Combustion and Flame 157 (2010) 632–640

Contents lists available at ScienceDirect

Combustion and Flame

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

POD-based analysis of combustion images in optically accessible engines

K. Bizon [a], G. Continillo [a,*], E. Mancaruso [b], S.S. Merola [b], B.M. Vaglieco [b]

[a] Università del Sannio, Piazza Roma 21, 81200 Benevento, Italy
[b] Istituto Motori, CNR, Via Marconi 8, 80125 Naples, Italy

ARTICLE INFO

Article history:
Received 15 January 2009
Received in revised form 5 May 2009
Accepted 14 December 2009
Available online 13 January 2010

Keywords:
Proper orthogonal decomposition
Internal combustion engine
Optical imaging

ABSTRACT

This paper reports on 2D images of combustion-related luminosity taken in two optically accessible automobile engines of the most recent generation. The results are discussed to elucidate physical phenomena in the combustion chambers. Then, proper orthogonal decomposition (POD) is applied to the acquired images. The coefficients of the orthogonal modes are then used for the analysis of cycle variability, along with data of dynamic in-cylinder pressure and rate of heat release. The advantage is that statistical analysis can be run on a small number of scalar coefficients rather than on the full data set of pixel luminosity values. Statistics of the POD coefficients provide information on cycle variations of the luminosity field. POD modes are then discriminated by means of normality tests, to separate the mean from the coherent and the incoherent parts of the fluctuation of the luminosity field, in a non-truncated representation of the data. The morphology of the fluctuation components can finally be reconstructed by grouping coherent and incoherent modes. The structure of the incoherent component of the fluctuation is consistent with the underlying turbulent field.

1. Introduction

Nowadays various optical systems allow for two- or even three-dimensional measurements of in-cylinder variables. The fast development of these systems today permits the investigation of the entire spectral range of flame light emission, with high spatial and temporal resolution. The amount of data collected can be impressive and computational methods for data reduction and analysis are being developed and used. Development of particle image velocimetry (PIV) resulted in many works concerning the application of the proper orthogonal decomposition (POD) technique to experimental two-dimensional data. POD was applied both to computational fluid dynamics and PIV data of simplified motored engine flows [1], where a decomposition of the complex spatio-temporal flow field into sets of spatial modes and the corresponding expansion coefficients was conducted. Those authors claim that such a decomposition, besides supplying information about the dynamics of the flame, may be suitable for creating a low-dimensional model of this process. Druault et al. [2] extended the use of the procedure to recovering the time information between two consecutive PIV time measurements, by coupling POD with simple time interpolation of the modal coefficients, to provide a continuous space–time description of the flow in a spark ignition (SI) engine. Subsequently, some attempts to analyse the cycle-to-cycle variations of the velocity field in SI engines were made [3,4]. There, a filtering approach, based on POD and statistical moments analysis, was proposed and used for the determination of the mean, coherent and incoherent parts of the in-cylinder flow, measured by means of PIV. It was shown that low-order POD modes, identifiable with the incoherent part, capture the cyclic variability of the flow. All works mentioned here concern SI engines, because, due to thermodynamic and geometric constraints, it was difficult to apply PIV techniques to diesel engines. However, some results are reported in [5] where in-cycle PIV measurements obtained from a transparent diesel engine were decomposed by means of POD, and the evolution of modal coefficients was analysed.

Most literature focuses on the application of POD to velocity measurements; however it appears that measurements of light emission during the combustion process also carry information on cycle-to-cycle variation phenomena, which can occur in all forms in engines. In an earlier work, POD was applied to reconstruct information in between consecutive measurements of flame luminosity measured during experiments conducted on an optically accessible SI engine [6]. Additionally, a weighting procedure based on dynamic in-cylinder pressure data collected together with flame images was proposed. This procedure allowed the reconstruction of in-cycle evolution of the flame, which is usually difficult to investigate only on the basis of the measurements, due to the limitation in the time resolution of the employed optical setup. Likewise, in a previous paper the structure of flame images obtained from a diesel engine was analysed by means of POD [7]. The procedure, coupled with linear interpolation

---

* Corresponding author. Fax: +39 0824325246.
E-mail address: continillo@unisannio.it (G. Continillo).

0010-2180/$ - see front matter © 2009 The Combustion Institute. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.combustflame.2009.12.013

of the coefficients, was used to reconstruct information in between consecutive, cycle-resolved experimental measurements.

This work reports on 2D line-of-sight averaged measurements of flame emission taken during experiments conducted in optically accessible SI and diesel engines. Proper orthogonal decomposition (POD) is applied to the recorded data. The procedure is first introduced and demonstrated by means of a "synthetic" example. Then, it is shown how POD permits the analysis of cycle variability, by extracting mean, coherent and incoherent parts of the luminosity field and by visualising their morphology, in a non-truncated representation of the collected data. One of the main advantages of POD is that analysis can be reduced to a small number of scalar coefficients, rather than conducting it on a full data set of pixel luminosity values.

2. Experimental setup

2.1. Spark ignition engine

An optically accessible single cylinder port fuel injection (PFI) spark ignition (SI) engine was used for the experiments. The engine was equipped with the cylinder head of the new generation of turbocharged SI engines [8]. This was a four valve head with a centrally located spark plug. A quartz pressure transducer was flush-installed in the region between intake and exhaust valves. Combustion pressure measurements were performed for all of the selected operating conditions. A flat piston featuring a quartz window (ϕ = 57 mm) to render it transparent was used. To reduce window contamination by lubricating oil, an elongated piston arrangement was used together with non-lubricated teflon–bronze composite piston rings in the optical section.

During the combustion process, the light passes through the UV fused silica window located in the piston, to be reflected towards the optical detection assembly by a 45° inclined UV–visible mirror in the bottom of the engine. The light is then focused onto an intensified cooled CCD camera (ICCD) by a 78 mm focal length, *f*/3.8 UV Nikon objective. The ICCD had an array size of 512 × 512 pixels and 16-bit dynamic range digitization at 100 kHz and a spectral range from UV (180 nm) to visible (700 nm).

All of the tests presented in this paper were conducted at an engine speed of 2000 rpm and full load. The spark timing was set at −14 CAD. An external boosting device fixed the absolute intake air pressure and temperature at 1400 mbar and 323 K, respectively. Commercial gasoline with octane number 95 was used. For all optical measurements, the camera was synchronised with the engine by a crank angle encoder signal. The exposure time of the camera was fixed at 41.6 μs, which corresponds to 0.5 crank angle (CA) degree at an engine speed of 2000 rpm. The camera was not a cycle-resolved detector. In this work, each image was detected at a fixed crank angle of different engine cycles.

2.2. Diesel engine

A direct injection four-stroke common rail (CR) diesel engine with a single cylinder and a multi-valve production head was used to conduct experiments for optical measurements. The modified research engine featured a classic extended piston with an UV–visible grade crown window (34 mm diameter) providing a full view of the combustion bowl and flame evolution [9,10].

All data presented in this paper was produced using commercial diesel fuel, without exhaust gas recirculation, at an engine speed of 1000 rpm and continuous mode operation. A typical common rail injection strategy of pre, main and post injections (PMP) [9] in every cycle was used, with pre, main and post injections starting at −9 CAD, 4 CAD and 11 CAD respectively, with durations of 400, 625 and 340 μs. Injection pressure was fixed at 600 bar.

Temporal and spatial evolution of visible flames were investigated by acquiring several images per cycle, with a high-speed digital complementary metal oxide semiconductor (CMOS) camera with a dynamic range digitization. A high frame rate (4 kHz) was needed in order to take several images per cycle, resulting however in low light sensitivity and spatial resolution (529 × 147 pixels). The exposure time of the camera was fixed at 83.3 μs, which corresponds to 0.5 crank angle (CA) degree at an engine speed of 1000 rpm. From these images, 128 × 128 staggered colour bitmaps were cropped and binned to yield 64 × 64 grey scale bitmaps, on which the analysis was performed [10].

3. Proper orthogonal decomposition

3.1. Mathematical background

Proper orthogonal decomposition extracts dominant structures from a given ensemble [11]. When the number of collected samples is smaller than the space discretization, it is more convenient to use the Sirovich approach [12] also known as "method of snapshots". The ensemble can be either generated by detailed numerical simulations or collected experimentally. Applications of POD span a broad range of physical systems. Amongst the most recent examples in combustion, we mention in particular the analysis of simulation data of autoignition on hydrogen–air mixtures conducted in [13] and the study of the unsteady modes of the oscillating flow in a ramjet combustor by means of POD applied to large eddy simulation (LES) results [14].

Suppose we are given a data set $u_k(x)$ where x is the space coordinate and k is the snapshot index. Such a set can be conveniently represented as a matrix $U \equiv u_{jk}$ where $j = 1, \ldots, M$ spans the number of space positions and $k = 1, \ldots, N$ spans the number of snapshots u_k. We can build a set

$$\Phi = \{\varphi_1, \varphi_2, \ldots, \varphi_N\} \tag{1}$$

of linear combinations of the snapshots:

$$\varphi_i(x) = \sum_{k=1}^{N} \psi_{ik} u_k(x) \tag{2}$$

where $\Psi = \psi_1, \psi_2, \ldots, \psi_N$ is obtained by solving the eigenvalue problem $C\Psi = \lambda\Psi$, C being the space correlation matrix:

$$C = \frac{1}{N} U^T \cdot U \tag{3}$$

Then, $u_k(x)$ can be approximated by a linear combination of the first K modes:

$$\tilde{u}_k = \sum_{i=1}^{K} c_{ik} \varphi_i(x) \tag{4}$$

where $K \leqslant M$ is the number of modes used for truncation, whereas c_{ik} are modal coefficients that can be determined by projection of the data ensemble onto the POD modes.

3.2. POD filtering of cycle-to-cycle variations

Application of POD allows for an analysis of the considered scalar field by decomposing it into mean, coherent and incoherent parts via statistical methods. This idea was earlier introduced by Roudnitzky et al. [4] who applied POD to PIV data of velocity components in spark ignition engines obtained for cold flow. In the present work POD is applied to the analysis of images (scalar field) of luminosity in reactive flow. In this section it is shown how application of POD greatly reduces the computational work involved in the statistical analysis, in that statistical properties of the field can