

Advanced Knock Detection for Diesel/Natural Gas Engine Operation

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ABSTRACT

As emission limits become increasingly stringent and the price of gaseous fuels decreases, more emphasis is being placed on promoting gas engines. In the field of large engines for power generation, dual fuel combustion concepts that run on diesel/natural gas are particularly attractive. Knock in diesel/natural gas dual fuel engines is a well known yet not fully understood complex phenomenon that requires consideration in any attempt to increase load and efficiency. Thus combustion concept development requires a reliable yet robust methodology for detecting knock in order to ensure knock-free engine operation.

Operating parameters such as rail pressure, start of injection and amount of diesel injected are the factors that influence oscillations in the in-cylinder pressure trace after the start of combustion. Oscillations in the pre-mixed combustion phase, or ringing, are caused by the rapid conversion of large parts of the injected diesel. This effect may lead to misinterpreting non-knocking combustion cycles determined from the in-cylinder pressure trace data or knock sensor data.

This paper describes a new knock detection methodology based on the in-cylinder pressure trace and knock sensor data applied to a diesel/natural gas dual fuel large engine. The approach compares oscillations in the pre-mixed diesel combustion phase to oscillations in the main combustion phase. Parameters that provoke oscillations (rail pressure, start of injection and amount of diesel injected) as well as other parameters influencing knock (IMEP, excess air ratio, manifold air temperature, methane number and compression ratio) are investigated and discussed. This specific approach requires only two steady threshold limits to cover all these parameters influencing knock and to distinguish between knocking and non-knocking combustion cycles.

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INTRODUCTION

As the price of gaseous fuels decreases as a result of new extraction methods, the use of dual fuel engines is gaining momentum. However, it is not just operating costs that have drawn attention to this combustion concept; emission legislation is another factor driving the integration of the advantages of both diesel and gas engine combustion into one combustion concept.

As in spark ignition gas engines, knock is still the limiting factor for power output and thus any increase in efficiency in engines that use diesel to ignite a homogeneous natural gas/air mixture. Compression

ignition combustion concepts require higher compression ratios than spark ignition combustion concepts, which is counterproductive because of knock. [Figure 1](#) shows the trade-off between engine load (IMEP), lambda (λ) and the compression ratio (CR) of a spark ignited large gas engine according to Wimmer et al. [1]. The engine operation range is limited on the one hand by knocking with richer mixtures and on the other hand by instabilities or misfiring at leaner mixtures. In addition, increasing the compression ratio would inevitably result in a smaller engine operating range.

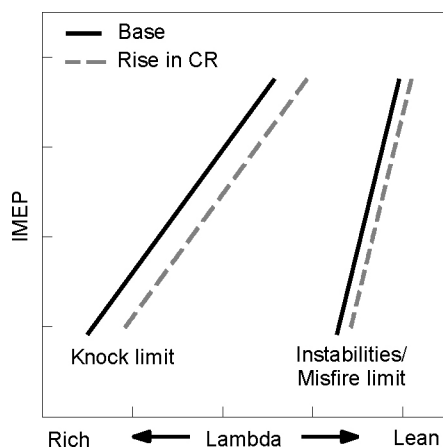


Figure 1. Trade-off between IMEP, lambda and CR in terms of engine operation range [1]

Testing revealed two combustion anomalies in dual fuel operation using diesel fuel ignition and a homogeneous natural gas/air mixture as the main charge. Under certain operation conditions, engines exhibit not only knocking from the combustion of natural gas fuel but also ringing from the combustion of diesel fuel. Knock detection algorithms commonly used for spark ignition gasoline engines or spark ignition gas engines lead to misleading interpretations of the single combustion process in terms of knock because pre-mixed combustion causes the occurrence of ringing. To overcome this problem, a new knock detection methodology was developed and tested based on in-cylinder pressure data as well as knock sensor data.

This paper describes the phenomenon of ringing and knocking combustion in large gas engines and introduces a new knock detection algorithm for diesel/natural gas dual fuel engines. This algorithm is verified using the in-cylinder pressure trace and knock sensor data.

RINGING vs. KNOCKING COMBUSTION

In both ringing and knocking combustion, a sudden conversion of larger parts of the fresh charge excites the whole cylinder charge, causing it to oscillate at a high frequency. These two types of combustion are familiar from diesel combustion, but when ringing or both ringing and knocking occur in one combustion cycle of a dual fuel engine, correct interpretation of knocking combustion becomes difficult.

Ringing Combustion

Ringing refers to the occurrence of pressure waves during pre-mixed combustion, and in most cases it continues until the end of combustion. As described by Eng [2], pressure oscillations from ringing combustion can often be five to ten times higher than those of combustion under knocking conditions. Such pressure oscillations result in increased engine noise due to an initial steep rise in pressure. Tsurushima et al. [3] stated that ringing is also problematic with HCCI combustion concepts, where the oscillations can be harmful in the event that combustion starts close to the combustion chamber

wall, which has a direct influence on the heat transfer. In the case of dual fuel operation, however, it is not yet known if these pressure oscillations have negative effects.

Figure 2 shows three consecutively measured combustion cycles under constant boundary conditions in steady state operation.

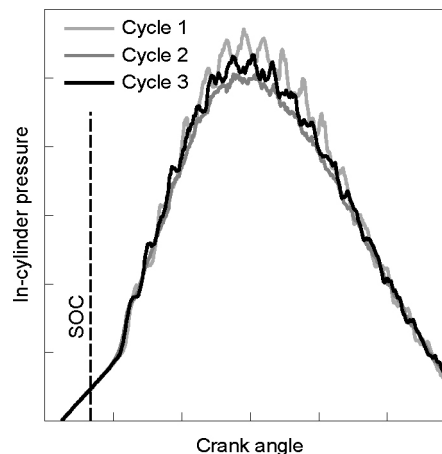


Figure 2. Comparison of three consecutive in-cylinder pressure traces with various ringing intensities

The start of combustion (SOC) given is the average of the three cycles shown. This engine runs under steady state conditions where the start of current is constant and the ignition delay for 60 recorded cycles varies within a range of $\pm 1.5^\circ\text{CA}$. Interestingly the intensity of ringing differs from cycle to cycle. It seems to arise randomly during normal combustion cycles, and the amplitude of the pressure waves appears to be determined by the amount of fuel consumed during pre-mixed combustion.

The phasing of the overlaid oscillations differs from cycle to cycle. When cycles 1 and 3 are compared, a shift can be observed. The reasons for this are:

- Fluctuation in ignition delay due to cycle based charge distribution and mixture preparation,
- Changes in the location of the start of combustion, and
- Different mass fractions consumed during the pre-mixed combustion.

This directly leads to the question of which parameters influence the mean ringing intensity. As experiments have shown, ringing is dependent on the following:

- Rail pressure
- SOI
- Amount of diesel injected

Advancing or increasing these parameters has a great impact on the ringing intensity. When all three parameters were compared with each other, they showed very similar effects.

Figure 3 shows one parameter that influences ringing, SOI variation, starting with a baseline SOI which is then advanced by 4 and 8 °CA, respectively. When SOI is advanced, more time is available for mixture preparation, thereby favoring ringing, and vice versa. At a constant IMEP and excess air ratio, the boost pressure was adjusted accordingly. The band pass filtered pressure trace (frequency range 1-12 kHz) is also shown in Figure 3. Due to the significant impact of SOI on ringing, severe amplitudes of more than 6 bar can be seen.

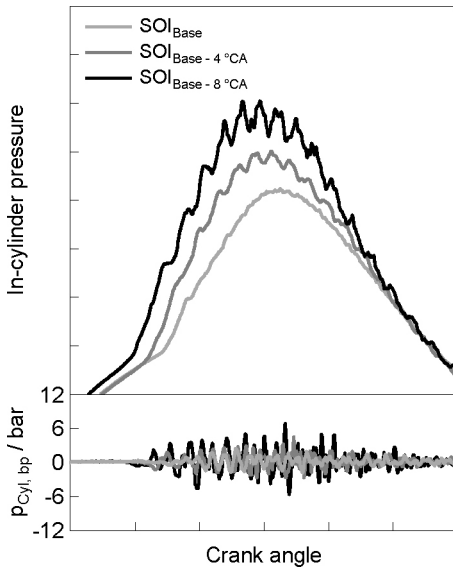


Figure 3. SOI variation at constant lambda and IMEP

When the amount of diesel fuel injected into the combustion chamber is reduced, less energy is released during pre-mixed combustion and thus less ringing occurs. Karim et al [4] stated that very small amounts of injected diesel cause a homogenization of the in-cylinder charge, which is consumed by combustion in a manner similar to HCCI combustion. Probable reasons for this fast combustion are:

- In-cylinder conditions that lead to special spray formation and therefore effective homogenization
- The geometry of combustion chamber and in-cylinder flow conditions

This cannot be confirmed when the amount of diesel injected is less than five percent of the total energy content of the cylinder.

Changing rail pressure has a different effect on ringing. At low rail pressures (600 bar), less diesel penetrates into the combustion chamber than at high rail pressures. Low rail pressures result in poorer mixture preparation and smoother consumption of the diesel fuel, which is why ringing becomes less severe. In contrast, high rail pressures allow the diesel to penetrate deeper into the combustion chamber, thereby resulting in better mixture preparation which in turn favors ringing.

Knocking Combustion

Since diesel/natural gas dual fuel operation is subject to the same restrictions as every Otto cycle engine, knocking is also the limiting factor in achieving higher power density and increased compression ratios, which are associated with higher efficiencies.

Past research has revealed that hot spots in the end gas are responsible for the spontaneous release of the remaining energy carried in this zone. Thermodynamically speaking, this irregular combustion is a sudden conversion of the remaining chemical energy into thermal energy. [5] The term “end gas” refers to the remaining cylinder charge in the specific combustion cycle that has not been consumed by the flame front.

Knock is a stochastic phenomenon, which means there is no abrupt transition from no knocking cycles to 100% knocking cycles [6]. Stochastic in this context means the sporadic occurrence of knock in individual combustion cycles, caused by significant cycle-to-cycle variations in the state of the cylinder charge.

Knock limited spark advance (KLSA) [7] is a term that refers to the distance between the current spark advance and the earliest spark advance where knocking occurs under certain boundary conditions. This implies that knock is dependent on time and is nonlinearly influenced by a number of operating parameters such as fuel properties [8], pressure and above all by the temperature of the unburned zone and thus the temperature of the intake air and the compression ratio.

This relationship to time can be determined by an Arrhenius approach (Equation 1), where A , n and E_a are fitted parameters depending on the fuel [9, 10]

$$\tau = A \cdot p^{-n} \cdot e^{\frac{E_a}{T_{uv}}} \quad (1)$$

When ignition timing is advanced under constant boundary conditions, the peak firing pressure is shifted towards top dead center (TDC), thereby increasing the pressure and the temperature level of the end gas, which is then more prone to auto-ignition.

As mentioned before, diesel/natural gas dual fuel combustion shows overlaid oscillations in the in-cylinder pressure trace after SOI (or ringing) under various operating conditions. These oscillations mask the occurrence of knock and are counterproductive to identifying knocking combustion cycles with commonly used knock detection methodologies.

Figures 4, 5, 6 show three examples of different in-cylinder pressure traces, their corresponding smoothed RoHR as well as their bandpass filtered signals. All three were taken in diesel/natural gas dual fuel operation. Figure 4 shows an in-cylinder pressure trace similar to that of a gas engine with severe knock and amplitudes over 5 bar as visible from the band-pass filtered pressure trace. The second example (Figure 5) shows a combustion cycle with only severe ringing. As the figure clearly shows, ringing begins at the start of combustion and indeed decreases but is detected throughout the whole combustion cycle. The last example depicted in Figure 6 shows ringing and knocking combustion that occurs at the same time within one cycle, indicating how knocking combustion can be masked by ringing.

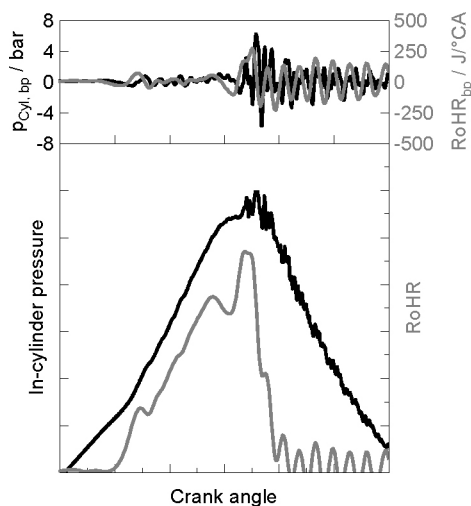


Figure 4. In-cylinder pressure trace and RoHR of a non-ringing but knocking combustion cycle of a diesel/natural gas dual fuel engine

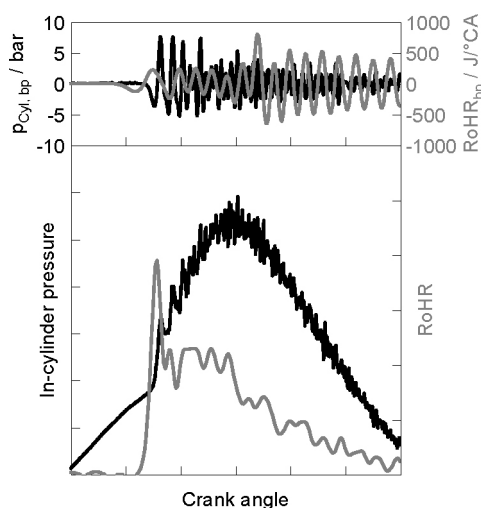


Figure 5. In-cylinder pressure trace and RoHR of a ringing but non-knocking combustion cycle of a diesel/natural gas dual fuel engine

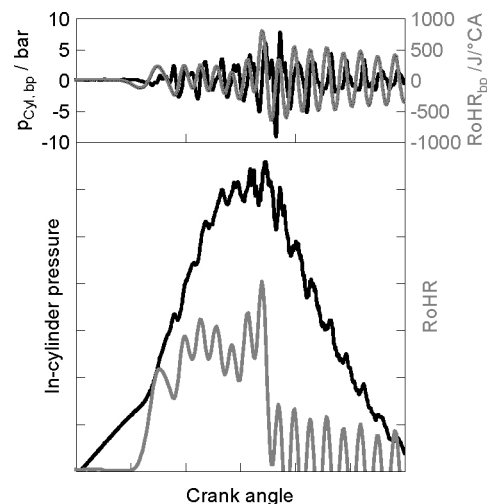


Figure 6. In-cylinder pressure trace and RoHR of a ringing and knocking combustion cycle of a diesel/natural gas dual fuel engine

These examples illustrate the broad variety of different in-cylinder pressure trace appearances and thus the importance of a reliable and robust knock detecting algorithm.

COMBUSTION CHAMBER RESONANCE

It is possible to perform a frequency-domain analysis when there are multiple oscillations modes present in the combustion chamber. To perform this analysis, the time-domain should be written in a Fourier series (see Equation 2 [11]):

$$P(x, t) = \sum_n A_n \cos(k_n x - \omega_n t) \quad (2)$$

According to Parseval's theorem, the total energy in the time and frequency domains must match. This relationship can be seen in Equation 3,

$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(f)|^2 df \quad (3)$$

where $x(t)$ is the time domain signal and $X(f) = F\{x(t)\}$ frequency domain transformed $x(t)$ [11, 12].

The left term is known under the abbreviation AEPO (average energy of pressure oscillations) and the right term under AEFD (average energy of frequency domain). Either the whole cycle or at best the knock sensitive window (KSW) $\Delta\phi$ should be used [13]. In this study, a KSW from 40 °CAbTDC to 100 °CAaTDC was used.

Figure 7 shows three in-cylinder pressure traces, their band-pass filtered in-cylinder pressure trace and the corresponding power spectrum calculated from the band-pass filtered in-cylinder pressure trace using Fast Fourier Transformation (FFT) analysis. Whereas the light gray combustion cycle represents the knock-free or normal operation, the dark gray cycle indicates intense ringing and black means (severe) knock.