Applied Thermal Engineering 31 (2011) 2869–2876

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Adaptive determination of cut-off frequencies for filtering the in-cylinder pressure in diesel engines combustion analysis

F. Payri, P. Olmeda*, C. Guardiola, J. Martín

CMT-Motores Térmicos, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022, Valencia, Spain

ARTICLE INFO

Article history:
Received 15 June 2010
Accepted 8 May 2011
Available online 14 May 2011

Keywords:
Diesel engines
In-cylinder pressure
Signal filtering
Combustion analysis

ABSTRACT

In-cylinder pressure analysis is a key tool for engine research and diagnosis and it has been object of study from the beginning of the internal combustion engines. One of its most useful application is combustion analysis on the basis of the First Law of Thermodynamics. However, heat release law calculations use the in-cylinder pressure derivative signal. Hence, the noise is increased and pressure filtering becomes necessary to remove high frequency noise, thus allowing for accurate combustion analyses. In this work, a methodology to set the cut-off frequency of a low-pass filter is proposed. Statistical criteria are used to separate the signal from the noise through the calculation of the Discrete Fourier Transform of several consecutive in-cylinder pressures cycles. Thus, only physically meaningful information is preserved. The proposed methodology is compared with some adaptive and non-adaptive algorithms used to select the cut-off frequencies, and it shows a good ability to adapt to different engine operating conditions.

1. Introduction

In the last years, numerous studies aiming at a deeper understanding of the physics underlying combustion in reciprocating engines have been published. The objective of such studies is twofold: to diminish pollutant emissions [1] and to increase engine performance. In this context, in-cylinder pressure measurement is considered a valuable source of information during engine development and calibration, as it provides relevant data such as peak pressure, and indicated and pumping mean effective pressures. In-cylinder pressure analysis can even be used for more complex applications, such as air mass flow estimation [2], on-line combustion detection [3], emissions control [4], noise control [5], heat transfer [6,7], etc.

Information is usually obtained from in-cylinder pressure signals by means of heat release analysis [8,9], which provide direct information about the instantaneous combustion evolution, thus allowing for a proper characterization of the combustion process. Among other possibilities, this characterization permits the adjustment of combustion laws, usually by means of Wiebe functions, which can be used by engine manufacturers and researchers in order to estimate the behaviour of the engine with the purpose to optimize engine design [10,11]. The *net apparent heat release*, $\mathrm{d}Q_n$, can be obtained from the First Law of Thermodynamics as [9]:

$$\mathrm{d}Q_n = \frac{\gamma}{\gamma - 1}\, p\, \frac{\mathrm{d}V}{\mathrm{d}t} + \frac{1}{\gamma - 1}\, V\, \frac{\mathrm{d}p}{\mathrm{d}t} \tag{1}$$

where p is the in-cylinder pressure, V is the instantaneous volume and γ is the adiabatic coefficient.

It can be seen in (1) that the main experimental input required for heat release analysis is the measured in-cylinder pressure (and its derivative), so that the accuracy of the obtained $\mathrm{d}Q_n$ is strongly dependent on the quality of in-cylinder pressure acquisition and processing.

Although the measurement of in-cylinder pressure has been subject of study since the beginning of the internal combustion engine, several problems are still present:

1 Pressure referencing, both in absolute level and angular phasing [12–14]
2 Different sources of error affecting the quality of the raw pressure signal and its subsequent analysis [15]
3 Cycle-to-cycle variations, which can be observed even when the engine operates in steady conditions This effect is due to different causes related with fuel supply, air motion, trapped mass and its composition [16,17].

According to the previous comments, a finite number of cycles (typically between 25 and 100) are acquired and then subject to a four-step data processing consisting of: level and angle referencing,

* Corresponding author. Tel.: +34963877650; fax: +34963877659.
E-mail address: pabolgon@mot.upv.es (P. Olmeda).
URL: http://www.cmt.upv.es

1359-4311/$ – see front matter
doi:10.1016/j.applthermaleng.2011.05.012

cycle averaging, and filtering. In this work, the last two issues are considered in detail.

The content of the paper is organized as follows. First, a description of different filtering techniques used in ICE applications is presented. Then, a short description of the specific test equipment used to obtain the experimental data is given in Section 3. The step-by-step methodology used to select the filter parameters is described in Section 4. The validation of the proposed method in terms of repeatability is presented in Section 5. Once the method is validated, it is applied to a representative set of experimental signals, the results being presented in Section 6, in which comparison with other filters is also shown. Finally, in Section 7, the most relevant conclusions extracted from the work are summarized.

2. Filtering techniques

Different filtering techniques may be used to obtain a smooth mean pressure cycle. Averaging diminishes point-to-point variation due to signal noise, thus becoming an easy, but usually insufficient, way to filter in-cylinder pressure. Another option is the moving average filter, but its ability to smooth depends on the sampling interval [18]; additionally, sharp pressure variations associated with premixed combustion are distorted. Slightly more complex, but more accurate, procedures are based on the use of least squares fits, such as the Savitzky–Golay filter [19].

However, digital filtering must usually be applied if high quality results are required. Low-pass filters are widely used as they are suitable for retaining the physical information useful for combustion analysis while removing high frequency noise. The main problem associated with low-pass filters is the determination of the optimum cut-off frequency [21,20], i.e., the frequency above which the noise-to-signal ratio becomes important. Moreover, the direct elimination of the high frequency band can cause overshoots in the pressure signal (the Gibbs effect) which cause non-negligible problems in the heat release calculation. This can be mitigated by smoothing the transition with a Hanning window [18], defined between two cut-off frequencies: the stopband initial frequency, k_1 and the stopband final frequency, k_2, as shown in (2).

$$\theta_k = \begin{cases} \theta_k = 1 & k < k_1 \\ \cos\left(\frac{\pi}{2}\cdot\frac{k-k_1}{k_2-k_1}\right) & k_1 \le k \le k_2 \\ \theta_k = 0 & k > k_2 \end{cases} \tag{2}$$

In most cases, the selection of the cut-off frequencies are based on ad hoc methods and rule-based algorithms. The main objective of this paper is to propose an automatic methodology allowing to select the values of cut-off frequencies so that the signal filtering of in-cylinder pressure is optimized for combustion analysis. As the methodology is based on the own signal characteristics, no rule-based criterion is necessary. The performance of the filter will be compared with other filters in order to illustrate the improvement achievable in terms of heat release. Although the filtering procedure will be applied to experimental data from direct injection diesel engines, the proposed approach is easily adaptable to other engines and measurement configurations.

3. Experimental set-up and tests

A sketch of the test cell layout with the basic instrumentation is shown in Fig. 1. Measurements were carried out on a high-speed direct injection 2.0 litre diesel engine currently in production, whose main characteristics are given in Table 1. The engine was directly coupled to an electric dynamometer allowing for engine speed and load control.

Mean variables necessary for controlling the engine operating point and also for combustion analysis were acquired at a constant sample rate of 100 Hz with an AVL test system. In-cylinder pressure was measured in one of the four cylinders by means of a Kistler 6055B glow-plug piezoelectric transducer connected to a Kistler 5015 charge amplifier. Measurements were performed with an angular resolution of 0.5 crank angle degrees and a Yokogawa DL708E oscillographic recorder was used. The pressure sensor was calibrated according to the usual method [22] based on a quasi-steady calibration by means of a deadweight tester with NPL and NIST traceability. With this procedure, the relative error obtained from the calibration of the transducer was $\pm$ 0.7%.

Table 2 summarizes the tests used for illustrating the results of the proposed methodology, which include a wide variety of engine operating conditions: motored tests at different engine speeds and also several combustion tests with different engine speeds and loads.

4. Methodology for the determination of the cut-off frequencies

The method used to determine the cut-off frequencies is based on the qualification of the frequencies according to their noise-to-signal ratio. The procedure is as follows:

1. The starting point is the raw in-cylinder pressure signal measured during n_c consecutive cycles at n_s samples per cycle.

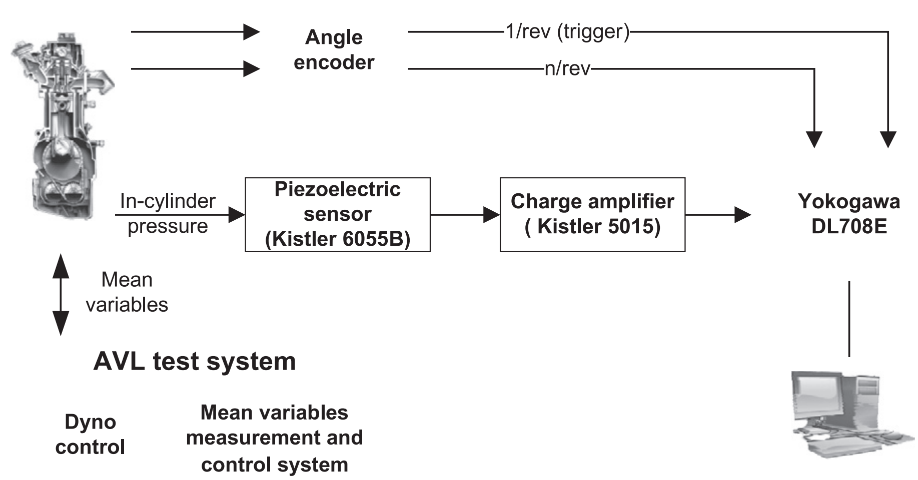

Fig. 1. Measurement chain layout in the engine test bench.