Defocusing PIV and ridge-detection algorithm for the analysis of flows laden with non-spherical particles

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Abstract. In this preliminary work, the feasibility of the combination of a volumetric velocimetry technique such as Defocusing Particle Image Velocimetry and a particle phase-discrimination methodology based on ridge detection algorithm for the analysis of turbulent multiphase flows with non-spherical fiber-like particles is discussed. Experimental results of a dilute suspension of fibers in an open-channel apparatus are provided.

1. Introduction

A wide range of industrial applications and environmental phenomena is characterized by the dispersion and transport of solid particles by a turbulent flow, which act as a carrier phase.

The comprehension of these suspensions is deeply connected to the investigation of the dynamic interactions between the fluid and dispersed particle phase. Relevant for many engineering applications and of interest for fundamental research on turbulence is the study of the effect of the dispersed phase on the carrier flow dynamics. With this respect, effects of turbulence modulation (enhancement or attenuation) represent a relevant subject and several studies have been carried out in this field (a comprehensive review is given in [1]). On the other side of the mutual interactions between the dispersed and carrier phase is the action that the flow turbulent motions exert on the dispersed solid particles dynamics. In particular, the latter will undergo preferential distribution and concentration within the turbulent flow depending on their dynamic characteristics [2],[3]. With this respect [4] shows how the Stokes number St, defined as the ratio of the particle response time to a characteristic flow time scale, in combination with the particles volume fraction can generally predict and describe the extent of the phase-interactions in multiphase flows.

Phase interplay increases in complexity when the dispersed phase is represented by non-spherical, anisotropic particles. Multi-phase turbulent flows with transport of non-spherical particles are encountered in several environmental and industrial processes, such as ice formation in clouds, pulp transport and marine pollution by micro-plastic. In these phenomena the dispersed phase is characterized by different shapes, ranging from platelets, disk-like particles to elongated, fiber-like particles. For such flows, which are widespread in nature and engineering applications, single particle orientation in three-dimensional space plays a pivotal role as it affects torques and forces exerted by the flow on the particle itself. In the last decades the interest in anisotropic particles behavior in turbulent flows has grown...
considerably ([5]) as witnessed by several experimental and simulation works focused on fiber-like particles behavior in a range of turbulent flow configurations ([6],[7],[8]). Recently rotation dynamics of fiber, rod-like particles were investigated in baseline configurations ([9]) but much work has to be carried out to account for factors such as particle deformability (e.g. bubbles), flexibility (e.g. fibers), mass density, volume concentration, size or shape and to investigate more complex flow configurations.

Experimental investigation of fiber-laden multiphase flows poses several difficulties in particular whenever the carrier phase and the dispersed particles are to be investigated simultaneously. Focusing on optical experimental methods, under these circumstances it is pivotal to implement ad-hoc phase discrimination techniques ([10]), in order to obtain separate images of fibers and carrier phase.

In this preliminary work we present a feasibility study of the analysis of a turbulent open channel flow laden with fiber-like particles via Defocusing Digital Particle Image Velocimetry (DDPIV)([11]). In particular it is presented a phase discrimination technique which is based on ridge-detection algorithm aimed at identifying the three-dimensional position (and orientation) of the fiber-like particles transported by the flow.

Figure 1: Experimental set-up: open channel apparatus, schematics and reference system. The green area shows the location of the acquisition volume.
Figure 2: Unladen flow: average velocity field components at the center of the test section.

2. Experimental set-up

The experimental apparatus is an open water channel depicted in Figure 1, along with the reference coordinate system. The square test section features 500 mm sides and the water level within the test section is maintained at 350 mm for all experiments. Overall water volume amounts to 2.5 m$^3$ and the flow is driven by a centrifugal pump, 2.2 kW power.

Flow and particles measurements were carried out via TSI Defocusing PIV system ([11]) equipped with three PowerView 8 Mpixels cameras, 3320 X 2496 pixel resolution. Nikon 50mm f1.8 lenses were mounted on each camera. Laser source is provided by a Big-Sky Nd:Yag Laser, model CFR400 with max power 400 mj. Although three different flow speeds were tested, we report here only the result from the highest speed tested.
The flow was laden with 10um neutrally buoyant hollow glass spheres as flow tracers whereas dispersed phase was represented by white Nylon fibers 2 mm long, featuring a length to diameter ratio L/d=40. Fiber density is $\rho=1150\ \text{Kg/m}^3$. The concentration of fibers in the flow is approximately 0.01% volume fraction, thus the multiphase solution is deemed dilute.

The acquisition volume is located at the center of the test section, and its size is 200 mm X 20 mm X 20 mm and is shown in green in Figure 1. For each acquisition, 1000 image pairs were collected with an acquisition frequency of 3 Hz. TSI software Insight 4G V3V was employed for DDPIV processing.

![Sample fibers and tracers image (left) and identification of fiber points by ridge detection algorithm (right)](image1)

Figure 3: Sample fibers and tracers image (left) and identification of fiber points by ridge detection algorithm (right)

![Reconstruction of a single fiber position in space. Red dot highlights the center of mass.](image2)

Figure 4: Reconstruction of a single fiber position in space. Red dot highlights the center of mass.
Figure 5: Identification of sample fiber positions in two correlated frames (white and red respectively). Time gap between two frames is 2.5 ms.

3. Fibers identification process and results

Figure 2 shows the flow velocity measurements obtained in the case of unladen flow. The mean value of each velocity component (U,V,W) is shown in a plane parallel to plane X-Z, located at the center of the test section. It appears that the components U and W are quite homogeneous whereas the cross-wise component V features a gradient probably caused by the convergent shape of the channel and its limited size. As mentioned in the previous sections, in the acquired images, both particle flow tracers and dispersed fiber-like particles were present, thus a phase-discrimination technique is necessary to separate the contribution from each phase prior to the estimate of each single fiber three-dimensional location. The entire process entails three phases: 1) Discrimination of pixels belonging to fiber particles for each instantaneous image and each camera; 2) Identification of the spatial location of each of the points identified at step 1; 3) Three-dimensional reconstruction of the whole fiber based on points identified at step 2.

For the first step, an approach based on the ridge detection algorithm was followed to identify fibers points ([12]) and specifically on its extended implementation in Fiji ImageJ v1.52E software package, [13]. The tuning of each parameter of the algorithm was based on a sensitivity analysis of the results, in terms of false positives and failed identification of fiber points, which is not reported here. A sample result obtained after step 1 is provided in Figure 3, which shows the identified fibers points. After identification of the spatial position of each fiber point, based on the images acquired by the three cameras, it is possible to obtain an estimate of entire fibre position in space, which can be used to retrieve information about its orientation angle and center of mass. The estimate is carried out by linear fitting of the fiber points, upon the assumption that the fibers are rigid and undergo no deformation, as it is confirmed by image inspection. The results of the step 3 is provided in Figure 4 for a sample fiber particle along with its estimated center of mass. This process may be easily extended to frame pairs, as...
those typically obtained by Particle Image Velocimetry so as to obtain time-correlated image pairs of fibers position in space. Fibers orientation and center of mass information can be employed so as to retrieve data on rotation and translation speed. An example of this approach is shown in Figure 5, where the outcome of the fibers identification phase for an image pair is shown, with a time delay between frames set to 2.5 ms. Although not provided in this preliminary study, dispersed phase dynamics information may be correlated to flow velocity measurements obtained via volumetric DPIV.

4. Conclusions

This preliminary study shows how the combination of a volumetric technique such as Defocusing PIV and the use of a phase discrimination approach based on ridge detection algorithm can be used to investigate the dynamics of fiber-like particles in turbulent flows and potentially correlate it to the carrier flow dynamics. The current limitations of this approach are related to the estimate of the dispersed phase spatial location step, which relies on the assumption that particles are rigid, rod-like objects. More challenging conditions, characterized by increased particle concentration, along with correlation between fluid velocity field and particles dynamics will be tackled in future studies.

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