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An application of Particle-Image Velocimetry to the study of the separated flow behind a cylinder

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1 Introduction

PIV (Particle Image Velocimetry) is an optical laboratory technique which in the standard application maps two-dimensional sections of the velocity field of flows, tracing ensembles of particles that are visible. The PIV of today combines advanced camera technology, lighting of the flow by means of (pulsed) lasers, and subsequent data processing using rapid computers. PIV is a powerful laboratory technique and is useful to estimate the velocity fields in real complex flows. Physical parameters in the flow are extracted, among others, vorticity, vortical structure, flow separation, the Reynolds stresses and turbulence characteristics in boundary layers.

This document aims at presenting the updated technical features of the PIV system used in the Hydrodynamic Laboratory at the Mechanics Division, Department of Mathematics, University of Oslo. It is designed for studying the separated flow behind a fixed cylinder at Reynolds numbers up to 10^5. The cylinder (diameter 8 cm, span 48 cm) is binded to a trailer, which is towed in a wave tank of dimensions 25 m (length), 0.5 m (width), 1 m (depth). As the cylinder passes by the PIV installation, measurements are performed. Force transducers are mounted on both ends of the cylinder to record the instantaneous drag and lift acting on the body. Procedures and principles of operation are described here, and their limits are emphasized. Part 2 presents the different components of PIV. Part 3 covers the processing of the data, and a few results obtained during the last two months are exposed in part 4.

2 Acquisition of PIV-data

The current PIV data acquisition combines a high speed digital camera and pulsed lasers used to enlight the flow in the area of interest, referred as field of view (FOV) in the folllowing.

2.1 The lasers

Presentation The laser component is identified as a CFR 200 Cabinet ICE, from the firma Big Sky Laser. It consists in two main components, the ICE (Integrated Cooler and Electronics), which provides both power and cooling to the installation, and the laser head. The ICE is in charge of the following functions:

- System timing
- Charging supply to flash pump the laser rod
- Synchronization
- Control and safety

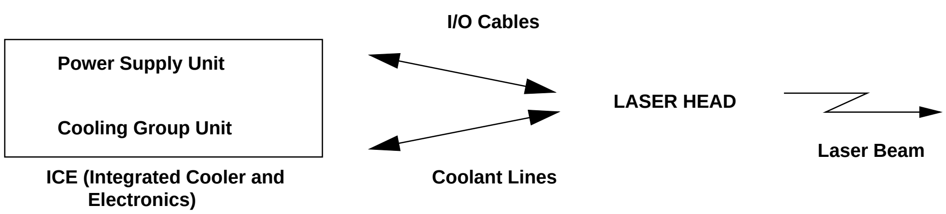


Figure 1: The CFR 200 Cabinet ICE laser.

The laser head controls the Q-switch electronics and the beam shutter.

Principles of operation The rod is the material in which lasing action takes place, here the YAG crystal. The lasant material is the three-times ionized neodynium ion, with a four-level transition scheme as shown in figure 2. A photon of frequency f1 pumps the atom to level E4 from the ground state E1. If the E4 to E3 transition probability is larger than that of E4 to E1, then if E4 is unstable, population will shift to E3 (the upper level of the laser). If E3 is metastable, population will increase with the cascade of population from higher levels like E4. The E3 level decays to level E2 emitting a photon of frequency f2.

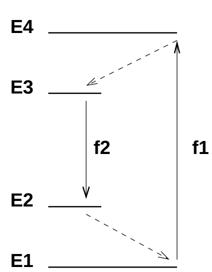
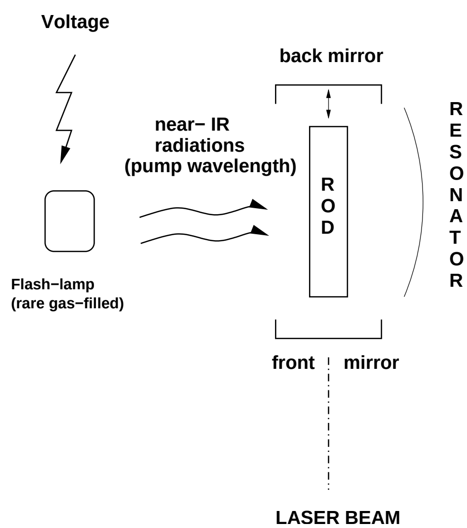


Figure 2: Energy levels of the Nd^{3+} ion.

This transition can be stimulated by the absorption of other f2 photons. The level E2 is also unstable and quickly decays to the ground state E1. The optical absorption of the Nd^{3+} ion is in the red end of the spectrum ($\frac{1}{f1} = 730 - 800\ nm$). The upper level has a metastable lifetime of about 250 microseconds. The major output wavelength ($\frac{1}{f2}$) is equal to 1064 nm.
The optical cavity consists in a back mirror, with total reflection, and a front mirror which transmits part of the incoming light. Thus, photons emitted are re-directed into the rod and stimulate the emission of more photons. If the resulting gain overcome losses in the resonator, the lasing action takes place and a continuous flux of highly directional, spectrally pure and coherent light is emitted, until the pump (the flashlamp) goes off.



The Q-switch operational mode consists in two steps. First, the flashlamp excites the rod while the losses in the resonator are maintained artificially high, to build up a very large population inversion in the rod. After 200 microseconds, the losses are removed, so that all ions relax at the same time. The resulting light pulse lasts about 10 nanoseconds, and delivers up to 200 mJ (20 MWatts!) with a repeatability rate of 100 Hz for the CFR 200.

Adjustable parameters

- Flash-lamp voltage: default value is 570 V. Higher voltage will increase the output power of the laser, but will also reduce the lifetime of the lamps.
- FL-QS delay: Time delay between the triggering of the flashlamp and the Q-switch fire order. The optimal value is 180 microseconds. Any deviation will decrease the output energy.
- Flashlamp synchronization external or internal.

- Delay sync: delay between the real internal flashlamp firing order and the output flashlamp signal. The value is set to 999 nanoseconds.

The PIV installation The PIV installation is depicted in figure 3. The slave laser receives its firing order from the master (identified with a gray stripe), with a fixed delay. The two output Q-switch signals, which correspond to the emission of the pulses, are fed into the General In input signal of the high-speed camera.

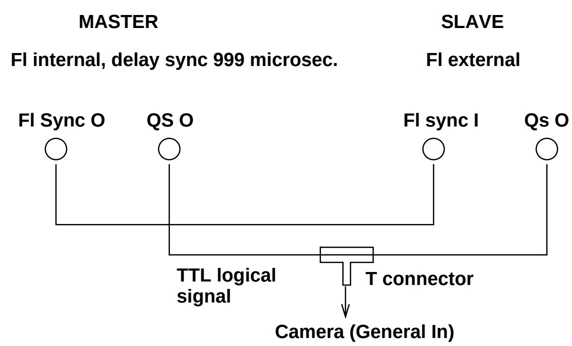


Figure 3: The PIV installation

The two laser heads are placed side-by-side. A set of mirrors deviates the beam of one laser, so that the the two light sheets are aligned. The ensemble sends a couple a pulses (separated by 1 ms), every 10 ms.

2.2 Image acquisition

The camera (FASTCAM-ultima APX, from the firma Photron) transfers the data directly to the separated hard-drive, which is linked through a Firewire port to a PC. The camera is controlled by the PFV v.1.4 software. The output signal from the Q-switch of both lasers (standard TTL signal) must be connected to the General In cable. Then the following parameters should be settled through the PFV interface:

- External In set to "Disable"
- General In set to "Trigger pos" (the camera will take a picture each time a pulse is emitted from one of the lasers)
- Trigger mode set to "Random 1", indicating that the camera will record one picture each time it receives a trigger signal.
- Frame rate 2000/s
- Resolution 1024x1024
- Linear LUT pattern

The lens used is a NIKKON 50 mm, with the maximal aperture of 1.2, so that the camera is placed very close to the tank. This configuration is optimal for two reasons: firstly, lenses with a longer focal will have a smaller aperture (2.8 for the 105 mm), and light is the critical parameter in this problem. Secondly the 50 mm is more than sufficient to cover the available field of view, which is limited by the area enlighted by the laser sheet. The camera should be placed so that the optical axis is perpendicular to the light sheet, and then correctly focused. It should also be centered on the area that gains most light from both lasers, as the two laser sheets are slightly misaligned. They only overlap over 75% of their total area.

Before each run, the tank must be brushed around the measurement area to ensure that walls are transparent, and to bring remaining particles in suspension. After about one hour, 50 micrometer particules are injected in the light sheet, as equally distributed as possible. We then have to wait another 20 minutes before any measurement, until the level of turbulence in the tank has decayed. Beyond that delay, the particles will be too low-concentrated in the FOV. Figure 4 shows the level of turbulence in the FOV, obtained from one hundred of subsequent velocity fields. This is representative of the current limitations of the lasers: while in the center the turbulence level is around 3% (which is still excessive to perform reliable turbulence estimates), on the boundaries it goes up to 8%. These extreme values are caused by wrong vectors from the PIV processing, issued by insufficient lighting from one or the other laser. We also observed that one laser emits weaker pulses than the other, despite a higher voltage.

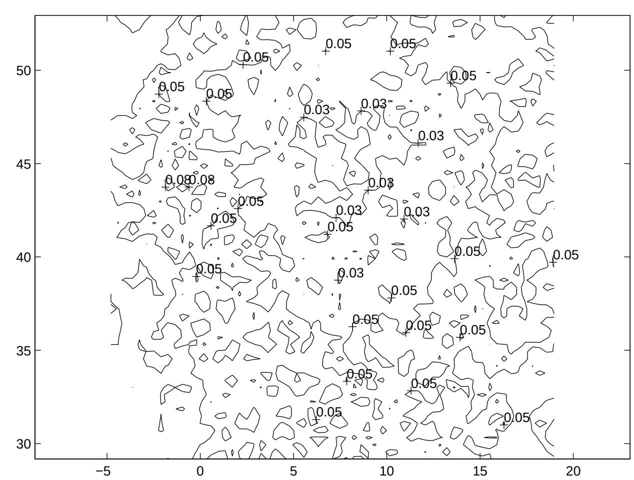


Figure 4: Turbulence level in the tank

This operation should be done before each run, and turbulence estimates in the flow must be restrained to the area which shows acceptable levels initially. Once the recording is done, the film is transferred from the separated hard-drive to the PC, and then analyzed with help of MatPiv v.1.6.

3 The PIV processing

3.1 Other information required

Apart from the .avi video file transferred from the camera, the PIV software needs the velocity of the cylinder, and a passage matrix from pixels to physical coordinates.

The latter is obtained by immersing a plexiglas plank in the light sheet, with regular marks which will appear to the camera. From this picture, the "definewoco" function then creates a file containing the coordinate transformation.

The velocity of the cylinder can't be computed from MatPiv using the displacement of the numeric mask, because this value is biased by parallax effects, as the camera is placed so close to the tank. It has to be measured previously, by external means (a single clockwatch gives good results). The speed is adjusted by varying the rotational speed of the motor driving the trailer.

3.2 Phase-assignment

It is crucial to correctly relate each instantaneous velocity field with the corresponding phase with respect to the shedding process, to perform ensemble-averaging over a constant phase. The phase is issued from transducers which record the lift force at each end of the cylinder. A base-pressure gauge, placed at the same section as the measurement plan, is usually employed for this purpose, because 3D effects are important at these Reynolds numbers (the correlation length at $Re = 10^4$ is 5 diameters). The phase varies along the span of the cylinder. However, it appears that the two force signals are almost in-phase. This is probably due to the very short length of the test cylinder, which has an aspect ratio of only 6. This, on the other hand, raises the question of end effects: the aspect ratios are usually close to 20 for this kind of investigation. These effects still need to be quantified, and a compromize must be found between the maximum Reynolds reachable and the aspect ratio.
Just before the cylinder arrives in the FOV, it passes in front of a photoelectric cell which sends a signal to the force recording software and switches off a diode placed in the FOV. We then calculate the time delay separating the picture where the diode switches off from the considered velocity field, and report this delay in the force history.

3.3 MatPiv

MatPiv, developped by J.K Sveen is this laboratory, is a program written with MATLAB which processes the digital images obtained from above and yields the velocity fields at different instants. MatPiv is the core of the PIV method, and here we simply describe the procedure followed in this application:

- The .avi video is loaded into Matlab. On the first picture of interest, we use the function "mask" to mask the cylinder's shape and shade.

- As explained before, the velocity must be manually entered. A timing sequence is created, so that the mask is simply displaced to follow the cylinder at each time step.
- The PIV algorithm will then correlate each pair of subsequent pictures, yielding the velocity fields. The sequence of pictures, the time step must be defined, as well as the following parameters:
  1. Method set to "multin": the program will make several pass with different interrogation window sizes.
  2. Window size :[64 64;32 32;32 32] (3 pass)
  3. Overlapping : 0.5.
  4. Signal to noise ratio : 1.2
  5. Global filtering parameter: 3
  6. Local filtering parameter: "median", 3

For more information about MatPiv and the PIV theory, refer to [3] and [2].

4 Examples

We briefly present here a few results obtained from the set-up depicted above in April and May 2004.

Figure 5 and 6 show the velocity and vorticity fields obtained at two different phases, identified 1 and 5 on figure 7. The instantaneous vorticity field is a superposition of the big vortical structures that appear clearly in the velocity field, and of the smaller Kelvin-Helmholtz vortices issued by instability in the shear layer. Ensemble-averaging over one phase removes these secondary structures very efficiently.

Figure 8 illustrate a vortex collapse event, which occurs randomly at these Reynolds and was identified from the force recording of figure 9, at $t \simeq 40s$. No organized structures are visible in the near wake.

Finally, figure 10 represents the global mean average velocity and vorticity fields (over all phases) obtained from different runs.

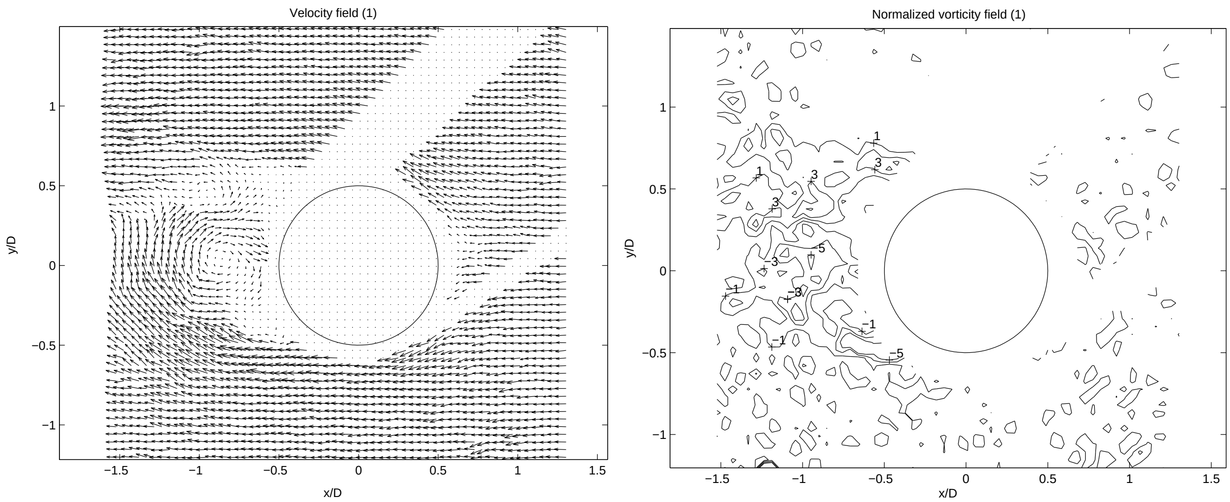


Figure 5: Velocity and vorticity field, phase 1 (Re 20800).

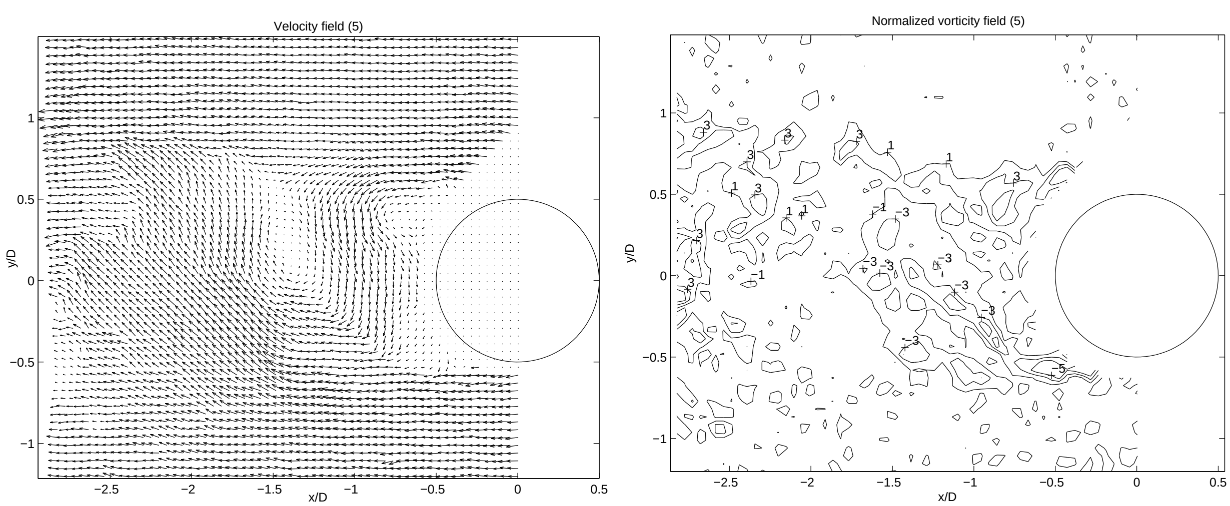


Figure 6: Velocity and vorticity field, phase 5 (Re 20800).

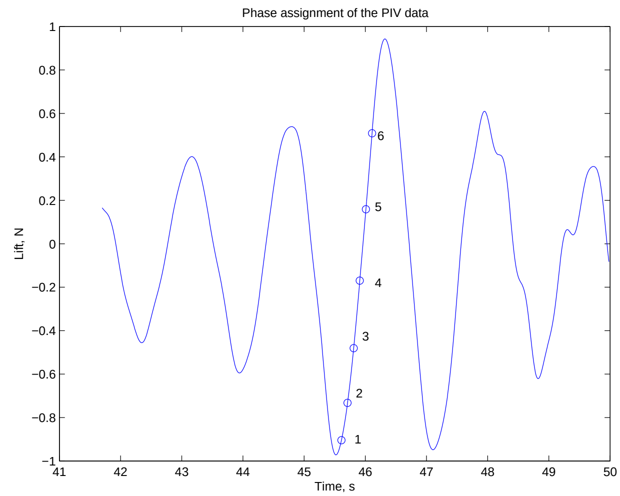


Figure 7: Phase assignment.

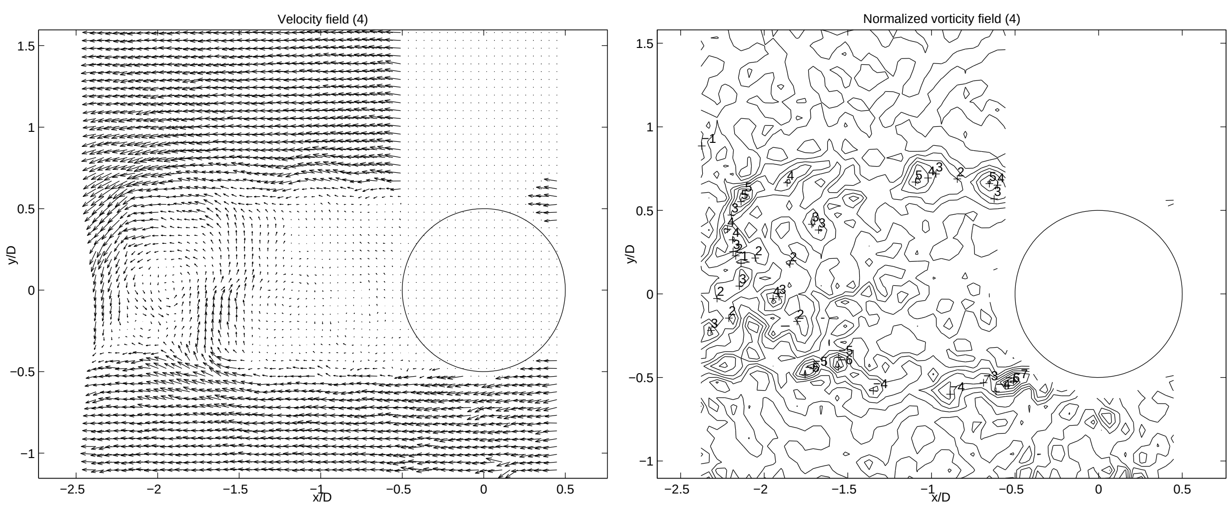


Figure 8: Illustration of a vortex collapse event (Re 20800).

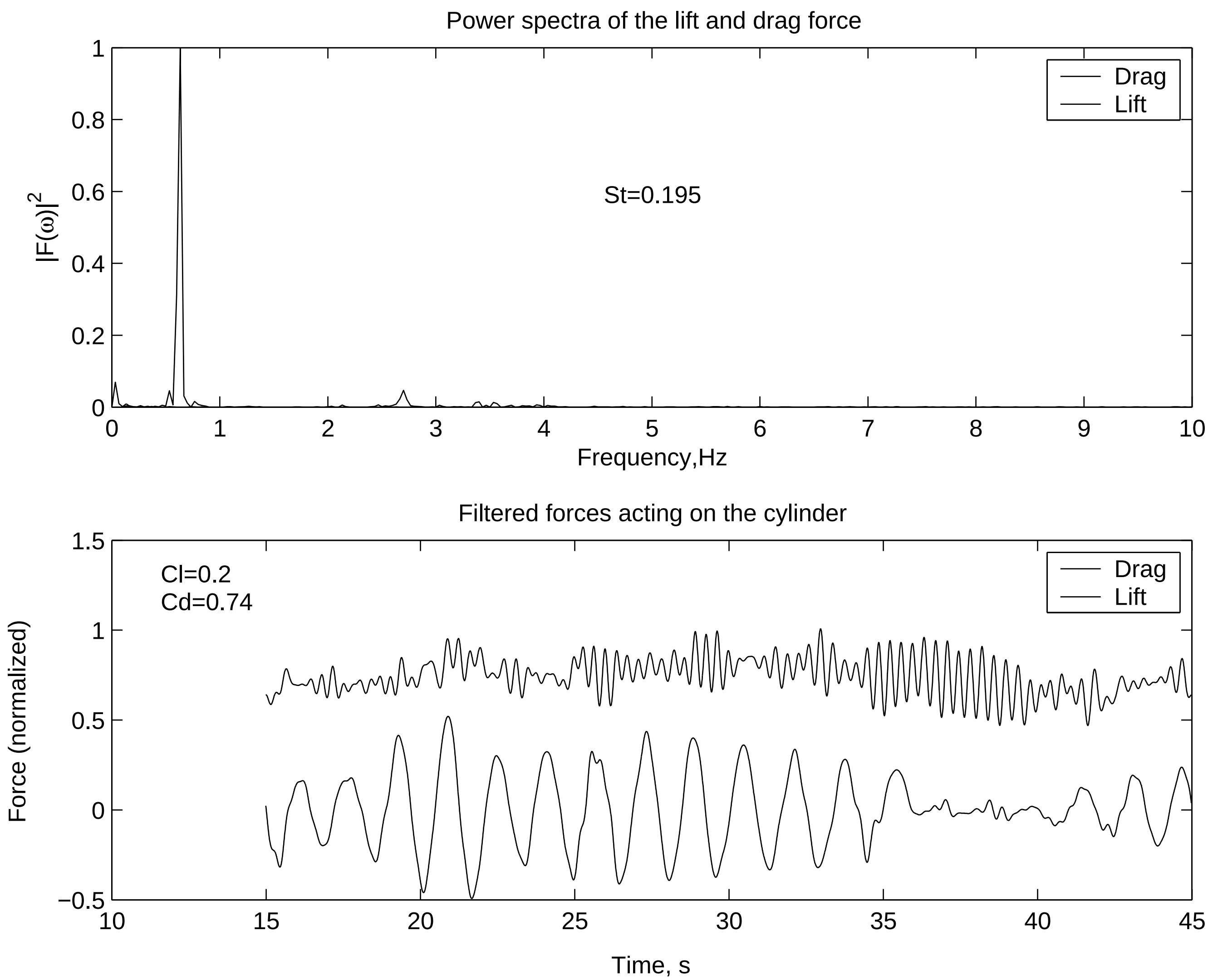


Figure 9: Force power spectra and time recording at Re 20800.

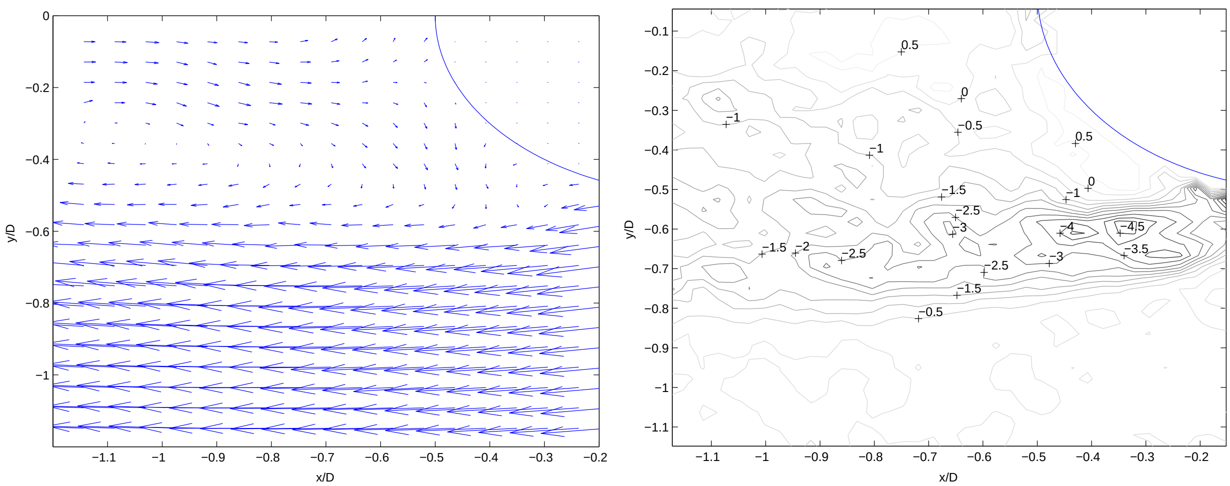


Figure 10: Global mean average velocity and vorticity fields at Re 46000.

5 References

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