Three dimensional flow dynamics beneath the air-water interface

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Abstract

The physical relation between shape of the surface, flow dynamics beneath the surface and related exchange processes such as gas transfer are not well understood. In order to gain insight into the dynamics of three dimensional flow fields close the air/sea shear layer we present a stereo particle tracking velocimetry method. The well established particle tracking velocimetry for two dimensional image sequences is combined with a stereo correlation algorithm. The stereo correlation is applied to the trajectories extracted from each image sequence of the stereo camera setup. Particle features can be extracted not only from one single image but from the whole sequence. These are then used in the correlation process, thus making the algorithm more efficient. A precise sub pixel calibration allows quantitative study of the properties of the flow field. Only two cameras are needed and therefore this method simplifies the experimental setup compared to multiple camera setups. Stereo particle tracking was applied for flow field investigations in a wind-wave flume and in a gas liquid reactor.

1 Introduction

The gas transfer rate between the atmosphere and the sea increases when wind induced water waves are generated [11]. Small scale waves of a few cm wavelength such as capillary waves are especially important.

The coupling mechanisms of the wind induced shear stress on the air-water interface and the physical properties of the 3D-flow field beneath the interface are of interest.

Our method is based on classical two dimensional particle tracking velocimetry (PTV, see [2],[9]) and on a stereo correlation method (Fig. 1). A sub
pixel precise calibration procedure yields high spatial resolution of the order 0.1 microns.

The stereo calibration supplies the parameter set for the camera model used for stereo PTV. The image sequences of the two cameras are processed separately and the trajectories of tracer particles are extracted. Finally the stereo correlation of the trajectories from the two cameras provide the three dimensional trajectories. In conjunction with the parameter set of the camera model, the spatial coordinates can be obtained.

A geometric camera model describes the projective transformation of a 3D-object onto the 2D CCD-sensor of the camera [8]. A pinhole camera model with an extension including lens distortion is used [4]. The quality of the camera calibration is crucial for the accuracy of the stereo triangulation [7]. The triangulation finally results in the 3D-world coordinates.

As a calibration target a plate with grid-lines is moved a given distance perpendicular to the baseline of the two cameras (Z-coordinate). The precision of the distance of the grid lines is substantial for the accuracy of the calibration.

2 Particle Tracking Velocimetry

Particle tracking velocimetry (PTV) tries to identify and trace particles on each image and to follow them over a sequence of images [1]. This results in a trajectory for each particle. Due to the time of exposure, the particles are imaged as streaks on the CCD sensor (Fig. 2). The streak lengths and the grey values correspond to the average speed and the velocity.

The first step is to identify the streaks where a region growing method was applied [9]. After this segmentation procedure the streaks of the image sequence have to be connected in order to construct the trajectories of the particles. The correspondence problem is solved by finding the overlap of the enlarged streaks. The enlarging is
a result of the region growing method and morphological operations such as
dilation. Further restrictions have to be taken into account if the overlapping
criterion does not solve the correspondence uniquely.

3 Stereoscopic Correspondence

3D-trajectories representing the fluid flow are reconstructed from the 2D-
trajectories by solving the stereoscopic correspondence problem. In order

![Figure 3: Left: Construction of the epipolar line in the retinal plane of camera 2 from an image point \((x, y)\) on the retinal plane of camera 1. Right: For a multi media setup a window of width \(2\varepsilon\) is taken instead of a line.](image)

to reconstruct the location of the trajectory in 3D-space, its image coordi-
nates \((x, y)\) and \((x', y')\) have to be found in both cameras (Fig. 3, left). From
\((x, y)\) and \((x', y')\) it is possible to perform the triangulation with the knowl-
edge gained by calibration.

The epipolar constraint is a very strong geometric constraint and as such
reduces the computational costs enormously. It arises as follows: The object
has to be located on the outgoing ray of the first camera as can be seen in
Fig. 3 (left). This ray is in turn depicted by the second camera as the so called
'epipolar line'. The endpoints of the epipolar line are called epipoles and are
defined by the finite depth range of the probing volume. Due to noise and
a small error in the camera parameters a certain tolerance \(\varepsilon\) is added to the
epipolar line; Fig. 3 (right).

For flow visualization we use a symmetric illumination setup for small
particles which are rotationally symmetric, and viewed as single points. They
may thus be regarded as point objects for which further (uniqueness-) con-
straints are applied [4].
4 Results

Results of flow field dynamics investigations in a wind wave flume\(^1\) and in a gas liquid reactor of the bubble column type\(^2\) are presented. The scheme of the setups is shown in Fig. 4.

Figure 4: Scheme of the bubble column (left) and of the flow visualization in the wind-wave flume (right).

In Fig. 5 the trajectories of the uprising bubbles can be seen. On the left side of the picture the bubbles move upwards more or less vertically, whereas the right side the flow is more turbulent [3].

The trajectories of visualized and tracked particles representing the flow beneath the shear layer are shown in Fig. 6. Small amplitude (< 0.5 cm) gravitational waves with little steepness (< 5°) can be seen as spirally shaped trajectories. The particle tracking algorithm works up to a particle density of about 1000 per image. The smaller number of 3D trajectories compared to the 2D trajectories is also due to geometric reduction of the intersecting volume from the two cameras. If the light intensity is homogeneous and constant over time, the stereo PTV can track particle or bubble trajectories over the whole sequence of images (Fig. 5).

In case of the flow visualization in the wind-wave flume the situation is more difficult. The number of reconstructed 3D trajectories is smaller than

\(^1\)Heidelberg University wind-wave flume [12] is built in a circular shape which avoids boundary effects of a linear flume.

\(^2\)BASF AG Ludwigshafen
extracted by PTV and the length of the trajectories is shorter compared to the bubble column. This is due to the higher density, the smaller size, and the larger velocity of the particles, and therefore the number of ambiguities in the correlation step is increased.

PTV methods are well suited to study dynamical processes [10]. Compared to the particle imaging velocimetry method [6] where vector fields are resolved for only one time interval, the tracking of particles yields the flow field over a larger time domain in Lagrangian coordinates.

Figure 6: 3D-trajectories visualising flow perpendicular to the main direction of flow and in a slight angle to the water surface.

References


