Hydrodynamic Instability and Particle Image Velocimetry

Instabilities in lid-driven cavities

First important investigations of hydrodynamic instabilities were published by v. Helmholtz (1868), Lord Rayleigh (1879) and Lord Kelvin (1880). Reynolds (1883) studied the transition to turbulence in pipe flows. A basic work regarding hydrodynamic stability was published by Taylor (1923). He examined flows in the concentric gap between two cylinders, the so-called Taylor Cylinder. When the Taylor number is increased beyond a critical value the basic flow changes to a system of regular vortices. If the Taylor number is further increased, other stable flow structures arise, up to the transition to turbulence.

Another classical experiment for investigations of hydrodynamic instabilities is the lid driven cavity. The flow in a rectangular container is driven by two opposing walls which can move independently. The moving walls are realized by two big cylinders. The geometry is sketched in fig. 1. The driving is described by two Reynolds numbers, one for each cylinder. Depending on the Reynolds numbers stationary vortices are generated. Their properties are defined by the geometry and the Reynolds numbers. Due to the primary instability the quasi two-dimensional basic flow changes to other flow stuctures, when the Reynolds numbers are increased up to a certain Reynolds number called critical. The new three-dimensional flow stucture can be stationary or time dependent.

Due to its basic geometry and simple boundary conditions, the classicle cavity is numerically as well as experimentally intensively investigated. Analogies concerning technical applications can be found in the drying and in the coating technology. Additionally the system is used as a benchmark for numerical calculations.

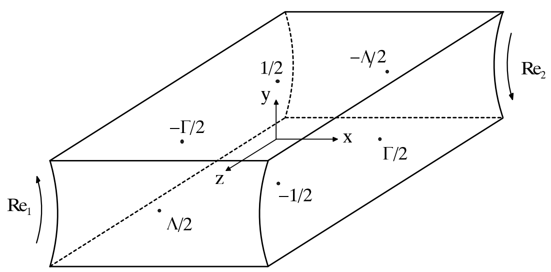

Figure 1: Geometry.

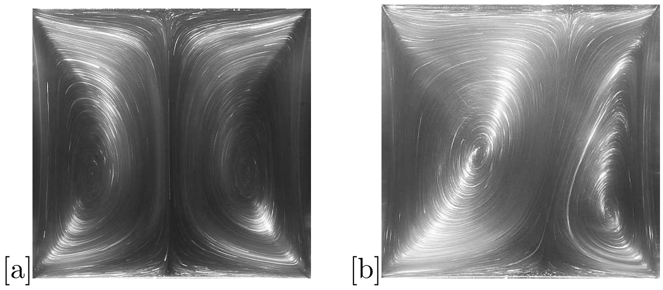

Figure 2: Pictures of the x, y-Plane at the parallel driving. Both sidewalls move down. (a) Quasi two-dimensional basic flow (b) Stationary three-dimensional pattern (C^p-Mode)

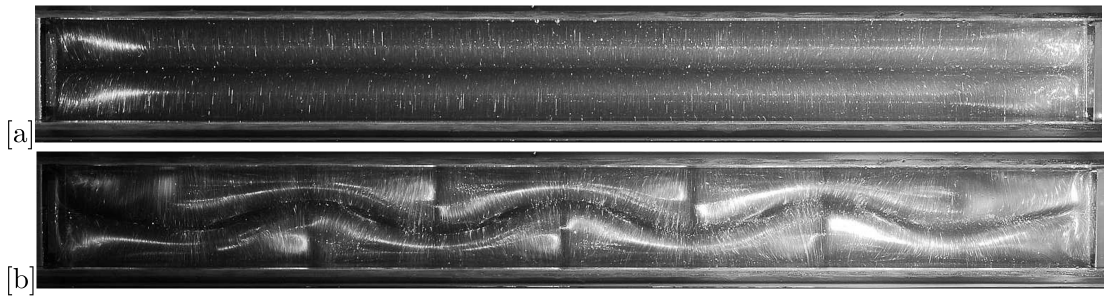

Figure 3: Pictures of the x, z-plane at the parallel driving. Both sidewalls are located at the top and the bottom and move into the plane. (a) Quasi two-dimensional basic flow (b) Stationary three-dimensional pattern (C^p-Mode)

The flow structures are examined qualitatively as well as quantitatively. Qualitative investigations are conducted by visualization techniques. Suitable paricles are added to the oil, which is used as experimental fluid. The movement of the particles can be observed with the help of a thin halogen light sheet. Quantitative measurements are carried out with a Laser-Doppler-Anemometer (LDA) and a Particle Image Velocimetry (PIV) system .

Figures 2 and 3 show as an example the quasi two-dimensional flow stucture and the stable three-dimensional flow structure (C^p Mode) which occur at the parallel driving. When driven parallel both walls move in the same direction. The quasi two-dimensional flow structure consists of two co rotating main vortices. The instability mechanism causes a spatially periodical sinusoidal deformation of the main vortices in z-direction. The deformation is to be seen as a sine wave on the pictures.

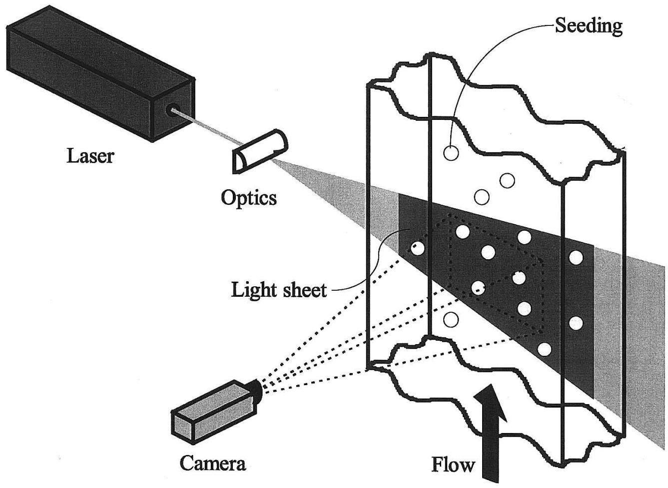

Figure 4: Basic principle of PIV. (DantecDynamics 2000)

Particle Image Velocimetry (PIV)

The used system is a Dantec FlowMap®PIV System of Dantec Dynamics (DantecDynamics 2000).

Particle Image Velocimetry is an optical method for velocity measurements. PIV obtains instantaneous whole field velocities.

The basic principle of PIV is shown in figure 4. It is based on the simple equation:

$$v = \frac{s}{t} \quad . \tag{1}$$

A section of the flow seeded with particles is illuminated with a thin light sheet which is generated by a pulsed laser. A camera arranged normal to the light sheet takes pictures during the light pulses. The pulses are synchronised with the camera. The pictures are snapshots of the particles which are following the flow. As the time interval between the pulses is known the velocity can be calculated by measuring the distance the particles moved comparing the images.

The camera images are divided into rectangular regions; so called interrogation areas (figure 5). For each interrogation area the two images are cross-correlated to determine an average particle displacement vector. By using the known time between the two images these vectors are converted into a map of raw velocity vectors. This process is carried out for all interrogation areas and provides a velocity vector field of the examined flow as a result. Further analyses can be carried out based on the vector field to obtain stream lines, vorticity etc..

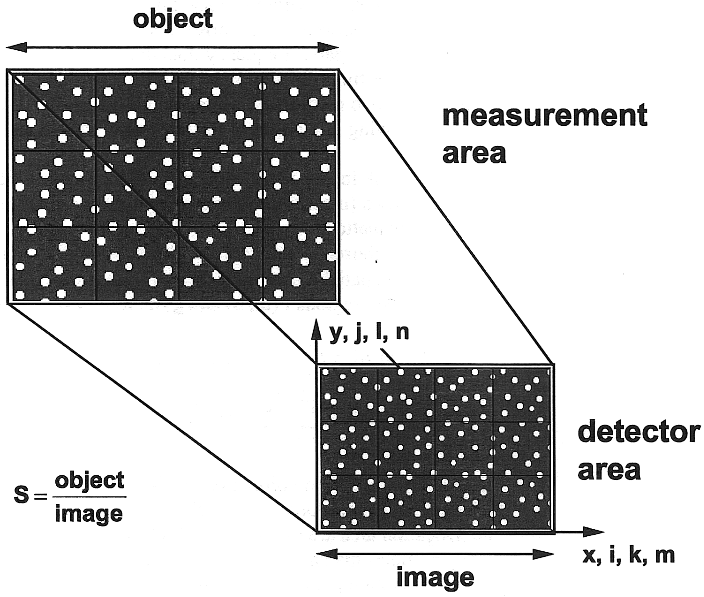

Figure 5: Co-ordinate system and image-/object-plane divided into interrogation areas (DantecDynamics 2000)

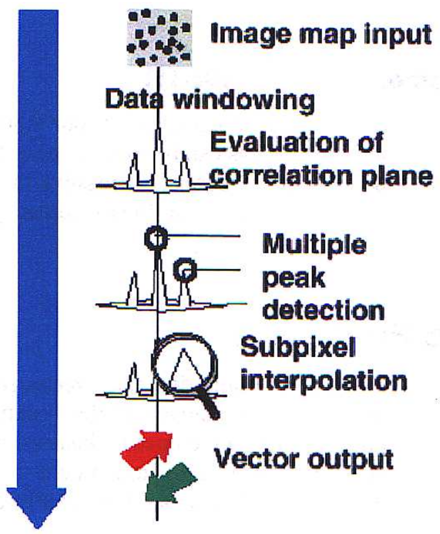

Figure 6: Processing stages in the correlator unit (DantecDynamics 2000)

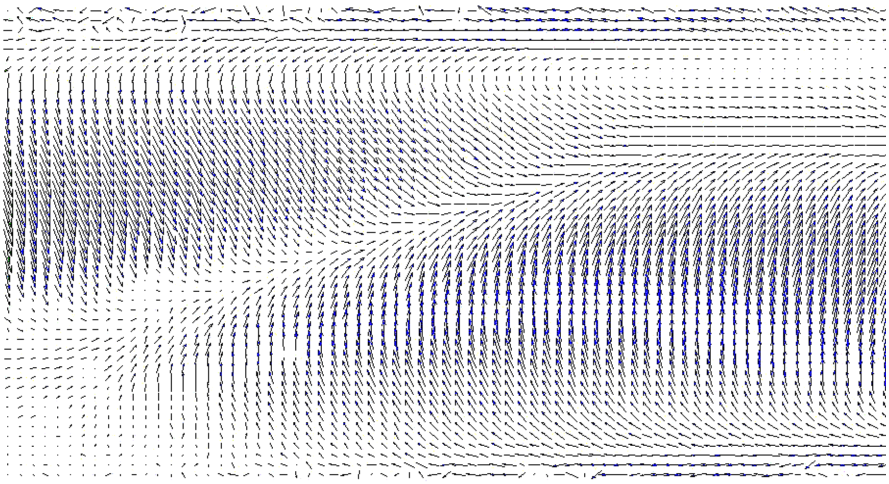

Figure 7: PIV-vectormap (stationary 3D flow structure, Cp-Mode, parallel driven).

The different stages in the correlator unit are shown in figure 6. As an example a velocity vector map is shown in figure 7.

The procedure of a PIV measurement can be described in keywords as follows:

- seeding
- illumination
- image capture
- data analysis

System components

The PIV system consists of three fundamental components :

- illumination system
- cameras
- FlowMap®: Prozessor

They are supplemented by a PC for the further processing of the gained data.

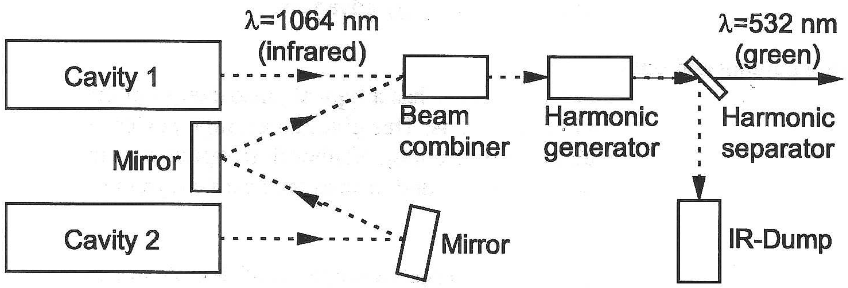

Figure 8: Double-cavity PIV-Laser. (DantecDynamics 2000)

Illumination System

For illumination a pulsed 200mJ double cavity SOLO PIV 200XT Nd:Yag Laser is used. The repetition rate is up to 15 Hz for each cavity. The laser emits green light (wavelength 532nm). The pulse width is 3-5 ns.

The assembly of the used laser is shown schematically in figure 8.

Camera

A Double-Shutter FlowSense CCD-Camera 2 Mega Pixel, 30Hz (bis 208Hz) Single Frame is used.

FlowMap®: Prozessor

A Dantec FlowMap®Prozessor processes the image data. It has a modular structure.

- correlator unit
  - data windowing
  - correlation plane evaluation
  - filtering
  - multiple peak detection
  - vector measurement to subpixel resolution
- input buffer

- synchronisation unit

Seeding particles

Not the actual velocity of the flow is measured by PIV, but in fact the velocity of the particles added to the fluid. For that reason the particles have to satisfy certain optical and flow-mechanical requirements.

The particles must be small enough to follow the flow accurately, but large enough to scatter sufficient light.

The motion of particles suspended in a fluid is affected by:

- particle shape
- particle size
- relative density of particle and fluid
- concentration of particles in the fluid
- body forces.

The particles should be:

- able to follow the flow
- good light scatterers
- conveniently generated
- cheap
- non-toxic, non-corrosive, non-abrasive
- non volatile, or slow to evaporate
- chemically inactive
- clean.

Safety instructions !!

The used laser is a Class 4 high power laser whose beam is by definition a safety and fire hazard. Diffuse as well as specular beam reflections can cause severe skin and eye damage including blindness. Although the used double pulse laser emits green laserlight, it is possible that the emitted light contains infrared light, which is invisible but extremely dangerous.

During operation of the laser it is essential to wear the correct type of laser safety goggles.

!!! You have to wear laser safety goggles!!!

- Never look into the laser or at laser light reflections!

- Remove all jewellery, rings, arm bands and wristwatches before starting to work with the laser !

- Your are not allowed to operate the laser!

References

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v. Helmholtz, H. (1868), *Über discontinuierliche Flüssigkeitsbewegungen*, Monatsberichte der königlichen Akademie der Wissenschaften Berlin, 215.