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A novel phase-averaging method based on vortical structure correlation

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Abstract

In this paper we investigate a new method for phase averaging based on the correlation of vortical structures in a flow field. The method requires the presence of a large scale precessing structure in the flow, such as for instance the precessing vortex core found in swirling flows. The transformation from time to phase is done by correlation of the instantaneous Q fields to determine the phase shift between two instants of the precession. Once the phase shift is determined, the different flowfields are rotated back to the zero phase reference and the data are ensemble averaged. The method is tested on tomographic PIV measurements of an annular jet flow and it is shown that it is able to extrude the large scale structures found in turbulent swirling jet flows.

Phase-averaging, Q-field correlation, coherent structure extraction

1 Introduction

It is well known that several coherent structures exist in flows fields like for instance the precessing vortex core (PVC) in swirling flows [6]. The most widely used method to separate these structures from other dynamic phenomena in the flow, such as turbulence, is by phase-averaging. In this method, time is transformed into phase and samples within a small phase interval are ensemble averaged [2]. For the time-phase transformation, this procedure requires a trigger signal and moreover, especially in highly turbulent flows, the ensemble averaging of each phase interval requires a large amount of measurement data. Other methods like POD decomposition [1] or DMD decomposition [4] overcome these problems if the phase is unknown or the number of samples is limited, but the main weakness lies in the somewhat arbitrary determination which modes correspond to the precession. A third class of methods involve filtering of the measurement data in the time or frequency domain. They require less samples, but the main issue is the appropriate choice of cut-off frequency [5, 8]. In this paper, we developed a new method for phase-averaging which uses the advantages of the techniques mention above, i.e. no need for a reference signal and a limited number of samples needed. The technique requires a large scale precessing vortical structure in the flow field and is therefore tested on tomographic PIV measurements of an annular swirling jet flow.

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2 Phase-averaging procedure

For the identification of coherent structures in a flow field, several methods exist, such as iso-surfaces of vorticity magnitude, pressure- minimum criteria, the λ_2-criterion or the Q-criterion [3]. In this paper we use the Q-criterion, where $Q = \frac{1}{2}(\|\Omega\|^2 - \|S\|^2)$, with Ω the antisymmetric and S the symmetric part of the velocity gradient tensor. Vortex cores are identified as regions were rotation is dominant over strain, i.e. $Q > 0$. Hence positive isocontours of Q reveal vortical structures in the flow field. If these vortical structures precess along the central axis with angular frequency ω, the relation between two phase averaged velocity fields at time instants t_i and $t_{i+1} = t_i + \Delta t$ is given by

$$\tilde{u}(r, y, \theta, t_{i+1}) = \tilde{u}(r, y, \theta + \omega\Delta t, t_i), \tag{1}$$

where the velocity field is expressed in cylindrical coordinates with r the radial direction, y the axial direction and θ the azimuthal direction. The rotation of the vortical structures between time t_i and t_{i+1}, $\Delta\phi_i$, can be found by correlating the Q-fields of the instantaneous flows at these time-instants by the function

$$R(\Delta\phi_i) = \langle Q(r, y, \theta - \Delta\phi_i, t_{i+1}) \times Q(r, y, \theta, t_i)\rangle\,, \tag{2}$$

where $\langle\cdot\rangle$ denotes the spatial average. The maximum of this correlation gives the angular rotation between the two time instants. By definition, $\Delta\phi_i{=}\omega(t_{i+1} - t_i)$. As vortical structures are only represented by positive values of Q, the negative values are not included in the correlation as these values are set to zero. The relation between time and phase angle is found incrementally. First, at $t = 0$, the phase angle $\phi = 0$. The phase of the next field in time is found as $\phi_{i+1} = \phi_i + \Delta\phi_i$, where $\Delta\phi_i$ is obtained from the correlation approach expressed in Eq. 2 and so on. Once the relation $\phi_i = \phi(t_i)$ is found, the phase averaged velocity field $\tilde{u}(r, y, \theta)$ can be found by calculating the ensemble averaging of the instantaneous velocityfields rotated back with their corresponding phases

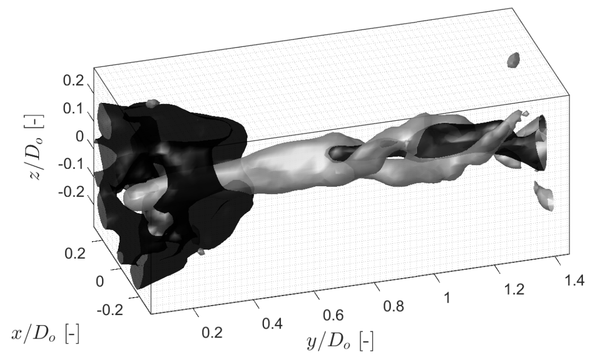
$$\tilde{u}(r, y, \theta) = \frac{1}{N}\sum_{i=1}^{N} u(r, y, \theta - \phi_i, t_i), \tag{3}$$

from which it follows that $\tilde{u}(r, y, \theta, t_i) = \tilde{u}(r, y, \theta + \phi_i)$. Note that, although no significant frequency modulation has been detected in the test case, this approach avoids the occurrence of phase jitter, as the precessing frequency may slightly fluctuate.

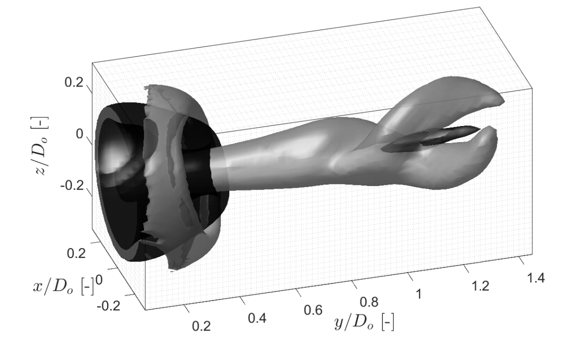
3 Results and discussion

As a test case of the phase-averaging method, tomographic PIV measurements of an annular swirling jet are used [7]. The annular jet has an inner diameter D_i = 18 mm and an outer diameter D_o = 27 mm. The symmetry axis of the jet is aligned with the y-axis in the measurement coordinate system with the origin located at the end of the inner tube. The velocity components in the x, y and z direction are labeled U, V and W respectively. The experiments were performed at a Reynolds number of 8,300 based on the hydraulic diameter of the annular jet (D_h = 9 mm) and the mean outlet velocity, U_m = 0.92 m/s. More details on the experiments can be found in the study of Vanierschot et al. [7].

The instantaneous flow structures are shown in Fig. 1a. The grey surface corresponds to the isocontour Q=$0.07{\times}10^6$ $1/s^2$ and the black contours are isosurfaces of V=0, hence denoting recirculation zones. Isocontours of Q show a central vortex core along the central axis of the geometry, which breaks up into a double helix downstream in the flow field. Analysis of the evolution of this structure at different time instants shows that the vortex precesses along the central axis of the jet with a well defined Strouhal number based on the hydraulic diameter of



(a) Instantaneous flow structures in the jet. The grey isosurface corresponds to the isocontour Q=0.07×10^6 1/s^2.



(b) Flow structures of the phase-averaged data. The grey isosurfaces correspond to isocontours of Q=0.015×10^6 1/s^2.

Figure 1: Instantaneous (left) and phase averaged (right) flow structures in the annular jet. The black contours are isosurfaces of V=0.

0.29. This precession frequency can also be found in the spectral analysis of various points in the flow field. These instantaneous flow fields are rotated back towards the zero phase reference and ensemble averaged according to equation 3. The result is shown in Fig. 1b. This figure clearly shows the double helix structure which can also be observed in the instantaneous velocity fields.

4 Conclusions

In this study, we developed a new method of phase-averaging based on the correlation of vortical structures found in a flow field. The method requires a large scale vortical structure which precesses in the flow field, like for instance the precessing vortex core (PVC) found in swirling flows. The method correlates the Q-values at different time isntants to determine the relation between phase angle and time. Once this relation is found, the different instantaneous flowfields are rotated back to the zero phase reference and the data are ensemble averaged. The advantage of this method compared to conventional phase averaging techniques is the absence of a reference signal to do the phase-time transformation, the need for much less measurement data to obtain converged statistics and the removal of any phase jitter.

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