Independent Component Analysis of transient reactive flows in optically accessible SI and Diesel engines

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1 Introduction

A fast development over the last decades of the optical setups has made available measurements of distributed in-cylinder variables such as instantaneous velocity or flame luminosity fields, with both spatial and temporal high resolution. This makes them a very powerful investigation tool for internal combustion engines (ICE). However, the interpretation of the collected – usually in impressive amounts – data can be quite challenging, mainly due to the variety of coupled phenomena taking place in the combustion chamber. This has lead to the necessity of the development of sophisticated mathematical tools which could facilitate and automatize the analysis of the in-cylinder processes. Perhaps the most notable is Proper Orthogonal Decomposition (POD) [1] – a powerful data analysis tool used to create low dimensional approximations of high dimensional systems. Among the other engineering applications, the method 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]. Even though the use of POD has contributed to the knowledge of many phenomena taking place in the combustion chamber, the method itself cannot separate statistically independent structures. Hence, alternative decompositions can be considered, in which the components are chosen according to different criteria. In this view, Independent Component Analysis (ICA) based on the assumption that signals coming from different physical processes are statistically independent, is expected to provide much better insight into the problem [4]. The method of ICA was originally conceived to deal with separation of speech signals from sample data of people talking simultaneously in a room (the so-called cocktail-party problem) [5]. The first, to our knowledge, attempt of application of the method to the distributed in-cylinder variable is reported in [6], where the independent components are extracted from the luminosity images collected from a Diesel engine.
This paper reports on the comparison of the application of ICA to 2D images of combustion-related luminosity acquired from two optically accessible engines: Diesel and spark ignition. The ICA application aims at the separation of the spatial structures related to the different combustion events, and is coupled with the analysis of the statistics of the coefficients of the independent components, and of the measured in-cylinder parameters.

2 Experimental setup

2D images of combustion-related luminosity were acquired during experiments conducted on two single-cylinder optically accessible engines: a common rail (CR) Diesel and a port-fueled injection

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spark ignition (SI) engine. In both cases, a 45° inclined UV-visible mirror located at the bottom of the engine reflects the combustion light, emitted through a quartz window placed in the piston, towards the detection assembly – a high-speed camera acquiring several images per cycle.

Particularly, a direct injection four-stroke common-rail Diesel engine with a single cylinder and a multi-valve production head was used for optical measurements. The experimental setup for the Diesel engine is essentially the same as the one used to produce the data presented in Ref. [6], although the data used are different. The engine features a classic extended piston with a UV-visible grade crown window (34 mm diameter) providing a full view of the combustion bowl; further details on the experimental setup can be found in [7]. The experiments were conducted at an engine speed of 1000 rpm and continuous-mode operation, using commercial Diesel fuel with a typical CR injection strategy consisting of pre, main and post injections (PMP) starting at –9°, –4° and –11° CA (crank angle) with durations of 400, 625 and 340 μs, and 600 bar injection pressure.

The second engine utilized to collect flame imaging data was a port fuel injection 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 were conducted with commercial gasoline, octane number 95, at 2000 rpm and full load. The spark timing was 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

The method, fully described in [6], is here briefly outlined. In the "cocktail party problem", let us denote by $\mathbf{x}(t)=[x_1(t), \dots , x_m(t)]$ a random vector of m temporal linear combinations (*mixtures*) of n mutually independent speech source signals, written in a vector form as $\mathbf{s}(t)=[s_1(t), \dots , s_n(t)]$. The mixing model can be written as [3]:

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

where $\mathbf{A}$ is the so-called mixing matrix. By assuming that the number of the mixtures is equal to the number of the source signals, i.e. $m=n$, $\mathbf{A}$ is a square matrix. This basic ICA problem consists of estimating both $\mathbf{A}$ and $\mathbf{s}$, when only $\mathbf{x}$ is observed, and can be recast as:

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

The latter 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 – i.e. characterized by the maximum statistical independence over time – of the independent source signals $\mathbf{s}$.

The variable t can be meant as physical time, as with sound signals, but can also be meant as spatial scan, as with sources made of individual images. In this case, 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 [3×3] mixing matrix $\mathbf{A}$ (with randomly generated elements) in order to yield three mixture images (Fig. 1b). ICA is then applied, by maximizing statistical independence over space, to determine signals $\mathbf{y}$, i.e. the estimates of source signals $\mathbf{s}$. The separation performance (Fig. 1c) of ICA is striking.

Source data may be pre-processed for various reasons. For example, projection on to some special basis function space could allow to separate shapes or scales [9]. In this work, source data are first pre-processed by centering and whitening [4], then the leading POD modes are extracted, and finally a FastICA algorithm [4] is employed which, by means of a gradient method, maximizes non-gaussianity, estimated by the absolute value of kurtosis, as a measure of statistical independence. Since, in practice, the number n of sources is often unknown, on a first application it is advisable to search for a low number of independent components, here two and three components respectively for the Diesel and SI engine. In fact, using too many degrees of freedom may lead to finding spurious source signals, physically inconsistent with the data set [4].

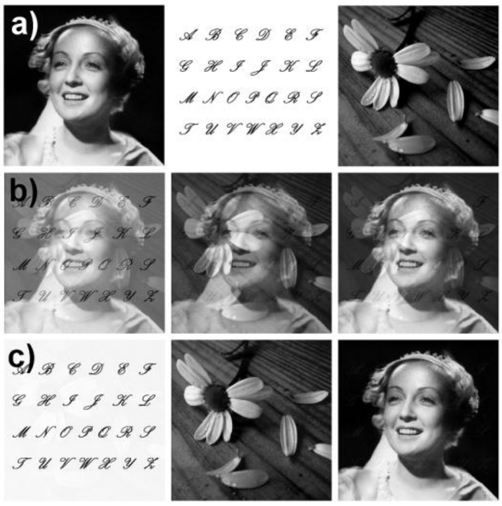

Figure 1. Independent source images (a), artificial mixtures of images (b), and images mixtures decomposed by means of ICA (c).

4 Results and discussion

A sequence of a 24 typical images of the combustion-related luminosity acquired during a single cycle of Diesel engine is presented in Figure 2. The presence of the light spots around the nozzle due to the pre injection can be observed at –2.5° CA. Later on, from about 2° to 5° CA, combustion is present on all jets and in the vicinity of the chamber wall, and it starts to move towards the bowl wall as fuel along the jet axes is consumed.

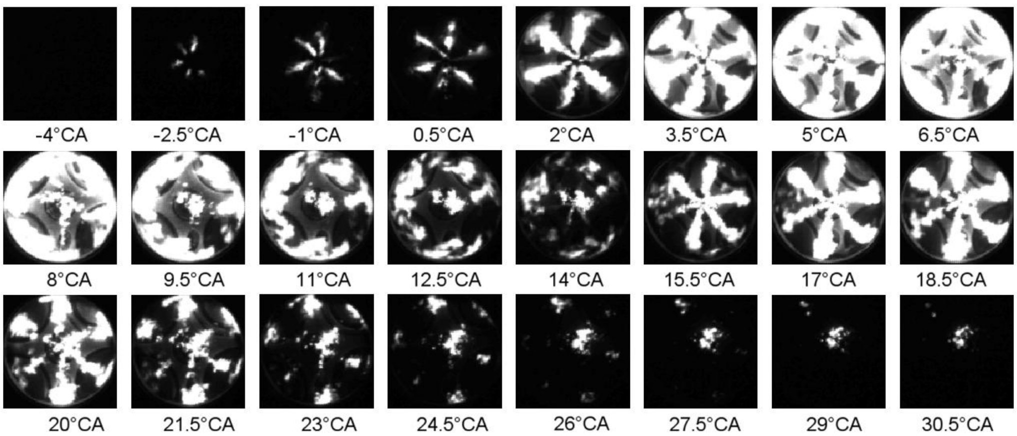

Figure 2. Sequence of crank-angle resolved images from Diesel engine.

ICA was first applied to the crank-angle resolved sequences of the images from the single cycle in order to determine the independent structures. Figure 3a and 3b shows independent components (ICs) y_1 and y_2 which were extracted from the cycle presented in Fig. 2. The relation to the combustion along the fuel jets (Fig. 3a) and near the wall of the combustion chamber (Fig. 3b) can be easily recognized in the determined ICs. Moreover, the swirl motion of the burning jets can be identified in the curved shape of the components' "jets" in y_1 (Fig. 3a). Figure 3c shows the corresponding crank-angle dependent coefficients of the components together with the calculated integral luminosity of the flame. It can be observed that 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

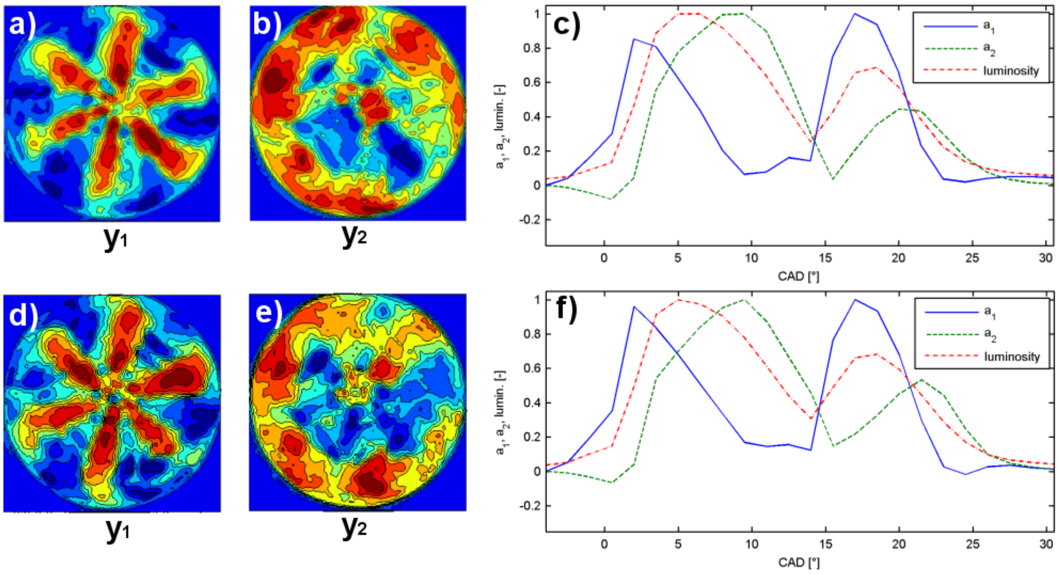

Figure 3. Independent components (a-b) and (d-e), and their coefficients a_1 and a_2 with a corresponding integral luminosity (c and f) vs. crank angle.

main and post injection. Figure 3d-f which reports the results of the ICA application to a different cycle confirms the generality of these observations. Again we can observed the clear separation between the early combustion along the fuel jets characterized by the swirl motion (Fig.3d) and the successive combustion near the bowl walls (Fig. 3e).
The satisfactory results obtained for the Diesel engine led to the attempt of the ICA application to the data collected from the SI engine in which we deal with different phenomena. Figure 5 reports a sequence of images collected during the experiments conducted on the research SI engine. As one can see, the premixed flame front, ignited at -14° CA and quickly expanding in the chamber, after 7.6° CA is barely visible. This is due to diffusion flames establishing around and between intake valve seats.

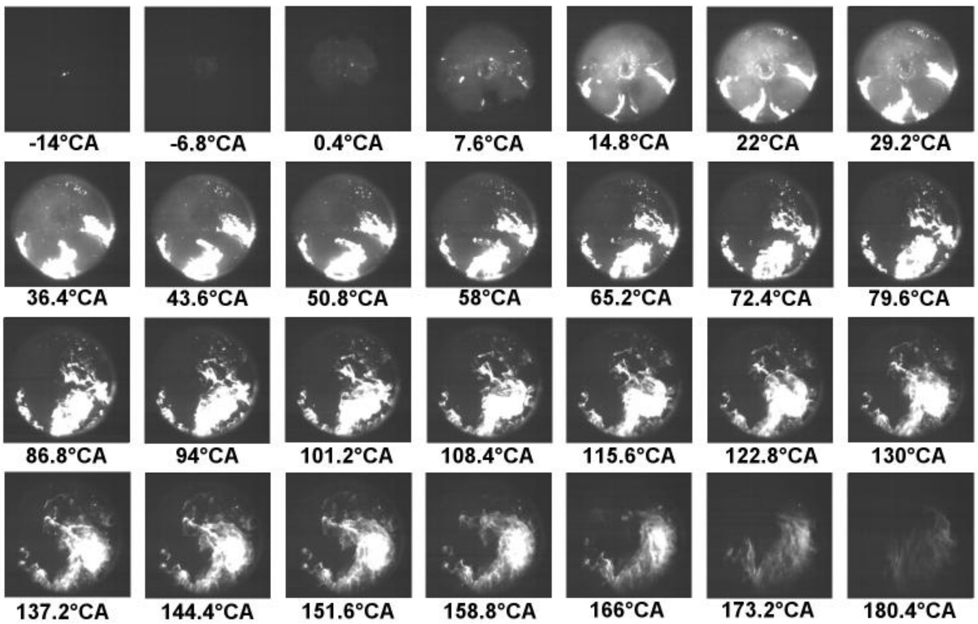

Figure 4. Sequence of crank-angle resolved images from SI engine.

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.

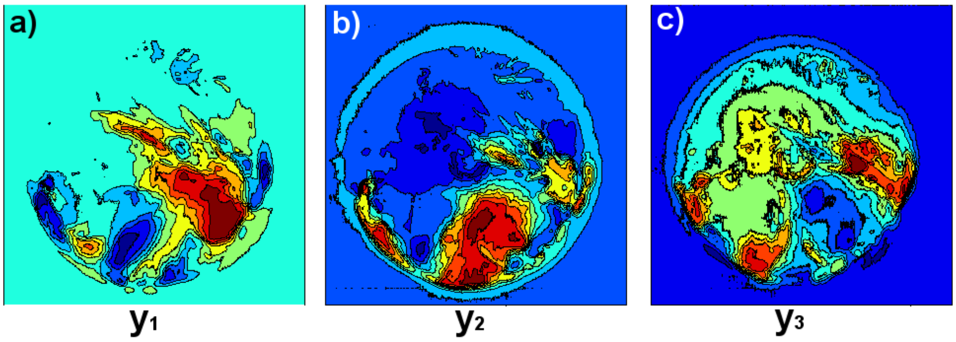

Figure 5 Independent components.

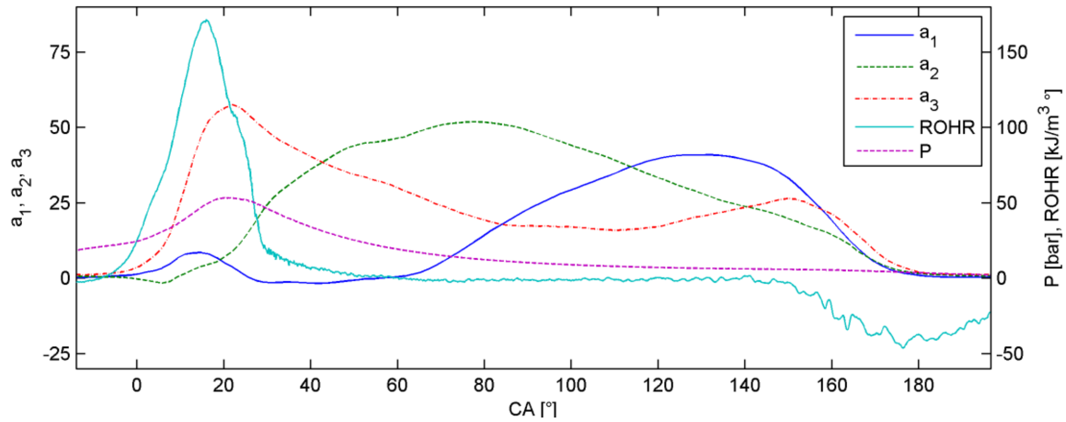

Figure 6 Coefficients a_1, a_2 and a_3, rate of heat release (ROHR) and pressure vs crank angle.

As for the Diesel case, the ICA was performed on the data sequence from a single cycle. The results of the analysis are presented in Figure 5 and Figure 6 together with the in-cylinder parameters collected during the experiments. This time three ICs were extracted which again can be correlated with the successive phases of the combustion process. When looking at the ICs (Fig. 5) and the corresponding coefficients (Fig. 6) it can be observed that y_3 represents the prevailing initial luminosity, corresponding with the peaks in the rate of heat release and in-cylinder pressure. In turn the components y_2 and y_1 represent the subsequent evolution of the luminosity field, i.e. flame propagation and luminous combustion, as it can be also seen from the visual evolution shown in Fig. 4.

5 Conclusions

This work reports on the comparison of the application of the ICA method to the 2D cycle-resolved images of the combustion-related luminosity, acquired during the experiments conducted on two optically accessible engines: Diesel and SI engine. Independent components and their coefficients were first extracted from sets of luminosity images, and then used to identify leading structures and to study the transient behavior of the combustion process.

The two components identified from the single Diesel cycle appear to be clearly related to early combustion along the fuel jets and later combustion near the bowl walls, respectively; quantitative analysis of coefficient statistics confirms the lower variability of the jet flames with respect to combustion near the chamber walls.

The same can be said of the results of the analysis for SI combustion images, which are separated in early (start of ignition), median (flame propagation) and final luminous combustion.

The analysis proposed in this work is fast and reliable (a single computation takes less than 0.1 s on a standard sequential single processor) and can be prospectively applied to many different optical engine configurations.

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