

# Analysis of the in-cylinder flow of a DISI engine using high-speed particle-image velocimetry

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## ABSTRACT

In addition to exploring electric drives, it is crucial to minimize emissions and improve the efficiency of transport based on internal combustion engines (ICE). For these, in particular, a significant reduction of emissions as well as a considerable efficiency of ICE are required. A reliable formation of an effective mixture prior to ignition and a fast, steady combustion process are two key elements that influence emissions and efficiency. While on the one hand, the air-fuel mixture is formed by strongly three-dimensional, time-dependent flow phenomena during the intake and compression stroke, the turbulence level of the flow near the approaching flame front has a direct impact on turbulent flame propagation. The flow field in the combustion chamber, on the other hand, is highly turbulent and sensitive to cycle-to-cycle variations (CCV). In order to understand the fundamental processes and interactions of the flow field, flow measurements with high spatial and temporal resolution are required. To analyze CCV, the resulting flow field data must be decomposed into its scales, since CCVs are different from random fluctuations due to turbulent flow motions. Besides velocity decomposition based on traditional Reynolds decomposition, which provides an average flow velocity and a fluctuation velocity, most studies include statistical and linear approaches such as proper orthogonal decomposition (POD) and Fast Fourier transformation (FFT). In this paper, time-resolved high-speed stereoscopic PIV (HS-SPIV) measurements on an optical single-cylinder engine are processed using a new nonlinear and transient decomposition method, namely the multivariate empirical mode decomposition (NA-MEMD) based on a data-driven decomposition algorithm. The decomposition is based on the inherent scales of the data and generates physically valid modal representations known as intrinsic mode functions (IMFs), which are arranged with respect to the contained scale values. The approach and the IMFs generated are described in detail using one engine cycle as an example. According to the results, three modes are obtained, the measurement noise and extremely tiny short-term scales, the turbulent scales, and the large-scale tumble vortex.

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## 1. Introduction

In addition to the increased use of electromobility, enormous improvements in emissions and efficiency in the transport sector, especially in combustion engines, are necessary to successfully drive forward the energy transition. The emissions and the efficiency of the combustion process in the engine depend essentially on two influencing factors. The first is reliable and effective mixture formation prior to ignition, and the second is a fast and stable combustion process. In direct-injection spark-ignition (DISI) engines, the air-fuel mixture is generated by three-dimensional and time-dependent flow phenomena during the intake and compression stroke (Druault et al., 2005). Turbulent flame propagation is one of the characteristics of a fast combustion process, which also has a high correlation with engine efficiency. Indeed, an increase in turbulence improves the mixing process on the one hand, and, on the other hand, the rate of turbulent flame propagation is significantly increased, leading to an improvement in combustion efficiency (Chen et al., 2014). In summary, the flow velocity and turbulence level at the flame front have a direct impact on the combustion process (Nishiyama et al., 2019).

A strong so-called tumble vortex is the predominant large-scale flow structure that transports kinetic energy during the intake and compression stroke (Borée & Miles, 2015). However, towards the end of the compression stroke, i.e., at about  $30^\circ$  before top dead center (btdc), the tumble vortex breaks up and dissipates into many small-scale turbulent flow structures which leads to a significant increase of the turbulence level just before ignition. The breakup process of the tumble vortex thus affects the combustion process. If the tumble vortex breaks up too early, the turbulent small-scale structures break up further and dissipate, leading to negative effects on combustion speed and stability (Borée & Miles, 2015).

Nevertheless, large-scale flow structures, such as the tumble vortex, are impacted by cycle-dependent fluctuations known as cycle-to-cycle variations (CCV) (Voisine et al., 2011). CCV impact, for example, turbulence, pressure variations during the intake and exhaust phases, mixing processes, flame speed, heat transfer, and acoustic phenomena (Vu & Guibert, 2012). Consequently, enhanced control or decrease of CCV is essential to optimize combustion behavior in internal combustion engines. The exact fundamental mechanisms and influences of CCV are not fully understood, yet. Therefore, optical flow measurements with high temporal and spatial resolution are required.

However, to analyze CCV, the resulting flow field data have to be decomposed into their scales, because the CCV are different from random fluctuations due to turbulent flow motions (Borée & Miles, 2015). For this, multiple approaches have been developed to extract the various scales that comprise the instantaneous velocity field. Braun, Klaas, & Schröder (2019), for example, used a standard Reynolds decomposition, in which the flow is decomposed into a mean and fluctuating part, to study the influence of different inlet pressures on the CCV. Other approaches focused primarily on linear and statistical decomposition methods, such as the Proper Orthogonal Decomposition (POD) (Braun et al., 2021; Chen et al., 2013; Graftieaux et al., 2001; Vu & Guibert, 2012) or the Fast Fourier Transform (FFT) (Joo et al., 2004; Li et al., 2017; Reuss et al., 1989).

Huang et al. (1998) developed the Empirical Mode Decomposition (EMD), which is a nonlinear and data-driven approach. It is suitable for nonlinear and unsteady processes but is not yet widely used in flow analysis, especially in the analysis of CCV in engine flows. Sadeghi et al. (2021) have presented an analysis of CCV using a type of EMD. They developed a bivariate 2D EMD (Sadeghi et al., 2019) and used it to decompose velocity data obtained from PIV measurements on an optical engine. However, the velocity field was not decomposed spatially, but the rows and columns of each degree crank angle were decomposed sequentially. Mäteling & Schröder (2022) developed a 2D noise-assisted multivariate EMD (NA-MEMD) which enables the extraction of spatially and temporally coherent modes.

In this article, the NA-EMD is applied to high-speed stereoscopic PIV (HS-SPIV) measurements of an optical engine. In contrast to Sadeghi et al. (2021), both the entire intake and compression strokes are decomposed and analyzed. 198 consecutive cycles with a sampling frequency of 2,000 Hz are measured. The aim is to give a new nonlinear unsteady approach to the flow analysis of CCV in internal combustion engines. The paper is organized as follows. First, the experimental procedures are explained. Then, the multivariate empirical mode decomposition approach is presented. Finally, based on the HS-SPIV results, the empirical mode decomposition results are presented and discussed.

## 2. Experimental Setup

The HS-SPIV measurements are performed on a single-cylinder optical engine at the Institute of Aerodynamics, RWTH Aachen University. The optical engine is a DISI engine with two intake and two exhaust valves. Furthermore, it is equipped with a pent-roof combustion chamber. The optical accessibility is provided by a cylindrical quartz liner covering the entire stroke of the piston and a silica glass piston crown which is fixed by a union nut. The engine is utilized in Bowditch design allowing the laser beam to enter the combustion chamber through the piston crown. This entails that the piston is an extended hollow piston, and a mirror is used to divert the laser beam toward the piston crown. It is a custom-made engine from FEV GmbH, Aachen, Germany. The engine parameters are shown in table 1.

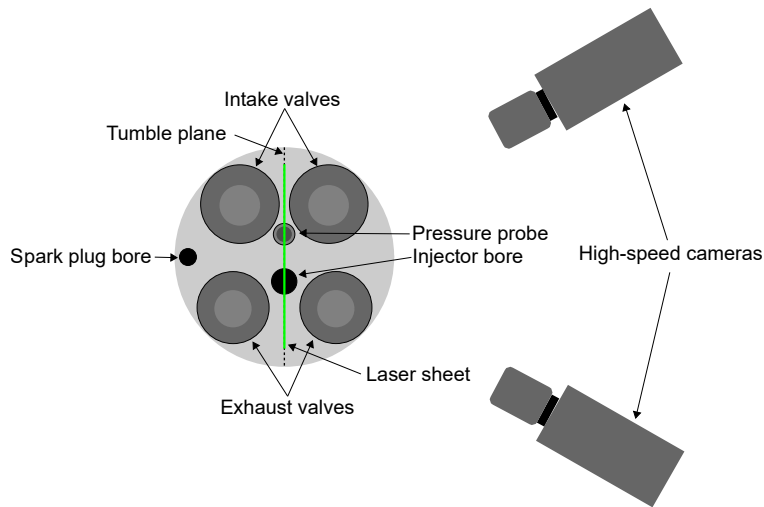
The engine is externally-driven by a 30 kW electrical engine to bypass the necessity of fuel combustion, since the combustion would hinder optical access due to soot and combustion residues. Therefore, only the intake stroke and compression stroke of the engine are investigated with this test rig. Additionally, an oil conditioning system is used to preheat the engine oil to approx. 60° C to meet lubrication properties. During the measurements, a heat exchanger regulates the intake air temperature to approx. 20° C, and a super charger is used to adjust the static pressure at the intake manifold to 1 bar. In the measurements, the engine speed is adjusted to 1,500 rpm. More details about the optical research engine are provided in Braun et al. (2018).

Figure 1 illustrates the HS-SPIV setup and the position of the valves and bores for the optical engine cylinder head. The setup of the cameras satisfies the Scheimpflug condition. Note that

**Table 1.** Engine parameters of the optical engine

| Engine parameter                 | Value                              |
|----------------------------------|------------------------------------|
| Bore                             | 75 mm                              |
| Stroke                           | 82.5 mm                            |
| Displacement volume              | 364 cm <sup>3</sup>                |
| Compression ratio                | 7.4                                |
| Number of valves                 | 4                                  |
| Intake valve diameter            | 27.1 mm                            |
| Exhaust valve diameter           | 23 mm                              |
| Valve lift                       | 9 mm                               |
| Intake valves open (1 mm lift)   | 12° atdc (after top dead center)   |
| Intake valves close (1 mm lift)  | 196° atdc                          |
| Exhaust valves open (1 mm lift)  | 204° btdc (before top dead center) |
| Exhaust valves close (1 mm lift) | 20° btdc                           |
| Connecting rod length            | 146 mm                             |
| Crank radius                     | 42.2 mm                            |
| Oil temperature                  | 60°C                               |
| Intake temperature               | 20°C                               |
| Intake pressure                  | 1.0 bar                            |
| Engine speed                     | 1,500 rpm                          |

dummies are inserted in spark plug and injector bores to prevent the flow field from being affected by the bores. As also shown in figure 1, the radial origin of the light section (approximately 1 mm wide) of the HS-SPIV measurements lies in the tumble plane. Just as in the investigation of Braun et al. (2021), the maximum measurement volume at the bottom dead center covers the entire height of the stroke of about  $50 \times 82.5 \text{ mm}^2$ . A high-speed double-cavity PIV laser with a wavelength of 527 nm, at a pulse spacing of 20  $\mu\text{s}$  and a frequency of 2,000 Hz per cavity, is used to provide the light sheet in the tumble plane. Two pco.dimax HS4 are used to acquire the particle images. The flow is seeded with DEHS particles, which have an average diameter of approximately 0.35-0.45  $\mu\text{m}$ . The cameras are operated at a resolution of  $1024 \times 1700 \text{ px}^2$  and are equipped with Tamron 180 mm macro lenses with a f-number of f/5.6. Both cameras are oriented at an angle of  $\pm 45^\circ$  to the normal vector of the tumble plane. The processing of the HS-SPIV measurements is performed with PIVView. Preprocessing of the HS-SPIV measurements includes background subtraction, masks for each CA, and high-pass filters. A multi-grid approach is used for processing with a final scan window size of  $32 \times 32 \text{ px}^2$  at 75% vector overlap, i.e., 8 px vector spacing. Multiple filters are used between passes to identify outliers.



**Figure 1.** PIV setup and position of valves and bores

### 3. Empirical Mode Decomposition

The empirical mode decomposition (EMD) is a data-driven decomposition method that was pioneered by Huang et al. (1998) to process non-linear and unsteady time-dependent data. The decomposition is based on the data-inherent scales and provides physically meaningful modal representations, so-called intrinsic mode functions (IMFs), that are ordered with respect to the contained scale sizes.

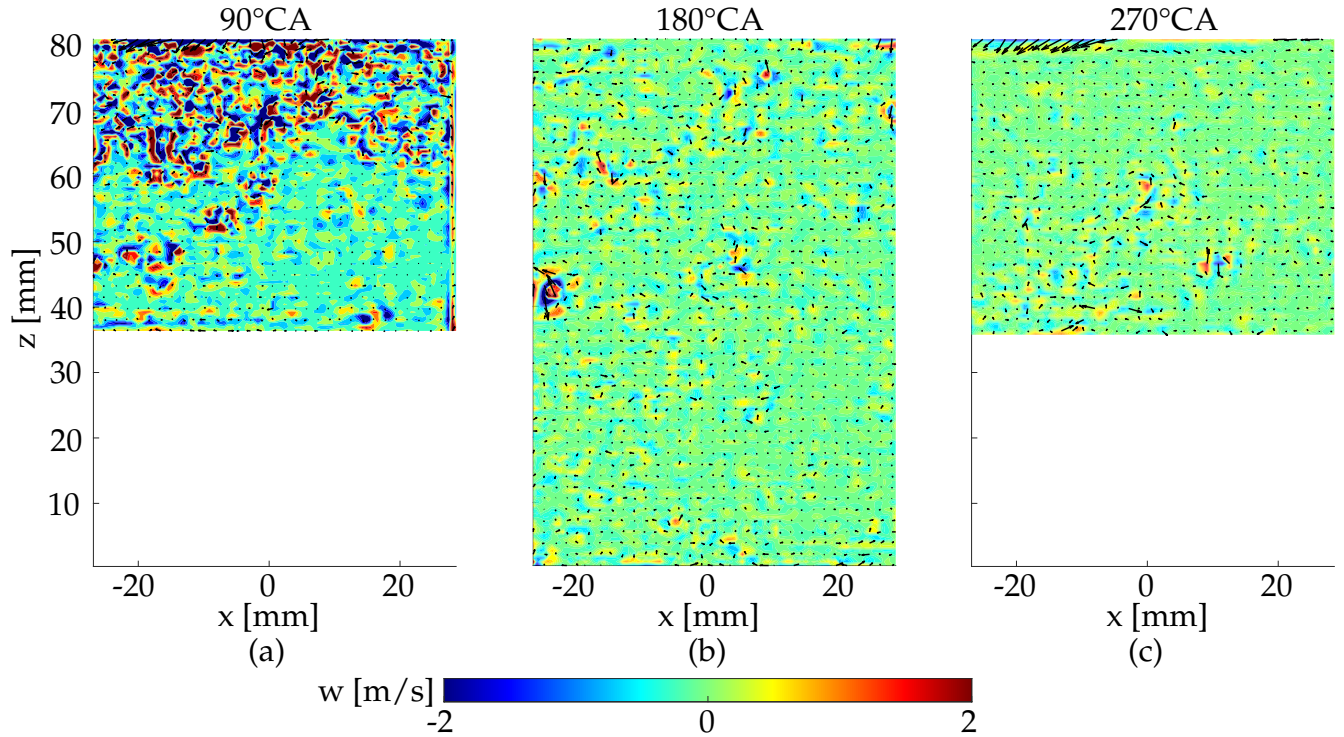
A recent extension to a 2D noise-assisted multivariate version (NA-MEMD) by Mäteling & Schröder (2022) enables the extraction of spatially and temporally coherent modes sharing properties across multiple variates. In the present application, several instantaneous, consecutive velocity fields obtained by HS-PIV are simultaneously decomposed for each engine cycle by the 2D NA-MEMD to obtain a spatial, scale-based decomposition of the instantaneous velocity field ensuring a temporal coherence of the resulting modes. More precisely, the three velocity components of six successive 2D flow fields are jointly decomposed with an overlap of one flow field between consecutive decompositions to ensure a steady transition between the IMFs of different decompositions. The multivariate nature of the NA-MEMD ensures that the scales contained in each mode agree across different flow fields, i.e., crank angles, while the noise assistance further promotes a temporal coherence beyond a single decomposition.

A detailed description of the NA-MEMD can be found in Mäteling & Schröder (2022). In the present study, 22 projection directions are used within the multivariate approach. Two channels of random Gaussian noise with zero mean and a variance of 2% of the flow fields' variance are concatenated with the flow data in view of the noise assistance. In total, three IMFs are obtained for each velocity field and exemplary visualizations of the IMFs are given in figures 2, 3 and 4. The modes are ordered depending on the inherent range of scales and the physical meaning of each mode is analyzed in section 4.

#### 4. Results

The three IMFs generated by the 2D NA-MEMD are discussed in detail. The analysis is based on the temporal evolution of the intake stroke and the compression stroke and is discussed using one engine cycle as an example. The temporal resolution between two snapshots is  $4.5^\circ$  crank angle (CA).

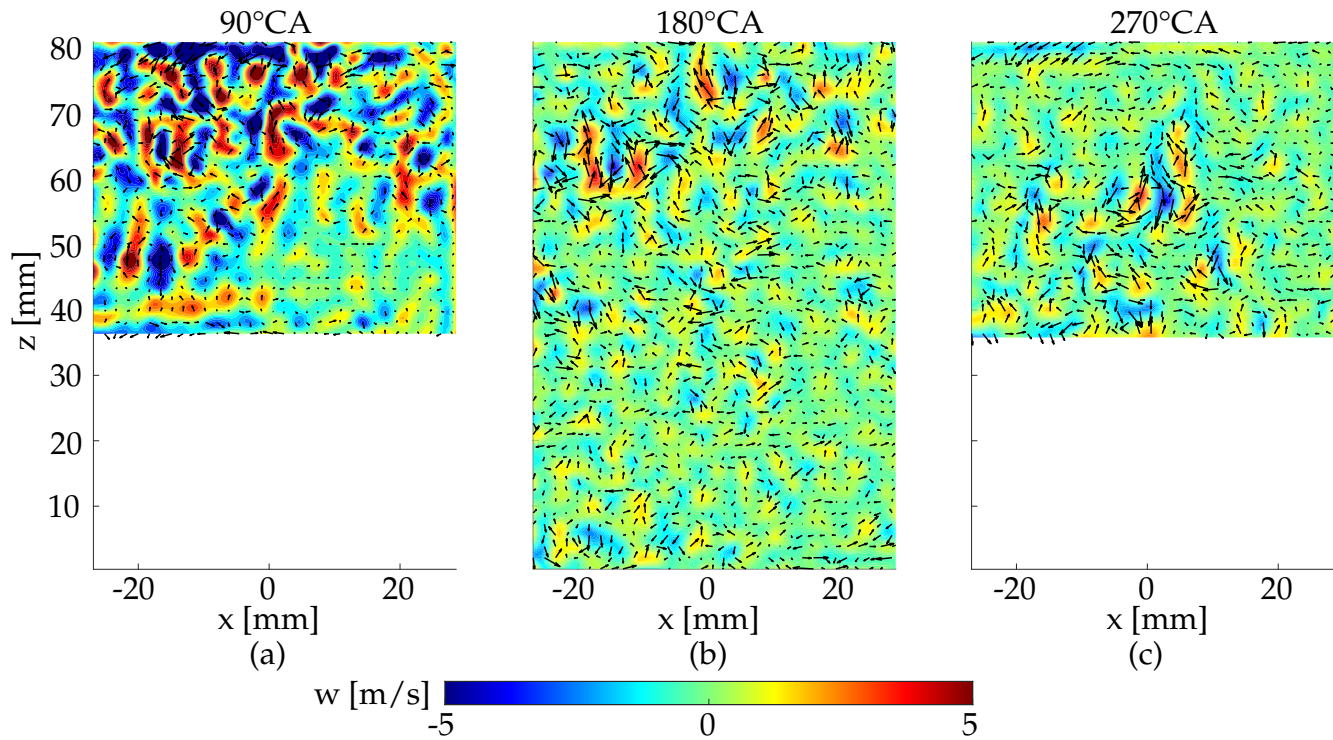
Figure 2 shows the first IMF for the fifth cycle, which contains the high-frequency and small scale structures. The first IMF is plotted for three crank angle positions, namely:  $90^\circ$  after top dead center (atdc), with the piston sliding down,  $180^\circ$  atdc, with the piston at the bottom dead center, and  $270^\circ$  atdc, with the piston moving up. The velocity component in z-direction  $w$  is represented by the colormaps and the velocity vectors indicate the flow direction, while the length of the vectors represents the magnitude of the velocity components in x-direction  $u$  and z-direction  $w$ .



**Figure 2.** Velocity distribution of component  $w$  for the first IMF for cycle five at  $90^\circ$  atdc,  $180^\circ$  atdc, and  $270^\circ$  atdc.

The first IMF shows a large number of many very small structures at the beginning of the intake stroke, i.e., at  $90^\circ$  atdc (fig. 2(a)), but these structures disappear for the next crank angle and new patterns arise. These disordered formations reduce as the crank angle increases and disappear until the bottom dead center is reached, see figure 2(b). During the complete compression stroke, no more of these very small structures are formed. Figure 2(c) shows an instance at the halfway point of the compression stroke at  $270^\circ$  atdc. Since this mode contains extremely small velocities and no detectable leading structure, it is concluded that this mode comprises both camera measurement noise and very small structures at the beginning of the intake stroke that dissipate directly and are not relevant for the CCV.

Figure 3 displays the velocity distribution of the  $w$  component of the second IMF for the fifth cycle at  $90^\circ$  atdc,  $180^\circ$  atdc, and  $270^\circ$  atdc.

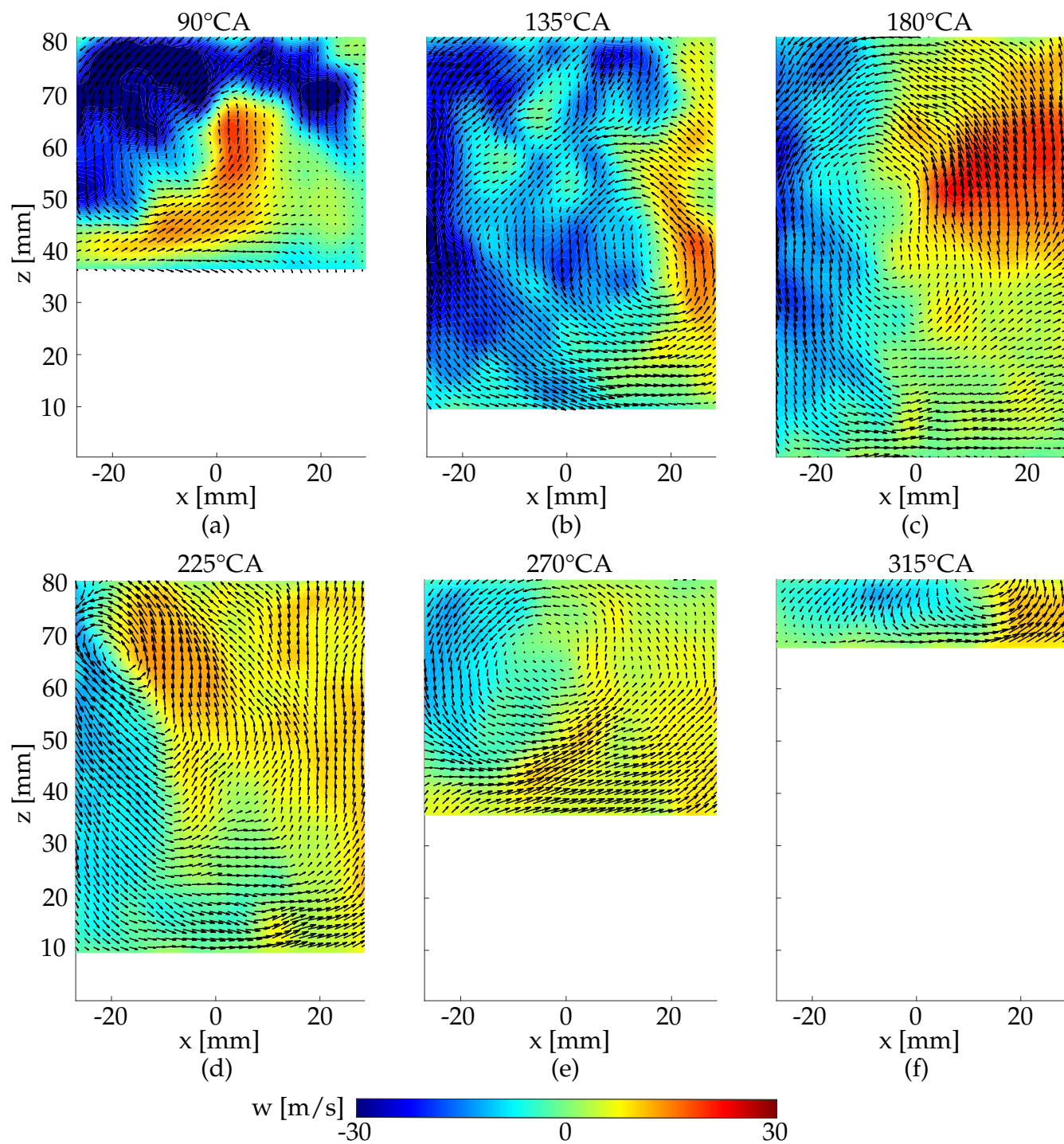


**Figure 3.** Velocity distribution of component  $w$  for the second IMF for cycle five at  $90^\circ$  atdc,  $180^\circ$  atdc, and  $270^\circ$  atdc.

Figure 3(a) displays the snapshot at  $90^\circ$  atdc during the intake stroke. There are numerous elongated structures that move downwards with the piston as the crank angle increases, but become weaker during the intake stroke. Only a few stronger structures can be identified near the end of the intake stroke in the upper part of the cylinder, see figure 3(b), but these disappear within two snapshots. Structures develop and vanish periodically during the compression stroke, as well as at the end of the intake stroke (fig. 3(c)). However, the structures become stronger and remain longer at the end of the compression stroke.

As stated above, the structures form at the beginning of the intake stroke as a result of fluid entering the combustion chamber through the open intake valves and the interaction of this fluid with the tumble vortex. The tumble vortex itself absorbs the kinetic energy and keeps structures weaker throughout the intake stroke. The breakup of the tumble vortex can explain the stronger structures at the end of the compression stroke. The whole procedure clearly fits with the turbulence progression within both strokes, as detailed in section 1. Thus, the second IMF contains the turbulence scales of the instantaneous velocity field.

The third IMF of the fifth cycle is shown in Figure 4 which contains the large-scale structures. The velocity distribution of the  $w$  component is shown for six distinct crank angles. The three snapshots in figs. 4(a) to (c) represent the temporal evolution of the intake stroke at  $90^\circ$  atdc,  $135^\circ$  atdc, and  $180^\circ$  atdc. Figs. 4(d) to (f) represent the temporal evolution of the compression stroke at  $125^\circ$  atdc,  $270^\circ$  atdc, and  $315^\circ$  atdc.



**Figure 4.** Velocity distribution and time evolution of component  $w$  for the third IMF for the intake stroke (top) and compression stroke (bottom)

The snapshot at  $90^\circ$  atdc shows the interaction of the entering mass flow with the tumble vortex developing during the intake stroke. A strong downward directed velocity field is detectable in the area above 65 mm, which may be explained by both the entering fluid from the upper right and the interaction of this fluid with the tumble vortex. No flow motion is evident in the bottom right region of the combustion chamber due to the simultaneous inflow and the tumble motion, which counteracts the incoming flow. The reverse effect can be observed on the left side of the combustion chamber. The incoming flow and the tumble motion supercompose and create a strong downward motion of the fluid. The vortex center is also detectable at  $x \approx -3$  mm and  $y \approx 57$  mm.

The vortex core moves downwards to the right during the compression stroke, reaching its outermost position at  $135^\circ$  atdc at  $x \approx 18$  mm and  $y \approx 35$  mm. A significant negative velocity field extends over the snapshot's complete left outer edge. The downward flow predominates due to the vortex center's location and the indicated piston motion. A positive flow velocity field is only observable at the right outer edge. Until the bottom dead center is reached at  $180^\circ$  atdc, the vortex center moves in the opposite direction to the top right. This results in a larger positive velocity field, with the negative field present only in the outer region. Note the strong positive velocity field in the upper third of the snapshot.

During the compression stroke, this structure is pushed towards the cylinder head and deflected to the left until, at  $225^\circ$  atdc, it provides a strong local circulation region in the upper left-hand area. By then, the vortex core had likewise shifted towards the outer left edge. The local circulation zone widens out and distributes equally throughout the decreasing combustion chamber as compression continues. The velocity field is uniformly distributed in both positive and negative directions at  $270^\circ$  atdc, and the vortex core shifts to the right. Only the velocity component in x-direction is notably greater in the lowest section of the snapshot.

Finally, this IMF is characterized as the tumble mode since the vortex described above follows the trajectory of the tumble vortex core reported from the literature (Borée & Miles, 2015; Braun, Klaas, & Schröder, 2019; Braun, Schröder, & Klaas, 2019) as well as the temporal evolution of the tumble vortex.

## 5. Conclusions

High-speed SPIV measurements were performed on an optical engine with a temporal resolution of  $4.5^\circ$  CA. A nonlinear decomposition method, the 2D noise-assisted multivariate empirical mode decomposition (NA-MEMD), was applied to the measured data to obtain modes based on physical meaning. This method considers both spatial and temporal coherence between snapshots and the modes are ordered depending on the inherent range of scales.

Three so-called intrinsic mode functions resulted from the NA-MEMD, which are based on a physical meaning. In the first IMF containing small and high-frequency scales, many very small structures are visible at the beginning of the intake stroke, but they disappear within the next snapshot

and were not of interest concerning cycle-to-cycle variations. As the compression stroke continues, these small structures are no longer visible. It is assumed that this mode, except at the beginning of the compression strokes, contains predominantly the measurement noise of the cameras.

In the second IMF, many small cigar-like structures are visible at the beginning, which move downstream with the piston and become weaker with increasing combustion chamber volume. During the subsequent compression stroke, stronger structures grow occasionally, but they disappear within the next two snapshots. These become stronger and remain longer at the end of the compression stroke. This mode includes the turbulent scales.

The tumble vortex is clearly visible in the third IMF, which contains the largest scales. The analysis demonstrated how the emerging tumble vortex interacts with the inflow from the intake valves and how the tumble vortex develops with increasing crank angle. The trajectories and position of the vortex's core may also be identified. This mode is referred to as the tumble mode.

In summary, the NA-MEMD analysis evidences two physical modes that are of interest related to cyclic variation, the turbulence mode and the tumble mode. The next step is to identify the cyclic variation based on different approaches. One approach is to average the tumble mode for each crank angle degree throughout the cycles. The difference between the average mode and the instantaneous mode is then used to calculate the dimension of cyclic fluctuations. Furthermore, a standard Reynolds decomposition of the data could be conducted to remove the average velocity field from the instantaneous velocity field and then apply the NA-MEMD to the fluctuating velocity field to get a decomposition into coherent and turbulent components. Finally, the temporal component should also be considered, since the NA-MEMD includes temporal coherence, but the current temporal resolution is limited by the  $4.5^\circ$  crank angle. Data at higher temporal resolution should be investigated.

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