

On Knock Intensity and Superknock in SI Engines

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ABSTRACT

Most studies on knock ignore the stochastic nature of knock and focus on the onset of knock which is determined by chemical kinetics. This paper focuses on knock intensity (KI) which is determined by the evolution of the pressure wave following knock onset in a hot spot and highlights the stochastic processes involved.

KI is defined in this study as the maximum peak-to-peak pressure fluctuation that follows the onset of knock. It depends on $\zeta = (a/u_a)$ where u_a is the speed of the autoignition front and a is the speed of sound. When u_a is small, KI can be related to the product of a parameter Z , which depends on P_{ko} , the pressure at knock onset and the square of $(\partial x/\partial T)$, which is the inverse of the gradient of temperature with distance in the hot spot. Both Z and $(\partial x/\partial T)$ were calculated using measured KI and P_{ko} for hundreds of individual knocking cycles for different fuels. The model for ignition delay as a function of pressure P and T in the hot spot and other data needed to calculate Z were available from a previous study (SAE 2016-01-0702). For a given fuel and operating condition, Z varies because P_{ko} varies, because of cyclic variation of combustion - a stochastic process. $(\partial x/\partial T)$ depends on the evolution of the hot spot during the engine cycle and depends on flow and turbulence - another stochastic process. All else being equal, Z increases and hence the probability of high KI increases as P_{ko} increases, e.g., by more advanced spark timing and/or faster flame development. For a given P_{ko} , Z is lower for a fuel with higher RON . In modern turbocharged engines extremely high intensity knock, informally termed superknock is observed to occur occasionally even though operating conditions are chosen to avoid knock. Superknock is caused by developing detonation (DD) which results when the value of ζ decreases and the pressure wave begins to couple with the autoignition front and gets amplified. Autoignition has to be initiated at high P and T for superknock to occur. At practical operating conditions, this can only happen via another abnormal stochastic phenomenon - preignition, when a flame is established before the spark plug fires. Both preignition and superknock become more likely as P increases. All else being equal, the probability of superknock decreases as the fuel RON is increased. However, even with high RON , high KI and superknock could occur with the right combination of P and $(\partial x/\partial T)$.

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1. INTRODUCTION

Knock is an abnormal combustion phenomenon which limits the efficiency of spark ignition (SI) engines [1, 2]. It is caused by autoignition of the fuel/air mixture in hot spots in the "end-gas" ahead of the advancing flame front, which depends on the evolution of pressure (P) and temperature (T) during the cycle and on the fuel anti-knock quality. Fuel anti-knock quality is normally specified by the Research and Motor Octane Numbers, RON and MON , of the fuel used. Interest in knock and fuel anti-knock quality is bound to increase as engine designers strive to improve engine efficiency.

The autoignition in the end-gas increases the heat release rate and sets off a pressure pulse causing the engine structure to vibrate - it is like hitting the inside of the engine with a hammer. The pressure inside the cylinder fluctuates and knock intensity (KI) is often defined as the maximum peak-to-peak pressure fluctuation - a definition we will use in this paper as well. The primary operating principle in SI engines is to avoid knock. However in downsized, turbocharged engines, even when operating conditions such as intake pressure and spark timing

are chosen to avoid knock, extremely intense knock events, informally termed as "superknock" are occasionally observed. Currently there is great interest in understanding superknock because it appears to limit the scope for turbocharging and downsizing, the main strategy being pursued by engine developers to improve the efficiency of SI engines.

Most knock studies focus on knock onset which is determined by chemical kinetics governing autoignition as the pressure and temperature in the unburned fuel/air mixture increase during the engine cycle. Such studies also usually ignore the fact that even when fuel and air are fully premixed, the mixture is never truly homogeneous primarily because of turbulent mixing of the hot residuals with the fresh charge. Hence autoignition in the end gas always occurs at local hot spots. Most knock studies also ignore the stochastic nature of knock. While this might be acceptable when the intention is to avoid "conventional" knock e.g. knock that can be controlled by changing spark timing, superknock needs to be considered in probabilistic terms.

This paper focuses on knock intensity (KI) which is determined by the evolution of the pressure wave following knock onset. We use a previously published theoretical framework that links the maximum amplitude of the pressure pulse following autoignition to $\zeta = (a/u_a)$ where u_a is the velocity of the autoignition front and a is the speed of sound. When u_a is small, this enables KI to be related to the product of a parameter Z , which depends on, P_{ko} , the pressure at knock onset and the square of $(\partial x/\partial T)$, which is the inverse of the gradient of temperature with distance in the hot spot. For the first time, both Z and $(\partial x/\partial T)$ are calculated using measured KI and P_{ko} for hundreds of individual knocking cycles for five different fuels. The model for ignition delay and other procedures such as the estimation of the temperature in the hot spot needed to calculate Z are based on previous studies and, for the sake of completeness, are discussed in some detail. The value of Z depends both on the autoignition characteristics of the fuel/air mixture and P_{ko} , which is determined by stochastic combustion processes. Since $(\partial x/\partial T)$ is also determined by stochastic processes, KI is also stochastic though it also depends on fuel autoignition quality. These insights are extended to the discussion of superknock, which previous studies suggest, is a manifestation of developing detonation (DD) that can occur at low values of ζ . High values of P_{ko} needed for ζ to be low enough for DDs to occur can only come about because of another stochastic process - preignition, which is also briefly discussed. The paper ends with general conclusions and comments about knock intensity, preignition and superknock.

2. KNOCK ONSET

The ignition delay, τ_i measured in rapid compression machines or shock tubes is a parameter of fundamental importance in studies of autoignition and chemical kinetics. It can be expressed as a function of temperature, T , and pressure, P , in general as:

$$\frac{\tau_i}{\tau_{i0}} = f(T) \left(\frac{P}{P_0} \right)^{-n} \quad (1)$$

Here, τ_{i0} is the ignition delay measured at a given temperature, T , at a pressure of P_0 and n is a constant. In internal combustion (IC) engines the mixture will have a different value of τ_i at each point during the cycle. In engine applications, it is then hypothesized that autoignition occurs when the integral (Livengood-Wu integral) of the reciprocal of τ_i with time, t , reaches unity (Eq. 2).

$$I = \int_0^{te} \frac{dt}{\tau_i(P,T)} = 1 \quad (2)$$

Chemical kinetic models aim to predict ignition delay as a function of pressure and temperature. However, practical gasoline fuels are too complicated to have kinetic models developed for them. Hence surrogate fuels that are made up of a few simple components but mimic the autoignition behavior of the gasoline are used to model the chemical kinetics of gasolines.

If a surrogate fuel has the same RON and MON as the gasoline it is extremely likely that it will show the same autoignition behavior as the gasoline [2]. This is because the true autoignition quality of a fuel is best described by an Octane Index (OI) which is a combination of RON and MON and is defined as:

$$OI = (1-K)RON + KMON = RON-KS \quad (3)$$

Here S is the sensitivity ($RON-MON$) and K is an empirical constant which depends only on the pressure and temperature history of the unburned mixture in the cylinder. Extensive empirical tests in knocking engines, HCCI engines and premixed compression ignition (PCI) engines have shown that fuel/air mixtures with two different fuels with the same OI will have the same global autoignition phasing if they are subjected to the same pressure and temperature history [2]. A surrogate with the same RON and MON as the gasoline will have the same OI as the gasoline at all operating conditions (K values).

A toluene/PRF (toluene, n-heptane and isooctane) mixture, TPRF, can be found to match any RON and MON combination. An accurate method to identify the composition of the TPRF surrogate to match a given RON and MON was described in [3]. Ignition delays at different pressures and temperatures can be calculated for such a surrogate TPRF using a chemical kinetic model [4]. A simple equation of the form shown in Eq. 4 to predict ignition delay as a function of temperature, T , and pressure, P , is identified from these data.

$$\tau_i = A \exp\left(\frac{B}{T}\right) P^{-n} \quad (4)$$

Only ignition delays below 15 ms are considered in deriving Eq. 4. This is because an ignition delay of 15 ms is equivalent to 135 crank angle degrees (CAD) in an engine running at 1500 rpm, so that a crank angle step of one CAD would contribute less than 1% to the Livengood-Wu integral. For engine applications with practical fuels it is not very important if the ignition delay greater than 15 ms is not modeled accurately.

Such calculations were conducted for many TPRFs with different RON and MON and the values of A , B and n in Eq. 4 were tabulated for these TPRFs in [3]. These data were used in [5] to derive equations for A , B and n as functions of RON and sensitivity, S . The ignition delay equation (Eq. 4) for the appropriate TPRF surrogate can be established if the RON and MON of the gasoline are known. Then, if pressure and temperature are known through the engine cycle for an engine running on gasoline, the Livengood-Wu integral, I (Eq. 2), can be calculated using the ignition delay equation for the surrogate TPRF and knock onset can be predicted.

This approach was tested in two different single-cylinder engines using six different gasolines and nine different operating conditions in [3, 5]. Many individual knocking cycles were considered and the measured pressure was used for each individual cycle but the temperature in the hot spot has to be estimated as a function of crank angle. This is a problem that has to be faced by any approach to study knock and inevitably requires some assumptions to be made. The

latter part of this paper uses the pressure and temperature at knock onset and hence the method that was used to estimate the temperature in the hot spot is described at this stage.

The value of T_{comp15} , the bulk gas temperature during the compression stroke when the pressure is 15 bar was calculated after estimating the total number of moles, m , in the cylinder (air, fuel, residuals) using the volume, V , in the cylinder when the measured pressure, P , reaches 15 bar and using the ideal gas equation ($PV = mRT$). It was then assumed that the temperature in the hot spot at this pressure of 15 bar was higher than T_{comp15} by ΔT .

The temperature in the unburned gas is calculated from the measured pressure in the following way. Assuming adiabatic compression, the pressure, P , is related to the volume, V , by:

$$PV^\gamma = \text{constant} \quad (5)$$

The temperature, T (in K) in the hot spot, at any pressure, P (in bar), is given by:

$$(T/(T_{comp15} + \Delta T)) = (P/15)^{(1-1/\gamma)} \quad (6)$$

The exponent γ was estimated from plotting $\log P$ vs $\log V$, during the last 25 CAD of compression before ignition and an average value of 1.31 is used in all the calculations.

The ignition delay and hence the Livengood-Wu integral, I , can then be calculated as a function of crank angle. Knock is predicted to occur when I reaches unity.

The experimentally observed knock onset crank angle for an individual cycle is determined from the pressure signal. First the measured pressure signal, P is smoothed by taking a simple running average over three adjacent crank angle positions. The smoothed pressure, $Ps(i)$, at a crank angle position i , is given by:

$$Ps(i) = \frac{P(i-1) + P(i) + P(i+1)}{3} \quad (7)$$

$Ps(i)$ is the pressure signal averaged over 0.3 CAD or 33.33 μs at 1500 RPM since in the region of interest, the crank angle resolution of pressure measurement was 0.1 CAD in [5]. This effectively filters the high frequency fluctuations from the pressure signal. The knock signal, $Pk(i)$, at a crank angle position, i , is given by:

$$Pk(i) = P(i) - Ps(i) \quad (8)$$

Figure 1 shows an example of the pressure and the knock signals from a single knocking cycle. The crank angle at knock onset, CA_{ko} , is defined as the crank angle position when the knock signal first deviates from zero by 0.05 bar. The pressure at knock onset, P_{ko} , is the pressure at CA_{ko} .

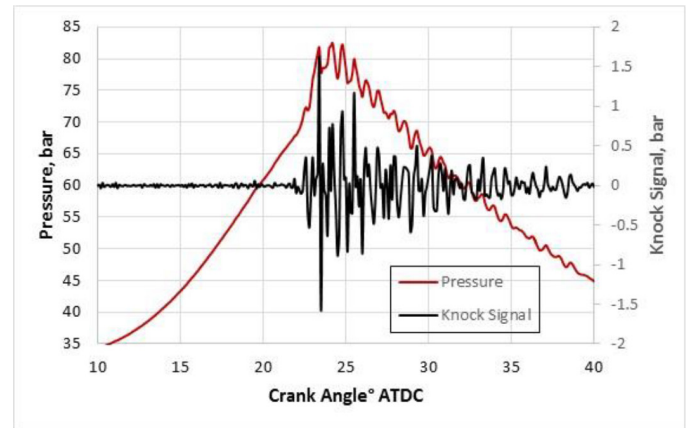


Fig.1. Example of a pressure signal and a knock signal for a single knocking cycle.

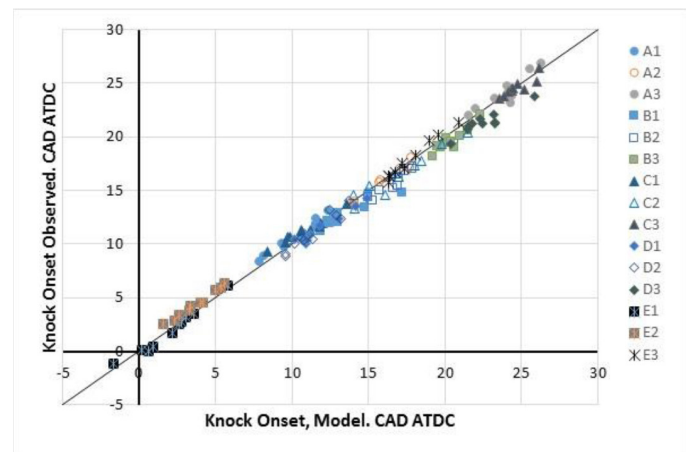


Fig.2. Predicted vs observed crank angle at knock onset from [5]. In the legend, A1 stands for Fuel A Condition 1 and so on.

The measured crank angle at which knock onset was observed agreed very well with that predicted using Eq.4 in all the cases considered in [3, 5]. This is illustrated in Fig.2 taken from [5] which shows results for ten individual cycles at three different operating conditions in a single cylinder engine for five different fuels - 150 cycles in total. The engine was operating at 1500 RPM and wide open throttle at all three operating conditions. The intake pressure was at 1.65 bar abs for Condition 3 while it was at atmospheric pressure but at different intake temperatures at the other two operating conditions. The value of ΔT , the temperature increment in the hot spot at 15 bar pressure, had to be chosen to be 30 K for Condition 3 compared to 10 K for the two non-boosted operating conditions to get the observed knock onset position to agree well with the predicted value as shown in Fig.2. With ΔT of 10 K for the boosted Condition 3, knock was predicted to occur much later than observed for all 50 cycles considered suggesting that the estimated temperature was too low. We cannot really be sure of the accuracy of either our estimation of the temperature evolution in the hot spot or the accuracy of the ignition delay equations - this is an inescapable problem in knock studies. However Fig.2 gives us confidence that the combination of the two is accurate enough for our purposes. These data will be used in the subsequent analysis.

3. KNOCK INTENSITY - THEORETICAL CONSIDERATIONS

We define knock intensity, KI , as the difference between the maximum and minimum of the knock signal. It should be noted that the value of KI in a given cycle depends on the width of the smoothing window (in the crank angle or frequency domain), the sampling resolution and also on the frequency response of the pressure measurement system. Hence it is not an objective measure - this is a dilemma faced in all knock studies. We also arbitrarily consider only those cycles with $KI > 0.5$ bar to be knocking in the rest of this paper. Again there is no objective definition of knock - one can choose any threshold for KI to characterize an engine cycle as a knocking cycle.

Knock intensity is determined by the evolution of the pressure pulse with time following autoignition in the hot spot i.e. knock onset. Bradley and co-workers [6, 7, 8, 9, 10] have shown, based on the work by Zeldovich and Oppenheim [11,12], that the evolution of the pressure wave is critically dependent on the velocity, u_a , of the autoignition wave as it traverses through the hot spot and is given by:

$$u_a = (\partial x / \partial \tau_i) = (\partial \tau_i / \partial T)^{-1} (\partial T / \partial x)^{-1} \quad (9)$$

Here, x is the distance from the center of the hot spot. In particular, “the resonance parameter”, ξ , the ratio of the local speed of sound, a , to u_a , is the critical parameter:

$$\xi = \left(\frac{a}{u_a} \right) \quad (10)$$

The speed of sound is given by :

$$a = \sqrt{\gamma R T} \quad (11)$$

Where γ is the ratio of specific heats and R is the specific gas constant. We will assume a fixed value of $375 \text{ m}^2\text{s}^{-2}\text{K}^{-1}$ for γR . From Eq.4, the gradient of ignition delay with temperature is:

$$(\partial \tau_i / \partial T) = -B \tau_i / T^2 \quad (12)$$

So that from Eq. 9:

$$u_a = - \left(T^2 / B \tau_i \right) (\partial T / \partial x)^{-1} \quad (13)$$

Note that the gradient of temperature with distance in Eq.13 is negative because the temperature in the hot spot is high at the center and decreases away from the center. Bradley and Kalghatgi [13]

showed that when u_a is small, the maximum amplitude of the pressure pulse, ΔP_{max} , following autoignition can be approximated by:

$$\frac{\Delta P_{max}}{P} = \xi^{-2} \quad (14)$$

Also, by our definition of KI , we assume:

$$\Delta P_{max} = \frac{KI}{2} \quad (15)$$

Hence from Eq.s 10, 11, 13, 14 and 15 we get:

$$KI = Z \left(\frac{\partial x}{\partial T} \right)^2 \quad (16)$$

Where, Z is given by:

$$Z = \frac{2PT^3}{375\tau_i^2 B^2} \quad (17)$$

Also:

$$\xi = -\sqrt{375T} \frac{B\tau_i}{T^2} \left(\frac{\partial x}{\partial T} \right)^{-1} \quad (18)$$

Note that since T is a function of P (Eq.6) for a given operating condition, Z is only a function of pressure, P . For each knocking cycle, we have measured values of KI and the value of Z from the measured value of P at knock onset (P_{ko}) and hence we can calculate $(\partial x / \partial T)$ from Eq.16. We use the framework described in this section to interpret the nature of knock intensity and superknock. In all the calculations, T is in K, τ_i is in ms, a , is in m/s, then $(\partial x / \partial T)$ will be in mm/K.

4. EXPERIMENTAL DETAIL

Five fuels were tested in a single cylinder engine at King Abdullah University of Science and Technology (KAUST) running in direct injection mode. Each of the fuels was run at different spark timings at each of the three conditions in [5] - one of which, Condition 3, was with a boosted intake. We only consider this operating condition in the rest of this paper.

The details about the engine and the operating conditions are provided in Table 1. For each spark timing, in-cylinder pressure was measured with a flush-mounted and water-cooled Kistler piezoelectric pressure transducer. The output of the transducer was preconditioned and acquired with an AVL data acquisition system. A synchronized rotary encoder was used to sample the data at intervals