ANALYSIS OF THE INDEPENDENT COMPONENTS FROM IMAGES OF TRANSIENT REACTIVE FLOWS

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Abstract

This paper reports on the application of independent component analysis (ICA) to 2D images of combustion-related luminosity, acquired from two single-cylinder optically accessible engines: a Euro 5 Diesel and a port fuel injection spark ignition. Independent components (IC) are extracted from sets of luminosity images, and their coefficients are used to identify leading independent structures and to study the transient during a single cycle. In a single Diesel cycle, the independent components appear to be clearly separated and related to combustion events near the fuel jets and near the bowl walls: quantitative analysis of coefficient statistics confirms lower variability of the jet flames with respect to combustion near the chamber walls. The spark ignition analysis employs three ICs, which correspond to start of ignition, middle propagation and end of combustion. The developed procedure, including the ICA, is fast and reliable and can be prospectively applied to many different optical engine configurations.

1. Introduction

Optical setups are potentially a very powerful investigation tool for the internal combustion engine. Nowadays, images of the flame with high spatial and temporal resolution are available. The impressive amount of data and the variety of phenomena taking place in the combustion chamber make interpretation quite a challenging task. This creates interest in the development and application of sophisticated mathematical tool permitting a more straightforward analysis of the experimental data. Among the others, proper orthogonal decomposition (POD) [1], which extracts dominant structures from a given ensemble, has been successfully applied to particle image velocimetry (PIV) fields obtained from a motored engine [2] and flame luminosity fields from Diesel and SI engines [3]. POD has contributed to the knowledge of internal combustion engine physics and chemistry, however it cannot separate statistically independent structures. Alternative decompositions can be considered, in which the components are chosen according to different criteria. In this view, independent component analysis (ICA) is expected to provide better insight [4]. ICA is based on the assumption that signals coming from different physical processes are statistically independent, and was originally conceived to deal with the cocktail-party problem, i.e. separation of speech signals from sample data of people talking simultaneously in a room [5]. The first attempt of the application of ICA to luminosity data from a Diesel engine is reported in [6], where the independent components related to the combustion along the fuel jets and near the bowl walls were found. This paper reports on the comparison of the application of ICA to images of combustion-related luminosity acquired from two optically accessible engines: Diesel and spark ignition. The coefficients of the independent components along with the measured in-cylinder parameters are used for the analysis of the transient during a single cycle.

2. Experimental setup

A direct injection four-stroke common-rail diesel engine with a single cylinder and a multi-valve production head is used for optical measurements. This modified research engine features a classic extended piston with a UV–visible grade crown window (34 mm diameter) providing a full view of the combustion bowl [7]. Data presented here is produced running with commercial diesel fuel at 1000 rpm, no exhaust gas recirculation and continuous mode operation. A typical common rail injection strategy of pre, main and post injections in every cycle was used, with pre, main and post injections starting at –9°, –4° and –11° CA (crank angle) respectively, with durations of 400, 625 and 340 μs, and 600 bar injection pressure. The second part reports on the analysis of images from a port fuel injection spark ignition (SI) engine, equipped with a four valve head with a central spark plug, from a latest generation turbocharged engine [8]. A flat piston featuring a quartz window (57 mm diameter) is used. All tests presented here are conducted with commercial gasoline, octane number 95, at 2000 rpm and full load. The spark timing is set at –14° CA. An external boosting device brings the absolute intake air pressure and temperature to 1400 mbar and 323 K, respectively..

3. Independent component analysis

Let us denote by $\mathbf{x}(t)$ the random vector whose elements are a temporal mixtures $x_1(t),\dots,x_m(t)$ of mutually independent temporal source signals $s_1(t),\dots,s_n(t)$ ($\mathbf{s}(t)$ in the vector form). Let us assume that m=n. The mixing model can be written as [3]:

$$\mathbf{x} = \mathbf{A}\mathbf{s} \tag{1}$$

where $\mathbf{A}$ is so-called mixing matrix. Then, the ICA problem consist of estimating both $\mathbf{A}$ and $\mathbf{s}$, when only $\mathbf{x}$ is observed. Eq.(1) can be recast as:

$$\mathbf{s} = \mathbf{W}\mathbf{x} \tag{2}$$

which can be solved by computing the matrix $\mathbf{W}=\mathbf{A}^{-1}$ in such a way that a linear combination $\mathbf{y}=\mathbf{W}\mathbf{x}$ is the optimal estimation of the independent source signals $\mathbf{s}$. Then the basic ICA problem can be solved by maximization of the statistical independence of the estimates $\mathbf{y}$. Depending on the definition of statistical

independence, the most popular ICA algorithms are either based on the minimization of mutual information or on maximization of non-gaussianity [3]. Here, a FastICA algorithm [3] is employed which maximizes kurtosis – one of the measures of statistical independence – by means of a gradient method.
The concepts of mixing and separation are illustrated with an artificial example in Fig. 1. A set of three independent source images (Fig. 1a) is chosen and multiplied by the mixing matrix **A** (with randomly generated elements) in order to yield mixture images (Fig. 1b). ICA is applied to determine signals **y**, i.e. the estimates of source signals **s**. The separation performance (Fig. 1c) of ICA is striking.

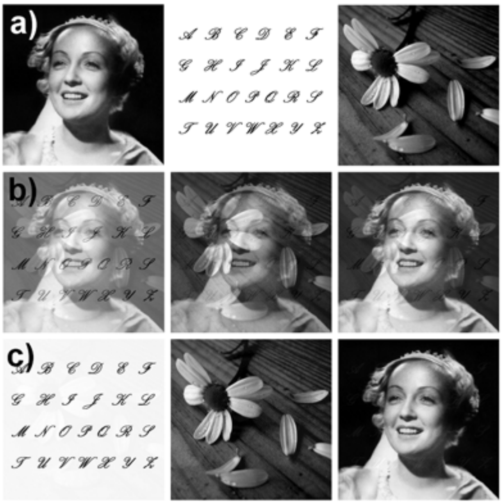

Figure 1. Independent source images (a), artificial mixtures of images (b), and images mixtures decomposed by means of ICA (c).

4. Results and discussion

Figure 1 shows typical images of combustion luminosity in a cycle obtained for Diesel engine, from –4° to 30.5° CA. Light spots are observed around the nozzle at –2.5° CA, due to ignition of the preinjected fuel. From 2° to 5° CA, combustion is present on all jets and in the vicinity of the chamber wall. As fuel along the jet axes is consumed, combustion moves towards the bowl wall, burning the impinged fuel.
ICA is applied to the crankangle resolved sequences of the 24 consecutive images. Figure 3 shows ICs y_1 and y_2, extracted from the cycle presented in Fig. 2 and recognized as being related to the combustion along the fuel jets (Fig. 3a) and near the chamber walls (Fig. 3b), respectively. The swirl motion of the burning jets can be identified in the curved shape of the components' "jets" in y_1 (Fig. 3a). It is interesting to see how time-dependent coefficients of the ICs correlate with combustion events. Figure 4a reports the rate of heat release (ROHR) and the integral rate of heat release for the analyzed combustion cycle. The start of combustion (SOC) of the various injections in the combustion chamber

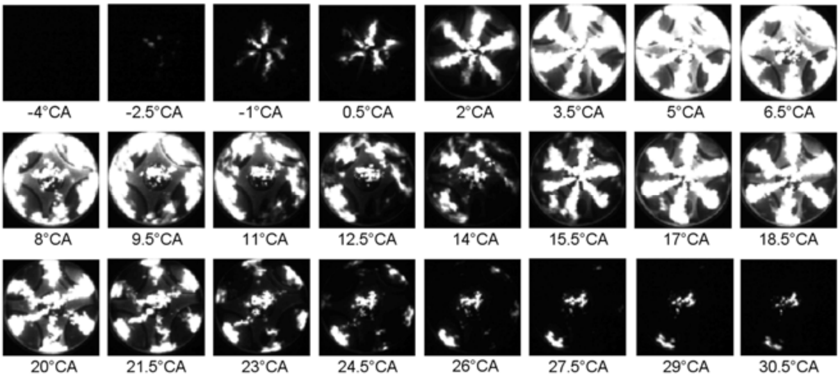

Figure 2. Sequence of crank-angle resolved images from Diesel engine.

corresponds to those crank angles where the ROHR becomes positive or changes its slope, i.e. –4°, 1°, and 14° CA, respectively. Figure 4b shows the time-dependent coefficients of the components together with the integral flame luminosity.

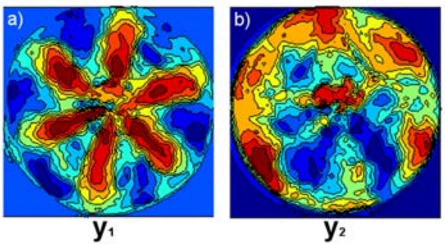

Figure 3. Independent components.

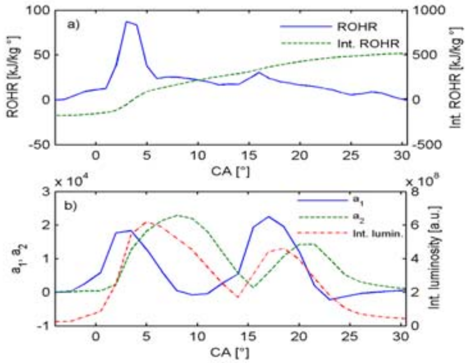

Figure 4. ROHR integral ROHR (a); IC coefficients a_1 and a_2, and integral luminosity (b).

The peaks of the coefficient a_1 of the component y_1, emerge at 3.5° and 17° CA, i.e. at the maximum luminosity of the regular combustion process near the fuel jets of the main and post injection.

Images collected from the SI engine at selected crank angles are reported in Fig. 5. The premixed flame front, ignited at -14° CA and quickly expanding in the chamber, after 7.6° CA is barely visible, due to diffusion flames establishing around and between intake valve seats. Intense diffusion flames are visible also later elsewhere in the chamber, due to the ignition of fuel film deposited on the cylinder walls, and to the gas motion from intake to exhaust. Such flames produce soot (rich zones), whereas chamber regions with lean mixture cannot sustain flame propagation and, hence, are responsible for unburned hydrocarbon emissions.

Figure 6 and 7 show the three ICs along with relevant coefficients as a function of

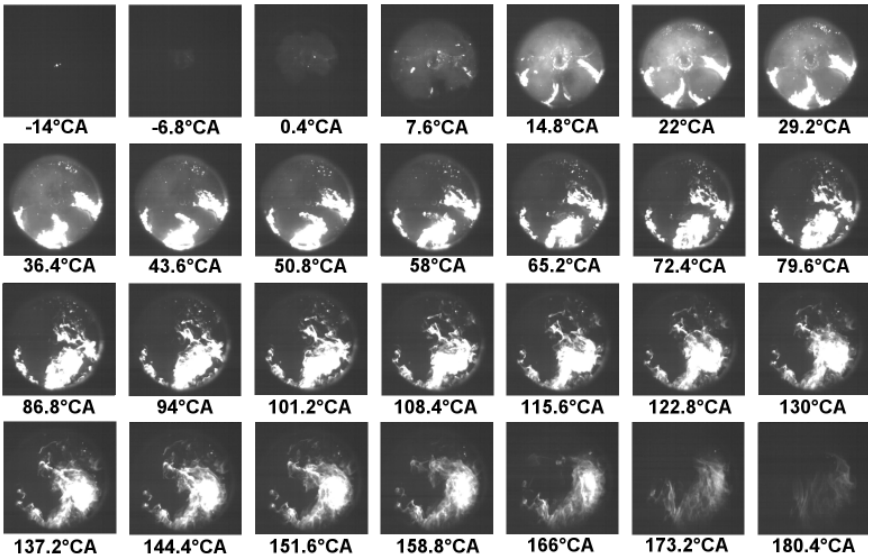

Figure 5. Sequence of crank-angle resolved images from SI engine.

time (crank angle). The coefficients show that, in this case, y_3 represents the prevailing initial luminosity, corresponding with the peaks in the rate of heat release and in-cylinder pressure; y_2 and y_1 represent the subsequent evolution of the luminosity field, as it can be seen from the visual evolution shown in Fig. 5.

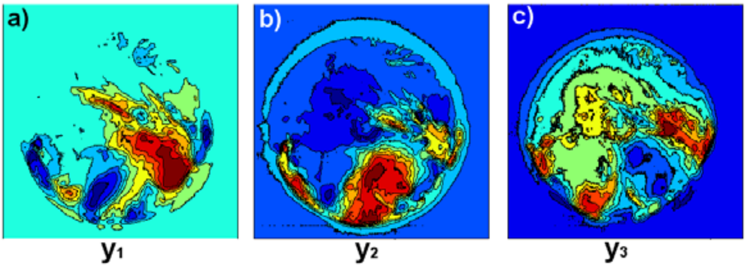

Figure 6. Independent components.

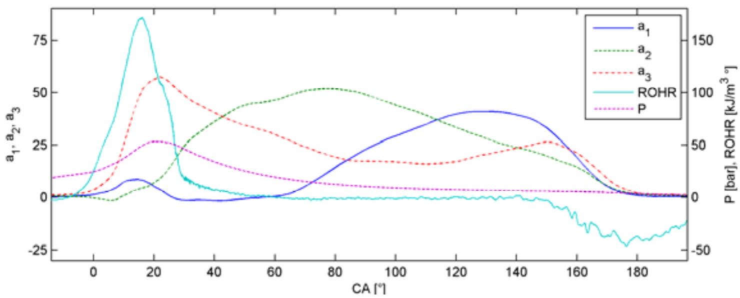

Figure 7. Coefficients a_1, a_2 and a_3, ROHR and pressure vs crank angle.

5. Conclusions

This work represents a first comparison of the results of the application of ICA to luminosity image data collected in Diesel and SI optical engines. Images are recorded and analyzed with sequential application of POD, followed by ICA. Two and three independent components were sought and found, for Diesel and SI respectively. The two Diesel components are clearly related to early combustion along the fuel jets and later combustion near the bowl walls, respectively. The same can be said of the results of the analysis for SI combustion images, which are separated in early, median and final luminous combustion.

This spatially distributed analysis is fast and reliable (a single computation takes less than 0.1 s on a standard sequential single processor). The benefits of ICA can be much higher than this simple application example shows: based on the demonstration shown in Fig. 1, more complex cases can be analyzed, and this is just a first and convincing example of how this technique works in an engine context.

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