AE4-180 # Flow Measurement Techniques

Student Manual for the Laboratory Exercise

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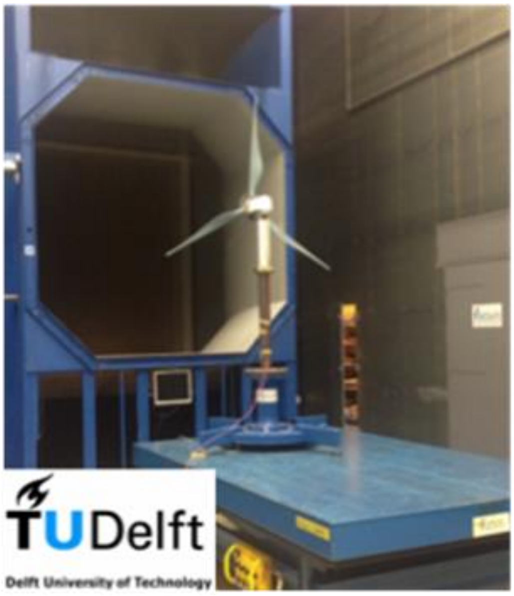

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1. Introduction

The laboratory exercise is an integral part of the course on Experimental Aerodynamics (AE4-180). The result of the laboratory exercise is a written report, which is evaluated and contributes to the final mark of the exam. Only students who have performed the exercise can enroll in an exam session. The report should be sent by email to the instructors of the lab exercise at least one week before the scheduled date of the exam.

Description of the exercise

The laboratory exercise introduces the student to the set-up and utilization of velocimetry techniques for the investigation of a typical problem in aerodynamics: determination of the flow distribution around a NACA-0012 airfoil at angles of attack. The experiments are performed in the *W-tunnel* of the aerodynamics laboratories where a low-turbulence free stream flow is produced at atmospheric conditions. The exit velocity of the *W-tunnel* ranges between 5 and 30 m/s. The airfoil is installed in a closed test section built with transparent material to allow optical access. Two techniques will be used: Particle Image Velocimetry (PIV) and Hot Wire Anemometry (HWA).

The students are required to set the wind-tunnel conditions, calibrate the instrumentation and conduct the measurement campaign for different airfoil angles of attack. The experimental procedure must be reported and the results of the experiments must be presented and interpreted. In particular, the consistency of the data between the two measurement techniques, or possible inconsistencies, should be carefully verified by direct comparison. The measurement uncertainty should be also estimated. The most important parameters influencing the measurement accuracy should be identified and discussed.

In the PIV laboratory experiment a class IV laser is used, which is the highest category meaning the laser beam is hazardous to skin and eye. Therefore all participants in the exercise need to be aware of and comply with the laser safety rules, which are found in the appendix A (#1 rule: always wear laser protection goggles).

Time schedule and organization

Each group is formed by three to four students. The laboratory exercise is consists of two experiments, organised with two sessions of activity:

Session 1: PIV. System set-up/calibration, wind tunnel experiments and data acquisition. Due to the Corona virus restrictions, this part has been conducted by the instructors, see video *PIV_experiment*.

Session 2: HWA. System set-up/calibration, wind tunnel experiments and data analysis. Due to the Corona virus restrictions, this part has been conducted by the instructors, see video *HWA_experiment*.

For the PIV data processing, a *matlab* data processing code is made available to perform the necessary data analysis and post-processing.

The report is to be delivered by email in PDF format no later than 1 week before the chosen oral exam session. The report grade is an integral part of the exam grade.

2. Experimental apparatus and arrangement

Wind tunnel

The experiments are conducted in the W-tunnel at the High Speed Laboratory of the TU Delft. The W-tunnel is an open, low speed wind tunnel. The inlet of the tunnel consists of a plenum with dimensions ($L \times W \times H$) $2.0 \times 1.5 \times 2.0$ m^3. Air is sucked into the plenum by a centrifugal fan driven by an electrical motor of 16.5 kW. In the PIV experiment seeding particles are added to the flow in the plenum to obtain a uniform seeding distribution in the test section. The air then passes through the diffuser which decelerates the flow, the settling chamber with inside two gauzes to diminish the turbulence intensity, the contraction which accelerates the flow and finally the nozzle where the air is blown into the free atmosphere. The nozzle exit has a cross-section of 0.40×0.40 m^2, where in the center (0.32×0.32 m^2) the flow is uniform (Bossuyt 2004). Based on Laser Doppler Anemometer measurements at 10.2 m/s (Tummers 1999, p. 82) the RMS of the fluctuations in the *u*-component of velocity in that region is <0.2% of the free-stream velocity.

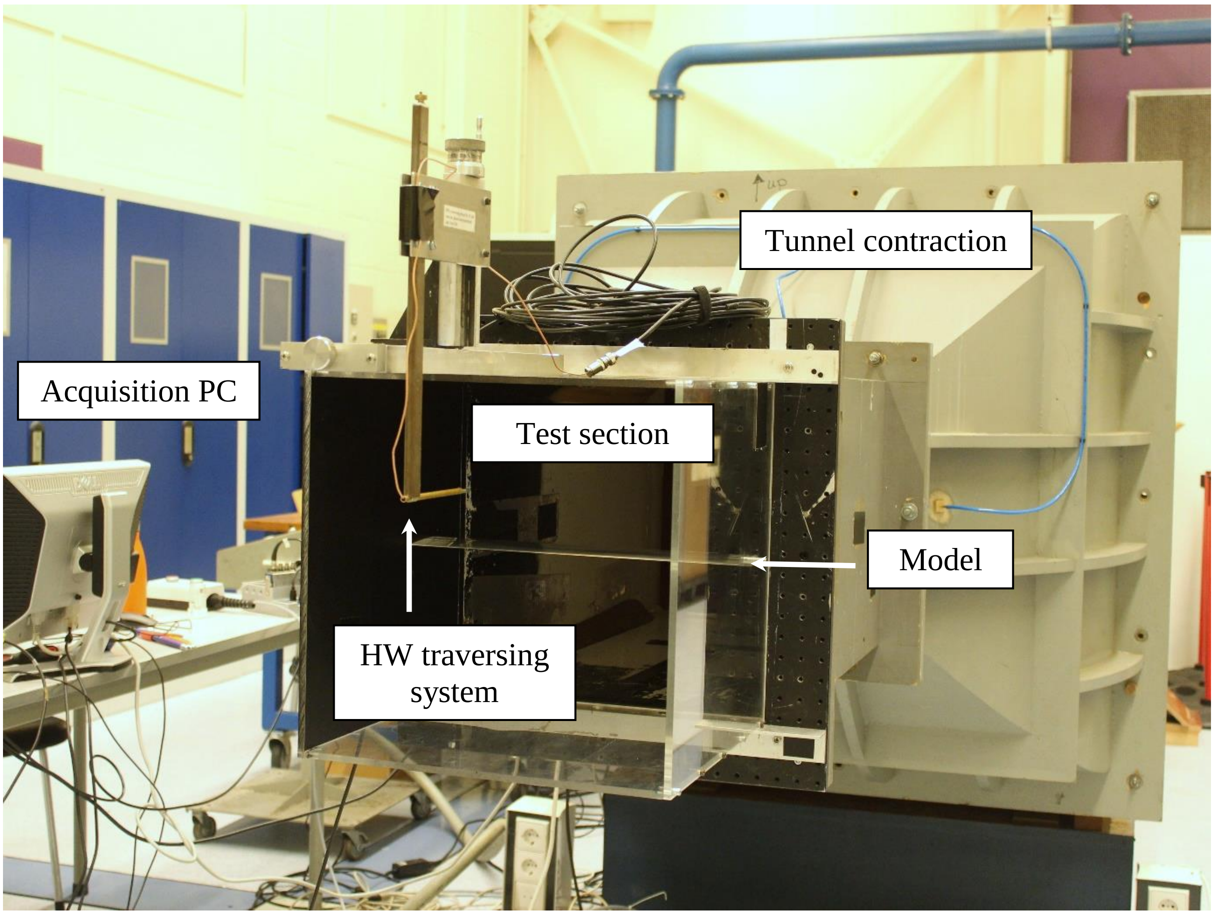


Figure 1. Test section of the wind tunnel with the model installed.

Model specifications

The airfoil model is a NACA-0012 airfoil, with a chord length c=10 cm spanning the entire width of the wind tunnel test section (W=40 cm) and it is made out of Plexiglas. The model is installed in a closed test section (cross-section: 0.40×0.40 m^2) built from transparent material to allow optical access for PIV measurements. The incidence angle α can be controlled over ± 30° by a lever. The point of rotation is at a quarter chord.

Hot wire instrumentation

The total hot-wire system consists of a hot-wire probe connected to a Wheatstone bridge. The output of the Wheatstone bridge is transferred to a PC by means of a National Instruments data acquisition system.

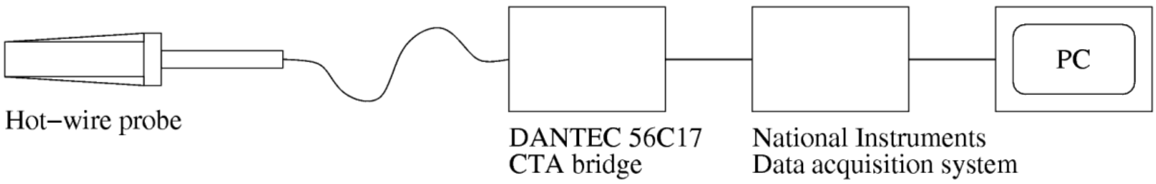


Figure 2. Diagram of the hot-wire measurement set-up.

<u>Hot-wire probe</u>

The hot-wire probe consists of a 5 μm platinum-plated tungsten wire (Figure 3). The wire is directly welded to the prongs and acts as the sensor. Be cautious with the probe since it is very fragile and expensive. **Touching the probe *will* break the wire.**

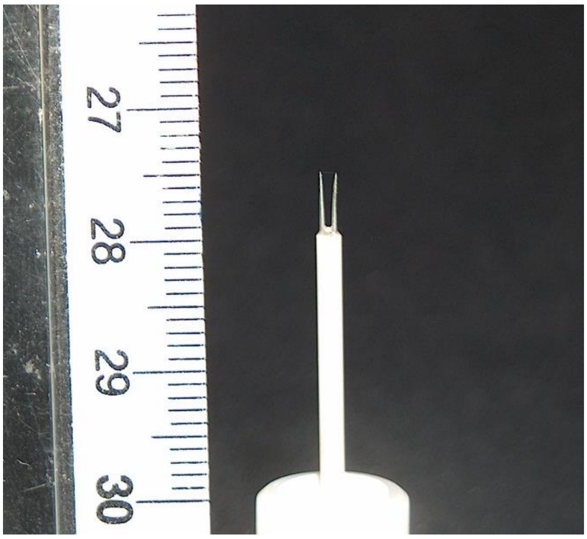


Figure 3. Hot-wire probe.

Figure 4. Dantec 56C17 CTA bridge.

<u>Constant temperature anemometer bridge</u>

The Dantec 56C17 CTA bridge is the control circuit for hot-wire anemometry (Figure 4). It is a Wheatstone bridge consisting of four electrical resistances, one of which is the sensor. When the required amount of current passes through the sensor, the sensor is heated to the operating temperature (depending on the overheat ratio), at which point the bridge is balanced. If the flow speed is increased, the heat transfer from the sensor to the ambient fluid will increase, and the sensor will thereby tend to cool. Since metals have positive temperature coefficients of resistivity (i.e., the electrical resistance will increase with increasing temperature or decrease with decreasing temperature), the accompanying drop in the sensor's electrical resistance will upset the balance of the bridge. This imbalance is sensed by the high gain DC amplifier, which will in turn produce a higher voltage and increase the current through the sensor, thereby restoring the sensor to its previously balanced condition. The DC amplifier provides the necessary negative feedback for the control of the constant temperature anemometer. The bridge or amplifier output voltage is, then, an indication of flow velocity.

A second feature of the 56C17 CTA Bridge is that it can also be used as a resistance-measuring device to set the correct overheat ratio.

<u>Data acquisition system</u>

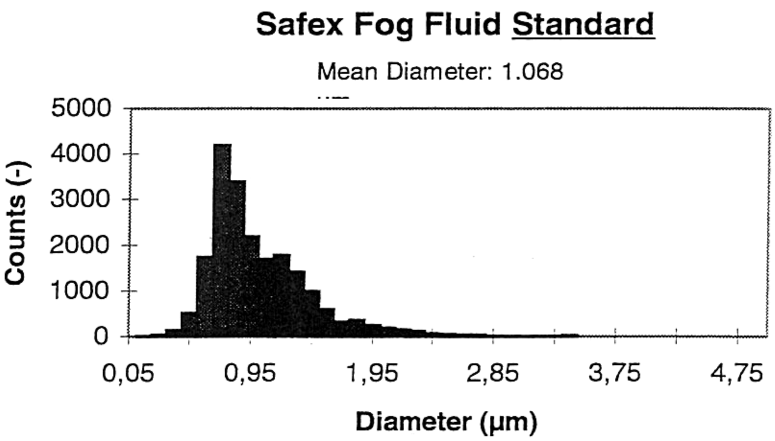
The raw voltage is acquired using a National Instruments BNC-2110 block connector connected to a NI PCI-6024E data acquisition board, which converts the analog voltage to a digital output. LABVIEW is used to read and display the measured voltage output supplied by the DANTEC 56C17 CTA Bridge. When setting the overheat ratio (during calibration), the voltage is measured using an analog voltmeter.

PIV instrumentation

The instrumentation specific to PIV is discussed in four parts: seeding production, laser, CCD camera and the PIV acquisition software.

<u>Seeding generator</u>

The *SAFEX fog generator* produces a non-toxic water-glycol based fog from the *SAFEX normal power mix* fluid. The droplet size distribution in the fog is shown in Figure 5. The mean diameter is 1 μm. The fog machine is activated simply by switching it on, then it needs to warm up for about 5 minutes before it can produce smoke (until the green control lamp READY goes on and the control lamp HEATING goes off for the first time). The seeding production level is set from a remote control unit. In order to have stable seeding conditions the knob on the remote control unit should be set at the third tick with the lower button on 10%.



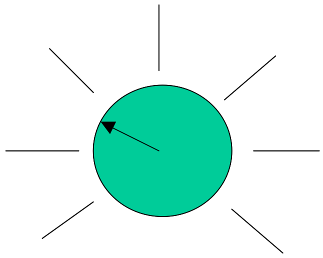


Figure 5. Droplet size distribution (left) [taken from the SAFEX fog generator user's guide]. Seeding knob position (right).

Laser

For the PIV experiments the *Quantel Evergreen 200* laser is used as light source, Figure 6. The laser system is a double pulsed Nd:YAG laser consisting of two cavities producing infrared light of a wavelength at 1064 nm. A second harmonic generator halves the wavelength to 532 nm (visible green). At maximum power the energy in each laser pulse is 200 mJ. The laser light is hazardous at any power to eye and at high power (>80%) to skin (class IV lasers). Therefore some safety requirements for operating this system are needed, which are found in the appendix A and are essential for you to read and understand them before coming to the lab. The pulse energy is controlled by a PC through the LaVision software DaVis. The pulse duration is 8 ns and the maximum repetition rate is 15 Hz for each pulse. At the laser exit the beam diameter is 6 mm.

Figure 6. Quantel Evergreen 200 laser head.

The laser is controlled from the Davis 8 software, where it is possible to set the repetition rate and the time separation between the two laser pulses. This information is sent from the computer to the digital delay control unit (PTU, programmable time unit), which produces the triggering signals for the laser and the CCD camera.

CCD camera

The PIV images are recorded with a Bobcat IMPERX IGV-B1610 CCD camera (Figure 7). The CCD has a resolution of 1628×1236 pixel with 4.40 µm pixel pitch and can record 10-bit black and white images. In double shutter mode, which is used in double frame PIV, the maximum recording rate is 8.3 Hz (120 ms separation time between image pairs). The camera is controlled by the DaVis software. The camera exposure is such that the first exposure (frame A) has a duration of 10 µs and the second exposure (frame B) lasts about 100 ms. Therefore in double shutter mode frame A collects much less light from the ambient with respect to frame B. This effect causes more intense background light in frame B, which results in noisier particle images. The camera settings are sent to the control box (Programmable Timing Unit, PTU), which produces the triggering signals for the camera and collects the recordings from the camera. For the imaging of particle onto the camera sensor a Nikon f = 35 mm lens is used. On the objective the f/# can be set from 2.8 to 32.

Figure 7. Bobcat IMPERX IGV-B1610 CCD camera.

PIV software

For image acquisition and analysis Davis is used. This software exploits the following functions:

1) Illumination and acquisition control (laser and camera settings, see Figure 8).
2) Image analysis (FOV analysis, region of interest, cross correlation)
3) Data post processing (velocity vector statistics, mean, rms, vector validation, calculate vorticity, streamlines)
4) Data display and output (plot velocity vectors, contours, tables, copy to clipboard)

The principle of the cross correlation algorithm implemented in the software is an iterative procedure: by cross-correlating corresponding windows of image A and image B, an initial guess of the particle displacement is computed. This is introduced as an offset for the window in frame B (window shifting). The new estimate of the displacement is used as the offset for the next iteration. In the process the interrogation window size is decreased also (multi-grid, which increases resolution while maintaining dynamic range, however the ¼ rule still applies in the first iteration). Furthermore, correlation window deformation is applied after the 1st iteration accounting for local deformation of the tracer particle pattern in the correlation widow (i.e. inside shear layers). A discussion of the window deformation is outside the scope of the present exercise. Details may be found in Scarano and Rietmuller (2000) or Westerweel and Scarano (2007).

To perform the cross-correlation, DaVis provides a graphical interface (see Figure 9) where the user has to set the interrogation window sizes, overlap and the number of iterations. Furthermore, it is possible to set some validation criteria to reduce the number of erroneous velocity vectors (the velocity vectors not meeting the criteria will be replaced by the value interpolated from its neighbours). The standard cross-correlation settings are presented in Figure 9. When scaling is applied the data is returned in physical unit (axes in mm and velocity in m/s).

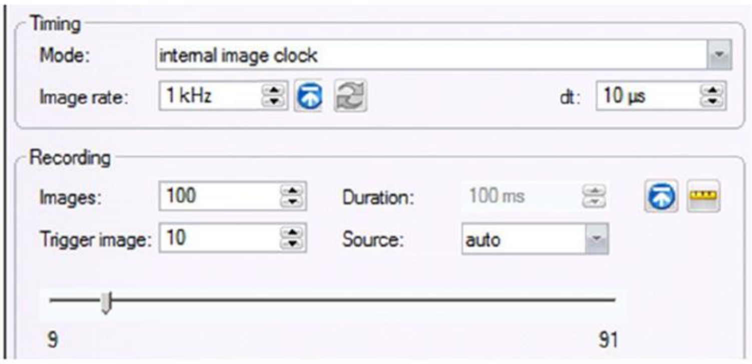


Figure 8. Screenshot of the graphical interface to set acquisition parameters of Davis.

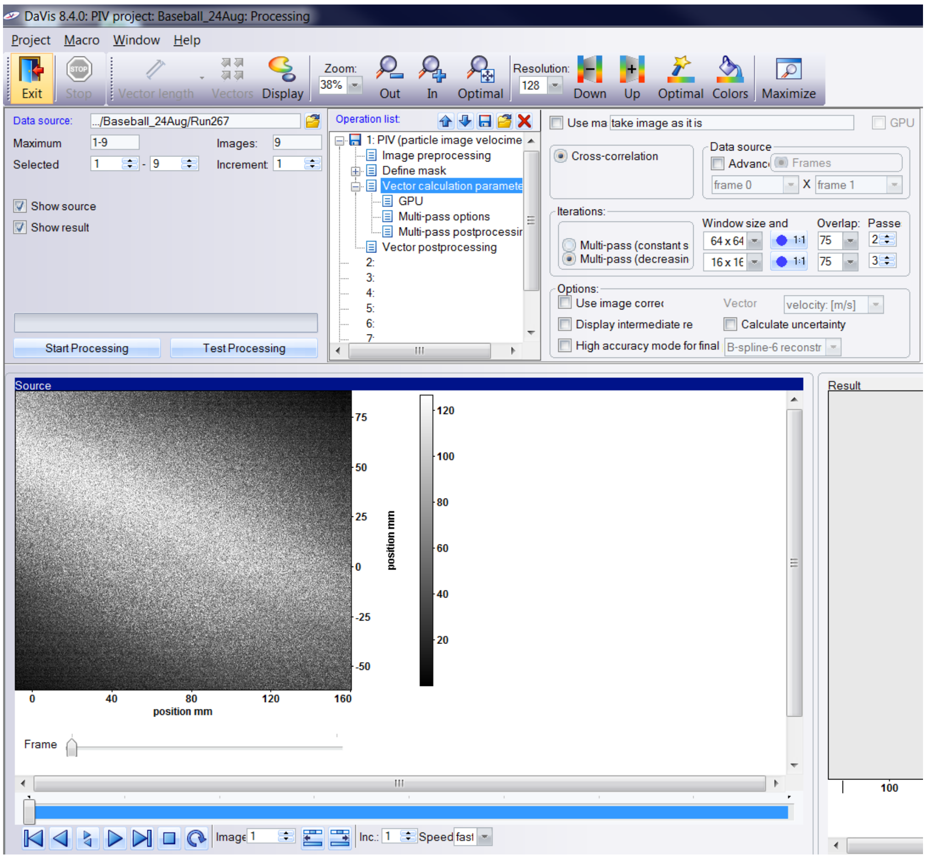


Figure 9. Screenshot of the graphical interface to set the parameters of the image analysis within Davis.

3. Hot Wire Experiment

Calibration Procedure

The calibration of the wire is needed in order to obtain the voltage – velocity relation (e.g. King's law coefficients or fourth-order polynomial). This consists of three steps. First the resistance of the system and cable must be determined. Second, the overheat ratio must be set. Finally, the calibration curve of voltage to velocity is determined empirically.

1. Determine cold resistance of entire system

1. Set the function switch to STD BY.
2. Connect the hot-wire probe and cable. Make sure that the FINE screw is completely turned to the left and that BRIDGE ADJ is set to 0 0.
3. Use the TEMP screw to set the voltage to 0 V.
4. Set the function switch to TEMP.
5. Balance the bridge:
    a. Shift the left-hand BCD-switch BRIDGE ADJ. from 0 to 9 by means of the pushbutton placed below the display. Shift the digits until the voltmeter shifts from a positive to a negative value.
    b. Shift one digit back with the pushbutton above the display. The voltmeter now shows 0 or a positive value. If the voltmeter does not shift polarity, keep setting 9.
    c. In the same way, activate the other BCD-switch from 0 to 9 until the voltmeter shows a negative value.
    d. Adjust the slotted screw FINE to 0 Volt.
6. Set the function switch to STD BY and connect the CTA Bridge Adaptor (Figure 10; put the switch on the adaptor to SHORT).
7. Set the function switch to TEMP and read the voltage. Now the resistance of the total cold system is measured: $R_{total,\ cold} = V \times 10$ [Ω].

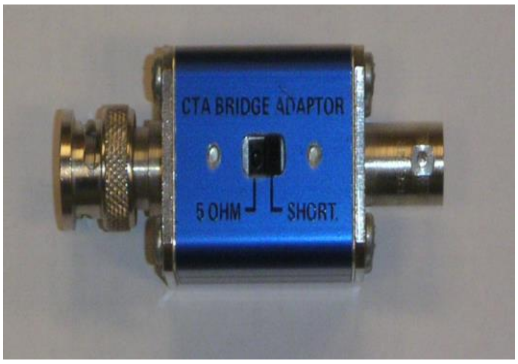


Figure 10. CTA Bridge Adaptor.

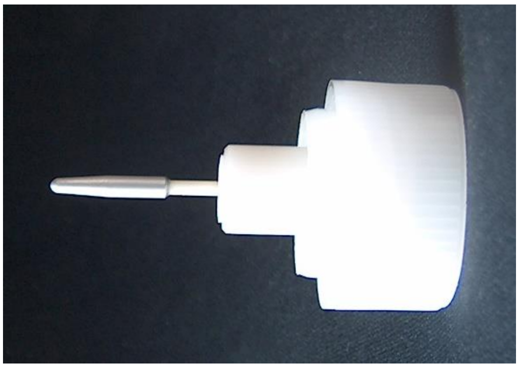


Figure 11. Shorting probe.

2. Determine cable-only resistance

1. Set the function switch to STD BY. Connect the cable to the other end of the CTA Bridge Adaptor and replace the hot-wire probe with the shorting probe (Figure 11).
2. Set the CTA Bridge Adaptor switch to 5 Ω (an extra 5 Ω is added since the system cannot measure below 3 Ω).
3. Set the function switch to TEMP and again balance the bridge (as in step 1.5).
4. Set the CTA Bridge Adaptor switch to SHORT and read the voltage. Now the resistance of the cable plus probe (5 Ω) is measured. So the resistance of the cable alone is: $R_{cable} = (V \times 10) - 5$ [Ω].

3. Set overheat ratio

1. The probe lead resistance cannot be measured separately therefore it is given by the probe manufacturer (see hot wire container). This should be $R_{probe\ lead} = 0.5\ \Omega$.
2. Calculate the probe cold resistance: $R_{probe} = R_{total,\ cold} - (R_{cable} + R_{probe\ lead})$.
3. In the experiments we use an overheat ratio of: $a = 0.5$.
4. Calculate the total desired resistance: $R_{total,\ hot} = (1+a)R_{probe} + R_{cable} + R_{probe\ lead}$.
5. Set the CTA Bridge Adaptor switch to SHORT.
6. Use the BRIDGE ADJ and FINE screw to set (read the voltage in the voltmeter): $V = R_{total,\ hot}/10$.
7. Set function switch to STD BY. Remove CTA Bridge Adaptor. Connect cable to bridge and mount hot-wire probe.

4. Perform velocity calibration

The system has to be calibrated for different flow velocities (to get the relationship between the measured voltage and local flow velocity). The calibration should be performed from 0 to approximately 20 *m/s* in increments of 2 m/s.

1. Set function switch to FLOW.
2. Set wind tunnel to the specified speed in m/s using the Labview velocity indicator.
3. Acquire measurement (5 seconds at 2 kHz), save as 'Calibration_xxx' where xxx is the speed in m/s.
4. Repeat measurements from 0 to 20 m/s in increments of 2 m/s.
5. Fit a polynomial of appropriate order through the measurement data points to determine the polynomial coefficients. Write the coefficients of your calibration in your report.

5. Determine correct sampling frequency

The correct measurement frequency should be used to ensure a proper convergence of the velocity statistics. Sampling at too high frequency can yield unconverged statistics; sampling at too low frequency causes an unnecessary increase of the measurement time. The proper way to determine the sampling frequency is to identify the sampling frequency corresponding to a low autocorrelation coefficient.

1. Ensure function switch is set to FLOW.
2. Set the hotwire 1 cm downstream of the trailing edge of the airfoil, and 5 cm above it (towards the suction side) at $\alpha = 15^o$.
3. Set the wind tunnel to 10 m/s using the Labview velocity indicator.
4. Acquire measurement (10 seconds at 10 kHz), save as 'CorrelationTest'
5. Compute the auto-correlation coefficient of the signal
6. Determine the integral time scale T_I as the time after which the auto-correlation coefficient drops below 0.1
7. Based on the integral time scale, determine the optimum sampling rate for amplitude domain analysis
8. Write this frequency down and use it for the remainder of the testing.

Measurement Campaign

Measure the velocity profile at *x/c=1.2* for $\alpha = 0^o$, 5^o and 15^o at 10 m/s.

1. Set the hotwire to y = -40 mm using the traversing system.
2. Set the tunnel to 10 m/s using the Labview velocity indicator.
3. Acquire measurement (5 seconds at the sampling rate determined previously), save as 'Measurement_sYY_sAA' where *s* is the sign (+ or –), YY is the y-position in mm (with respect to the position of the trailing edge at zero degrees angle of attack) and AA is the angle of attack in degrees.
4. Repeat measurements from -40 to +40 mm in increments of 4 mm
5. Repeat the above procedure for $\alpha = 0^o$, 5^o and 15^o

4. PIV Experiment

Set up the Experiment

1. Calculate Measurement Parameters ***(DO BEFORE COMING TO THE PRACTICAL; FOR THE REPORT, USE THE ACTUAL VALUES FROM THE EXPERIMENT)***

1. Determine required field of view (FOV) to capture 1.5 times the chord length of the airfoil.
2. Calculate the magnification M (given the FOV and properties of the digital camera as given on page 6).
3. Calculate image and object distance i and o using the thin lens equation and based on the lens focal length of f = 35 mm.
4. Determine the f# yielding good particle imaging (use criteria in the course notes for particle image diameter and depth of field)
5. Determine the light pulse separation Δt according to the maximum-displacement-criteria in the course notes (one-quarter rule).

2. Experiment Preparation

1. Measure the light sheet thickness at the measurement location using a piece of millimetre paper.
2. Focus the camera and set the FOV using millimetre paper.
3. Record a calibration image and set the field of view in the software.
4. Introduce some seeding into the tunnel.
5. Set f# and focus the camera on the particles.
6. Check the particle images for sufficient brightness and if needed adjust f# (look at particle diameter and focus!)
7. Set a very small Δt (e.g. 1μs) and check light beam overlap (cross-correlate the two frames and look at the vectors and signal-to-noise SN).
8. Determine if a background image should be acquired for subtraction. Consult your lab practical supervisor for guidance.

Measurement Campaign

Measure the velocity field for α = 0º, 5º and 15º at 10 m/s.

1. Check if all experimental settings are correct and write down the experimental parameters on the table
2. Set the free-stream velocity at 10 m/s using the Labview velocity indicator.
3. Add seeding to the room. Consult your lab practical supervisor for the correct seeding density. The seeding should be approximately 10-20 particles within an interrogation window of 32 x 32 pixels.
4. Acquire 20 image pairs for the cases $\alpha = 0^\circ$ and 5° and calculate the mean flow field.
5. Acquire 100 image pairs for the case $\alpha = 15^\circ$ and calculate the mean flow field based on 10 recordings
6. Acquire 20 image pairs for $\alpha = 15^\circ$ with about 1/20th of the original Δt.

The images have been exported in tif format, which can be read in Matlab with the matlab function *imread*.
For the case $\alpha = 15^\circ$ with the large Δt, you should analyse one image pair in Matlab with a self-made PIV code, and compare the results with the code provided by the instructors.

5. PIV Analysis

This year, the PIV analysis will be done completely in Matlab. The following steps shall be made:

1) Read the calibration image and use the matlab function *Determine_Magnification.m* to:
   a) determine the magnification factor (hints: use the matlab function *ginput*(2) to determine the pixel positions of two points in the image at a known distance in mm or cm)
   b) Determine the pixel location of a suitable origin point, e.g. the leading edge of the airfoil

Use the matlab function *WIDIMtif_Main.m* to:

2) Cross-correlate one image pair of each set and look at the effect of the interrogation window size on the image analysis (choose 0% overlap, single pass, that is *iterNum* = 1. Process with the following window sizes: 64, 32, 16 pixels)

3) Based on your judgement, decide for the optimum window size. Cross-correlate all images with an overlap of 50%, 3 multipass iterations (*iterNum* = 3), and the selected window size.

4) Process the instantaneous vector field for the runs at 15˚ with different pulse separation Δt (100 μs and 6 μs)

Use the matlab function *Stat.m* to:

5) Compute the velocity statistics (mean and fluctuations root-mean-square of the velocity magnitude, and of the individual components u and v) for all processed datasets using all available samples. Additionally, for the case of α = 15˚ compute the mean flow field using 10 and 100 samples.

Make the figures:

6) Make velocity vector plots with *u*-component of velocity contours (see example in appendix B) for an instantaneous and the mean result for all values of incidence α.

7) Create plots for your report in matlab or tecplot or equivalent. Extract the velocity profiles at x/c = 1.2.

For one image pair at α = 15˚ with the large Δt, you shall analyse this image pair in Matlab both with the code provided by the instructors <u>and with your self-made code</u>.

6. Requirements for the final report

Laboratory exercise report must include the following topics

1. Wind tunnel description. Describe how the velocity of the tunnel was determined using the Pitot-static probe.
2. Brief description of HWA instrumentation and set-up (include overheat selection, velocity calibration procedure, and calibration curve)
3. For HWA describe the way the sampling rate was determined to obtain uncorrelated samples
4. Brief description of PIV instrumentation and set-up (include your calculations to design the setup, see section 3, and explain your choices)
5. Display HWA velocity data: the mean velocity + fluctuations root-mean-square profiles in the airfoil wake and discuss them.
6. Display PIV data (at least 1 instantaneous flow field and the mean flow per angle of incidence α, see for some sample plots appendix B) and discuss them
7. For PIV discuss the effect of the correlation window size, Δt and ensemble size (when averaging) in relation to your results
8. Perform the cross-correlation of PIV images with the code you have developed during the course. Discuss the advantages and disadvantages of the self-made code compared to a professional one, underlining the reasons of the different accuracy level.
9. Compare the PIV velocity profiles at x/c = 1.2 (both mean and fluctuations root mean square) with those measured with the hot-wire. Explain the differences between the profiles obtained with the two techniques. Clearly indicate where the different measurement techniques do not return reliable data and explain why.
10. Discuss (shortly) the added value of HWA w.r.t. PIV (and vice versa) in aerodynamic investigations

The report should be structured with: Cover (containing the names of the authors, supervisor, and group number), Introduction, Table of Contents, Experimental Apparatus, Results and Discussion, Conclusions and References. In no case should the report contain integral parts of the material from the present notes. The report should be delivered in PDF file format.

References

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Appendix A. Laser safety

Class IV lasers are high power (c.w. P >500 mW or pulsed E >10 J/cm²) devices. Some examples of Class IV laser use are surgery, research, drilling, cutting, welding, and micro-machining. The direct beam and diffuse reflections from Class IV lasers are hazardous to the eyes and skin. Class IV laser devices can also be a fire hazard depending on the reaction of the target when struck. Much greater controls are required to ensure the safe operation of this class of laser devices. Whenever occupying a laser-controlled area, wear the proper eye protection. Most laser eye injuries occur from reflected beams of class IV laser light, so keep all reflective materials away from the beam. Do not place your hand or any other body part into the class IV laser beam. The pain and smell of burned flesh will let you know if this happens. Realize the dangers involved in the use of Class IV lasers and please use common sense. Watch the video on lasers safety and classification before coming to the lab exercise: https://www.youtube.com/watch?v=9ZEMWslK-7o

Rules:

1. Inform the others in the room when you make the laser flash.
2. When flashing the laser you are required to wear protective goggles.
3. Switch on the laser cavities only when absolutely necessary for the experiment.
4. The laser and the laser sheet optics will be handled for you in this lab-exercise: do not touch them!
5. Never look at the laser light directly with your eyes but also with the camera: we don't want eyes or pixels to get burned. Moreover light reflections from, for instance, the model can be quite strong. Make sure that reflections do not give blooming (large areas of overexposed pixels) in your images.
6. If possible, for example when adjusting/focussing the camera, use the laser at low power. Maximum power is used for the measurements only.

Appendix B. Examples of data display

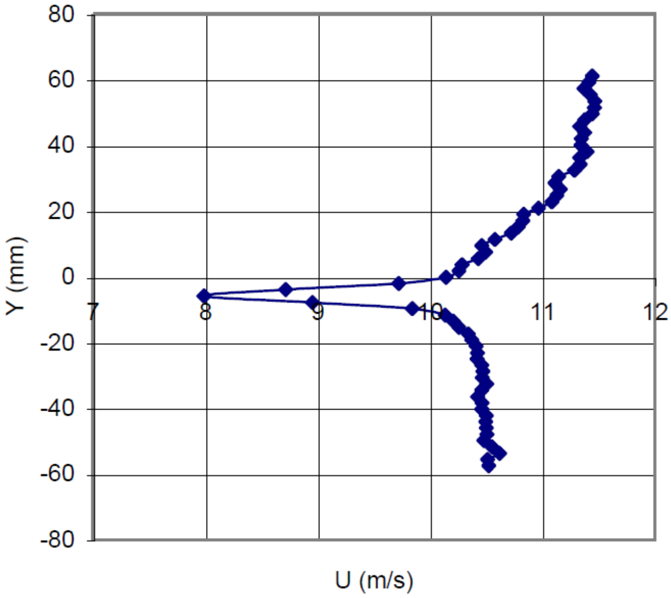

Figure 1. Mean U-component of velocity at x/c=1.2 for α=5 deg (PIV data, mean over 20 recordings)

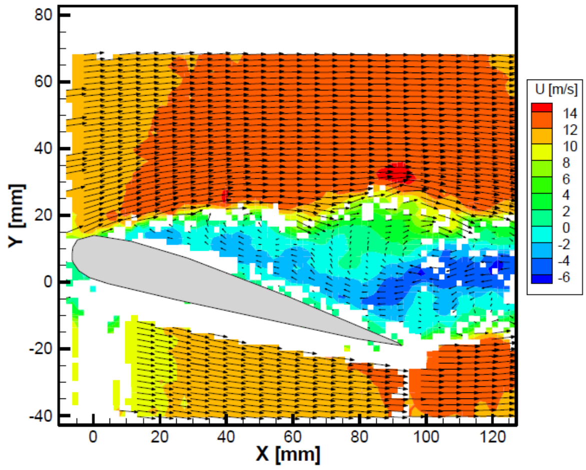

Figure 2. Instantaneous velocity field at α = 15 degrees. Velocity vectors and color contours of streamwise component. Settings: Ws = 31x31, OF = 50%. Spurious data (S/N < 1.2) are blanked.

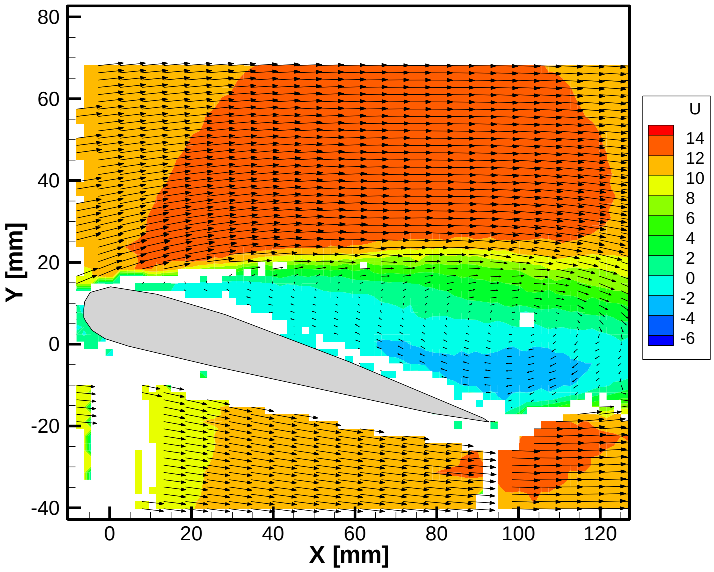

Figure 3. Averaged velocity field at $\alpha = 15$ degrees. Velocity vectors and color contours of streamwise component. Settings: $N_{snapshots} = 30$, Ws = 31x31, OF = 50%. Spurious data (less than 50% accepted) are blanked.

Sample test matrix for PIV experiments

The test matrix below is an example! If you feel that valuable information is missing, include it in your own table.

		Wind tunnel			**Acquisition**					**Image processing**			
Run #	Date	V (m/s)	Δp (Pa)	α (deg)	Δt (μs)	Laser sheet thickness (mm)	Sample rate (Hz)	f/#	FOV (mm²)	Window size (pixels)	Overlap (%)	# of images	Storage location
1	01-05-2018	5.2 ±1	16±2	4±0.5	80	2.5±0.5	3.3	4	128×102	32×32	50	10	C:\usr\group1\data
2	01-05-2018	8.5 ±1	48±2	12±0.5	50	1.5±0.5	1	2.8	50×40	64×64	50	100	C:\usr\group1\data
3													
4													
5													
6													
7													
8													
9													
10													