resolving the acoustic waves. Therefore it is useful to establish a relationship between ΔP and the global charge properties so that a knock metric common to both experimental and modeling work could be devised.

For pressure oscillation at frequency f , the amplitude ΔP may be estimated from the pressure rise rate as [1]

$$\Delta P = \frac{1}{4f} \left(\frac{dP}{dt} \right)_{\max} \equiv \beta \text{MPRR} \quad (4)$$

Eng [2] has used the value of $\beta \equiv 1/(4f) = 0.05$ ms, and define a ringing intensity (RI) by

$$RI = \frac{\sqrt{\gamma R_u T_{\max}}}{2\gamma P_{\max}} [\beta \text{MPRR}]^2 \quad (5)$$

Strictly speaking, β depends on the resonant frequency f , which is engine sized dependent. Nevertheless, the RI with $\beta = 0.05$ ms is often used as a metric for knock. Eng has recommended a threshold value of 2 MW/m². Values in the literature vary from 2 to 5 MW/m².

In summary, a knock metric based on the acoustic energy flux of the pressure wave may be devised as in Eq. (3). What is in question is the relationship between ΔP and the charge global properties. It will be shown through experimental data that relating ΔP to MPRR by Eq. (4) is unsatisfactory because a proportional relationship with a constant β value cannot be established. The ΔP , MPRR relationship depends on the engine operating condition and on the extent of charge stratification. Thus a different correlation needs to be developed.

EXPERIMENTAL

A modified Renault/ Mitsubishi F9Q B800 common rail diesel engine was operated in CAI mode for the purpose of this study. The engine specifications are given in Table 1. The information has been obtained from the Mitsubishi F9Q series manual [4].

Table 1. Engine Specification

Description		Specification
Number and cylinder arrangement		4 in-line
Total displacement		1870 cm ³
Cylinder bore x stroke		80 mm x 93 mm
Compression ratio		19
Valve timing	Intake opening	BTDC 3°
	Intake closing	ABDC 21°
	Exhaust opening	BBDC 46°
	Exhaust closing	BTDC 6°
Fuel injection system		Direct injection plus Port Fuel Injection

The engine was converted to run under single cylinder operation to reduce fuel consumption and to eliminate issues with cylinder variations. Separate intake and exhaust runners were created for the firing cylinder, while the original manifolds were modified to connect to only the non-firing cylinders.

The original turbocharger connected to the engine was removed. In its place, a separate intake air system (adapted from Ref. [5]) was connected to the intake of the firing cylinder. The system was designed to operate from 1 to 2 bar absolute pressure and 40° to 140° C intake temperatures, independent of engine operation. A schematic for the intake and exhaust system is given in Fig. 1.

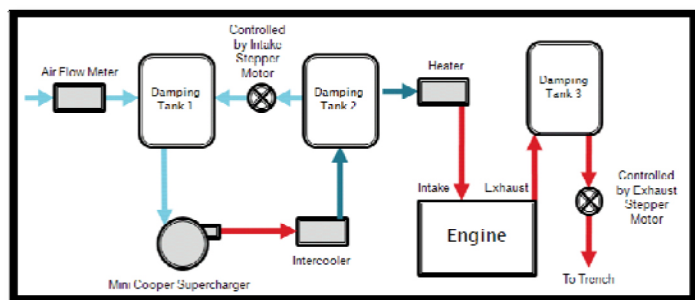


Figure 1. Engine flow system schematic

Fuel Delivery System

The fuels used are gasoline blends with a range of ON and a gasoline with 10% ethanol. All fuels have been supplied by Chevron. To study charge stratification effects, the engine employed two fuel injection systems that could be used separately or simultaneously. In addition to the common rail direct injection that came with the engine, a port fuel injector, with a separate fuel tank, was added at the intake runner targeting the intake valve. The latter fuel delivery system used a standard fuel pump and pressure regulator common in SI engines. The fuel pressure was set to 2.7 bar gauge for all engine runs. To prevent formation of bubbles, all fuel returns were cooled through a heat exchanger (with ice water) before going back to the fuel tank.

Pressure Data Processing

The various quantities for evaluating the knock metric are obtained as follows. The pressure trace is sampled at 100 KHz; 10 consecutive cycles under knocking condition are shown in Fig. 2.

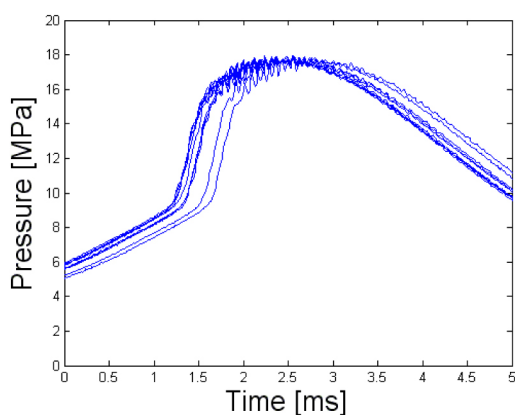


Figure 2. Pressure of 10 consecutive cycles

The pressure is processed by a band pass filter of 4 to 20 KHz; see Fig. 3. Then the amplitude ΔP of the pressure oscillation is defined as the cycle-average of the maximum absolute value of the pressure amplitude in each cycle of the filtered pressure trace. The average is over 3 seconds of data,

which, at an engine speed of 1300 rpm, correspond to 32 cycles.

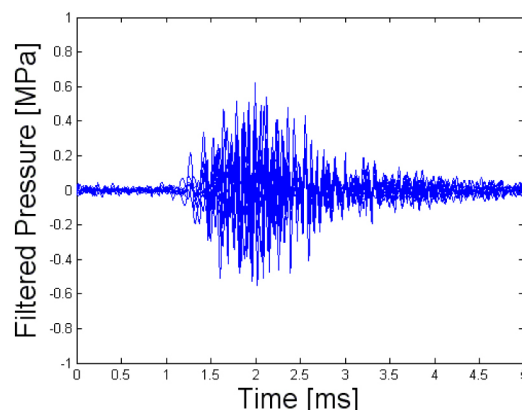


Figure 3. Band-Pass Filtered Pressure (4KHz-20 KHz band) of 10 consecutive cycles

The MPRR of the pressure data is obtained from numerically differentiating the low-pass filtered (below 4 KHz) pressure trace; see Fig. 4. The cycle-averaged MPRR is then the average of the MPRR of each cycle. The average is again, over a 3 second interval.

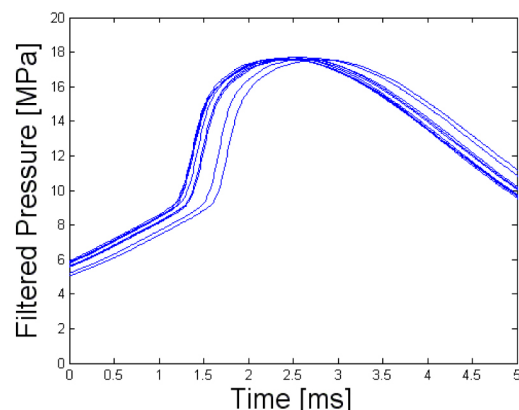


Figure 4. Low Pass Filtered Pressure (below 4KHz) of 10 consecutive cycles

Audible Data Processing

A Behringer ECM 8000 microphone (frequency response flat from 15 Hz to 20 KHz) is mounted 5 cm from the valve cover of the firing cylinder to monitor the sound radiation from the engine. The acoustic delay from the engine to the microphone is 0.15 ms. The microphone amplifier (Yamaha MG 10/2) is set at a fixed gain. The recorded signal is passed through a band-pass filter (4 to 20 KHz). The filtered signal is shown in Fig. 5. The cycle averaged amplitude (volt) of the filtered acoustic signal is used as a metric of the acoustic radiation. The average is again, over 3 seconds.