# Coupling time-resolved PIV flow-fields and phase-invariant proper orthogonal decomposition for the description of the parameters space in a Diesel engine

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Particle image velocimetry (PIV) results obtained from one Diesel transparent engine with a cylindrical bowl-in piston are investigated. Beyond the standard statistical description of in-cylinder flows, time-resolved PIV (TRPIV) now allows to access the in-cycle evolution. Unfortunately, experimental limitations prevent from solving a large number of cycles and thus from precisely describing the dynamics of the compressed flow. To overcome this issue, a new coupling approach between TRPIV data and phase-invariant proper orthogonal decomposition (POD) obtained on statistically converged data is proposed. This method allows accessing cycle-to-cycle fluctuations, in a parameters space obtained from a relevant number of flow realisations.

## 1. Measurements and datasets

Experimental set-up is a motored four valve single-cylinder engine with plate roof combustion chamber. The geometry tested, except for the piston shape, which is cylindrical, is a direct replica of a Diesel engine and operates at a compression ratio of 20:1. PIV measurements were carefully performed on this transparent engine to characterize the cyclic variations of the swirling flow during the compression stroke. Two datasets denoted (i) and (ii) are obtained from these measurements:

(i) A statistically converged dataset, which corresponds to planar velocity fields obtained at consecutive engine cycles, for several fixed crank angle degrees (CAD), in the plane (P). Seven CAD of the compression stroke were acquired, each of them consisting in 300 individual events. The result is a total number of M=2100 fields.

(ii) A time-resolved dataset resulting from TRPIV measurements at the plane(P), for 12 consecutive compression strokes, every 4.8 CAD.

## 2. Coupling TRPIV and phase-invariant POD

To precisely understand the dynamics of the flow during the compression stroke, we propose to combine in an optimal way the sets (i) and (ii). A phase-invariant proper orthogonal decomposition has been applied to normalized fields of (i) to obtain an optimal decomposition basis $\left\{\Phi^{(k)}(x)\right\}_{k=1,M}$. We showed that the flow could be described by the first three eigenmodes, which correspond to the most important large-scale variations. The first mode is carrying information concerning the swirling structure, whereas the second and third modes characterize the swirling motion wandering, during the whole compression stroke. The coefficients associated to the POD modes can then be used to quantify a particular structure of the flow. Even though this extension of POD is beneficial from a convergence point of view, it does not allow the investigation of the dynamics of individual cycles, since the snapshots used to perform the POD basis are statistical and not time-resolved. To catch the temporal dynamics of the flow field, we observed the evolution of the projection of the TRPIV measurements on the phase-invariant eigenmodes:

$$a_n^{(k)}(\theta_m) = \left(u^r{}_n(x, \theta_m), \Phi^{(k)}(x)\right)$$

Where $u^r{}_n(x, \theta_m)$ represents the temporal velocity field at the engine phase $\theta_m$. The approach proposed gives a description of the compressed flow dynamics and proves that the fluctuations linked with both the structure and the displacement of the swirling motion increase during the compression stroke.

## 3. Description of the parameters space

Keeping 3 POD modes only, the state of the compressed flow can be defined by the vector $\left(\gamma_n^{(1)}(\theta_m), \gamma_n^{(2)}(\theta_m), \gamma_n^{(3)}(\theta_m)\right)$ where $\gamma_n^{(k)}(\theta_m)$ are the normalized coupled projections defined in the paper. To fully describe the changes that occurred during the compression, each component of this vector, i.e. each parameter, have been examined along their in-cycle trajectory. During one cycle, the vector could stay in one particular sub-region of the parameter space (a region which would then change from cycle to cycle) or could evolve over the whole parameter space. The analysis of some particular trajectories revealed that many possible states of the system could be described throughout only few cycles. We also proved that even if one parameter is quasi-constant during the compression, the trajectory of the two other ones can strongly vary. The orbits are thus not restricted to particular locations in the parameters space.

The coupling approach developed in this paper can also be applied either to DNS or LES data provided a reliable POD basis is obtained. The state of the system has been here considered as a combination of structure of swirl and displacement. The influence of higher POD modes on the flow features, such as structure fluctuations, should also be investigated to improve the understanding of in-cylinder flows. The method we proposed in this paper could obviously be used in such an aim.