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Analysis of in-cylinder engine flows and their constituents by proper orthogonal decomposition

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INTRODUCTION

Measuring flow in the internal combustion engine (ICE) presents unique challenges to popular non-invasive techniques. The large range of velocities, flow scales and variation contributions that characterize engine in-cylinder flow requires unique post-analysis of measured flow fields. Study of both the small-scale turbulence and large-scale flow features are vital in ICE research and development as the large-scale motion in particular may provide insight into the cycle-to-cycle variation [1]. Conversely, turbulence plays a significant role in the subsequent combustion process [2].

This work presents experimentally obtained, phase-dependent in-cylinder flow velocity fields measured using particle image velocimetry (PIV) in a full-length optically accessible single cylinder research engine operated under various valve strategies. Proper orthogonal decomposition (POD) combined with a proposed methodology allows the separation of the flow fields into what are nominally demonstrated as coherent and turbulent constituent velocity fields. Separation of the constituent fields allows representative statistical information to be obtained from the flow which may otherwise be over-estimated. Stone shows how by interpreting the kinetic turbulent energy of the raw vector fields, it may be overestimated by as much as 300% [3]

In existing literature, there are several methods proposed for decomposing fluctuating flow fields; Olçmen et. al. [4] provides a comprehensive comparison of methods. POD, has found widespread application in the field of fluid flow amongst others (see [5] for references). In the context of fluid flows, the POD technique decomposes time dependent velocity fields, $u(x,t)$ into a set of spatial modes, $\varphi^{(k)}(x)$ and temporal modes $a^{(k)}(t)$ according to: $u(x,t) = \sum_{k=1}^{M} a^{(k)}(t)\varphi^{(k)}(x) \quad i = 1, \dots, N$, determined by the method of snapshots [6]. Using this method, the lower order modes are representative of large scale motions and contain the most energy, while higher order modes contain the turbulent flow. A truncation mode is often defined based on the energy contained, typically this could be 90% but is highly dependent on the flow. The problem is that the choice of truncation can significantly influence the resulting flow fields as described in [7]. The presented work outlines a proposed methodology for consistently defining a truncation of a flow without a priori knowledge.

VECTOR FIELD SEPARATION METHODOLOGY

In repeated engine PIV measurements of the same configuration, it is expected that both resulting sets of flow fields would have common large-scale, coherent features albeit with the presence of cycle-to-cycle variation. It then follows that POD analysis of the fields would identify highly similar lower order modes; representative of the energetic, coherent motion. Conversely, the higher order modes would exhibit little or no correlation between the sets as they represent flow with stochastic properties. The proposed method utilises the expected correlation between the coherent constituents to define a truncation mode between those representative of the coherent motion, and those representatives of turbulence. Correlation between two vector fields (or POD spatial modes), sets A & B is calculable by:

$$R_{ii,AB} = \frac{\overline{u_i(x)_A u_i(x)_B}}{\sqrt{\overline{u_i^2(x)_A}}\sqrt{\overline{u_i^2(x)_B}}}$$

In the presented case, a single dataset of 800 vector fields is randomised and split into two equal sets of 400 with POD carried

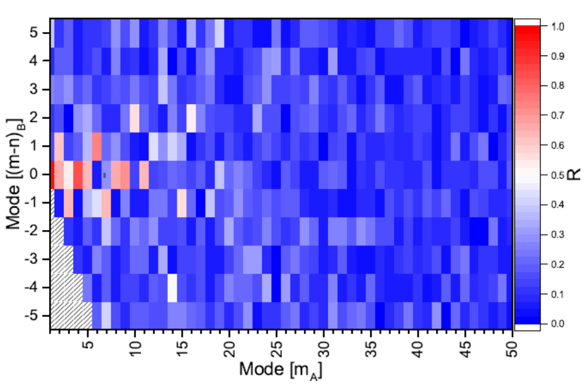

Figure 1 POD spatial mode correlation

out on both sets independently. Each spatial mode from set A is correlated against the corresponding mode in set B as well as the neighboring 10 modes (+/- 5 modes) as shown in Figure 1. This allows the modest re-ordering of modes of similar energies. The maximum magnitude for each mode is taken with no correlation assumed once this value falls below 0.5. Modes lower than the cut-off, with high correlation represent the coherent structures (Figure 2 A&B), with those above the cut-off representative of the turbulence (Figure 2 C&D). An example of an instantaneous vector field and its constituents is presented in Figure 3.

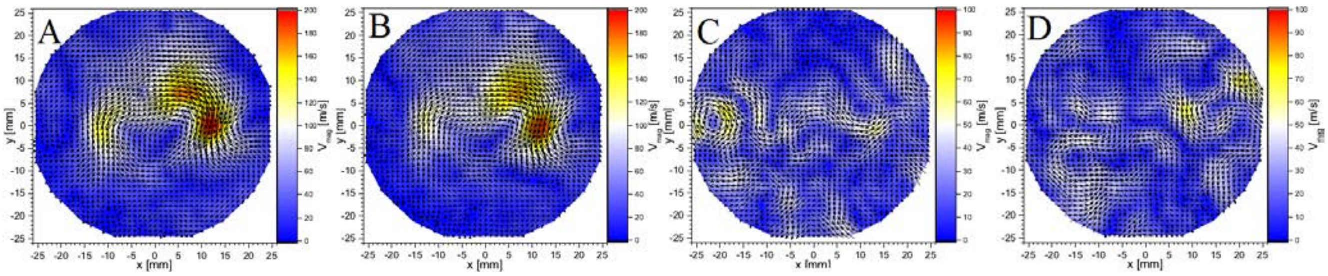

Figure 2 POD spatial modes showing high correlation (A&B – mode 1) and low correlation (C&D – mode 22)

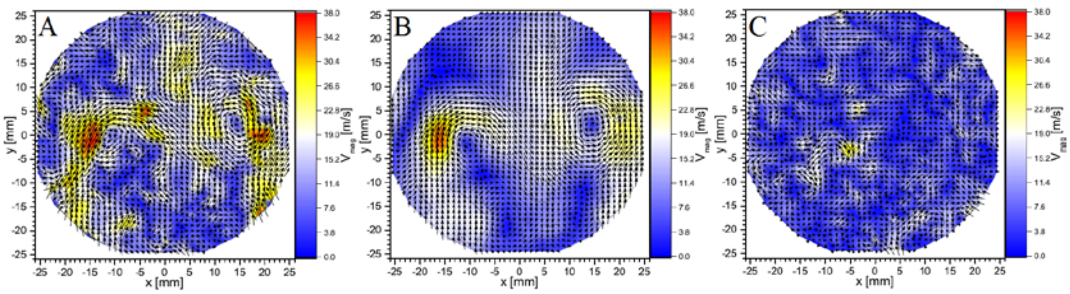

Figure 3 (A) original field, (B) coherent constituent, (C) turbulent constituent

ANALYSIS OF CONSTITUENT FIELDS

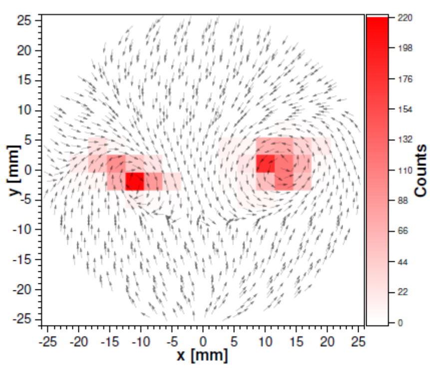

Figure 4 Vortex center distribution

Through analysis of the coherent constituent fields, it was found that not only the spatial location of the largest vortex centers could be identified, but also their cyclic variation was revealed (Figure 4). It was found that most examined cases exhibited either a two-vortex structure as is the case in Figure 3A, or a single central vortex. Analysis of the turbulent fields reveals the distribution of turbulent kinetic energy without the distortion of the coherent motion. It is also shown how the calculated turbulent kinetic energy from the original field is equal to the TKE calculated from each of the constituents according to: $TKE_u = TKE_{U^*} + TKE_{U'}$ where U* and U' are the coherent and turbulent constituents respectively, thus accounting for the typical overestimation of turbulent kinetic energy.

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