H10

MEASUREMENT OF AERODYNAMICS FORCES ACTING ON SIMPLIFIED AIRFOIL GEOMETRIES

1. Aim of the measurement

The aim of the measurement is to investigate the aerodynamic forces $\underline{F}$ (F_d, F_l) acting on various airfoil geometries, that are mounted in a 2D wind tunnel. In aerodynamics, aerodynamic drag is the fluid drag force (F_d) that acts on any moving solid body in the direction of the fluid freestream flow. Lift force (F_l) is the component of the aerodynamic force that is perpendicular to the oncoming flow direction (*Fig. 1.*). The sum of drag and lift force is the aerodynamic force acting on the body.

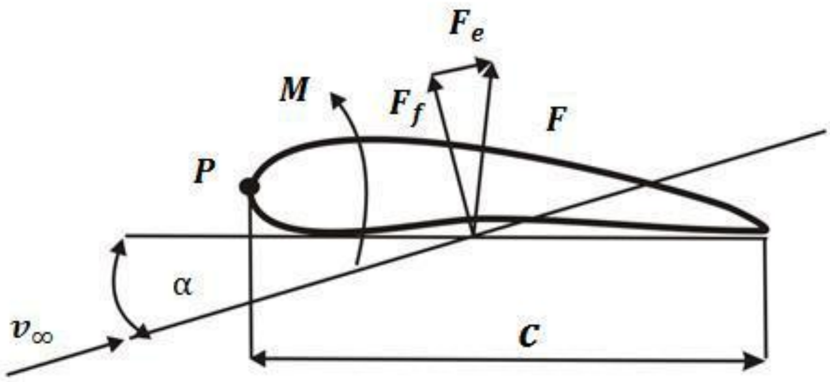


Fig. 1. Forces acting on an airfoil

After the force is determined the drag coefficient (c_d) and the lift coefficient (c_l) can be evaluated. If the Reynolds number remains the same for the measurement of various geometries, the dimensionless quantities can be used to compare the different geometries. This is an important aspect when designing airfoils for aircrafts or rotors (e.g. fan blades). Typical characteristics of airfoils are designed and then the most adequate profile is chosen according to the flow parameters (e.g. velocity, fluid density, etc.). Another important aspect, is to minimize the construction cost by using a simplified geometry.

2. Measured bodies and geometries

The Wright brothers designed their first airfoil geometry by using a simplified plane geometry in the early 1900's. As reported in the literature, a cambered plane (f/l=2%) has a significantly higher lift coefficient. A cambered plane generates lift (unlike the simplified plane) even at a zero angle of attack. This will be investigated in Task B.

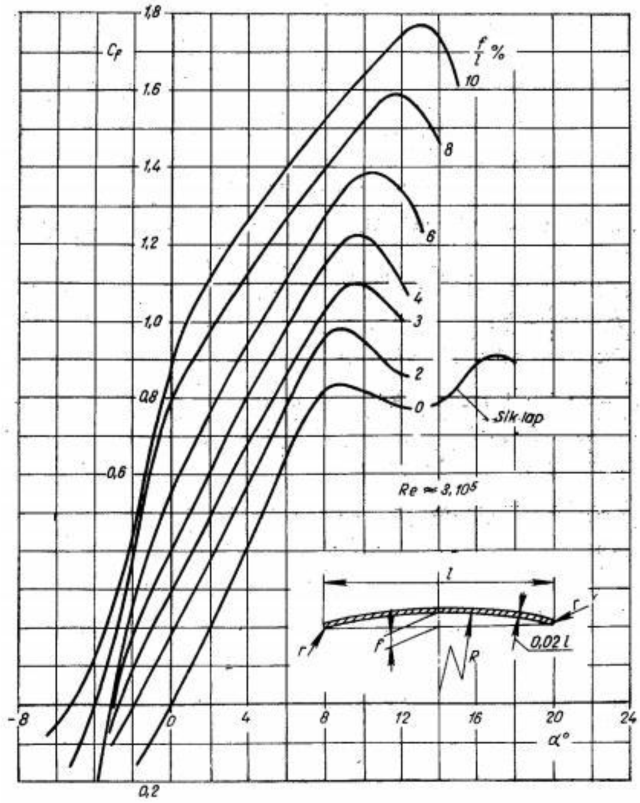


Fig. 2. Typical curves showing section lift coefficient c_l versus angle of attack for cambered airfoils. (source: Gruber – Ventilátorok)

Turbomachinery blade geometry needs to be relatively simple and low-cost, since a large number of blades need to be produced. Basic axial fan impellers can therefore be made using a simplified plane geometry. High performance fan blades however need to use airfoils. A typical airfoil cross-section, which is commonly used in propeller design is the RAF6E geometry.

The RAF6E geometry can be seen on *Fig. 3*. Unlike many other airfoil geometries, the RAF6E airfoil has a flat pressure side, which makes the airfoil easier to produce. The RAF6E airfoil was originally developed by the RAF (Royal Aircraft Factory) in the early 1900's. Today it is mostly used in fan designs.

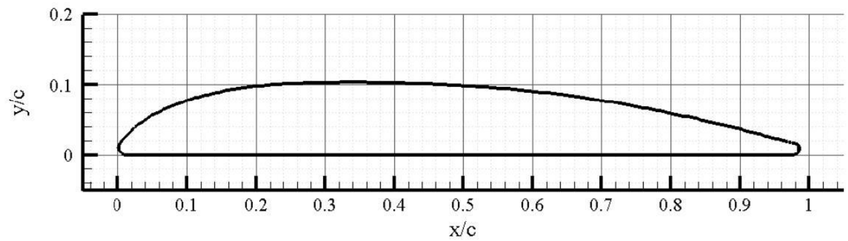


Fig. 3. RAF6E airfoil profile

The aim of Task A will be to determine the RAF6E airfoil's flow parameters versus angle of attack and compare them to that of a simplified plate geometry. The most important parameters are the Reynolds number and the drag and lift coefficients as a function of the angle of attack (see *Fig. 8.*).

The different geometries used during the measurements can be seen in Fig. 4. (The cambered plate parameters, f/l [%], are equal to the 3% and 8%, as seen in Fig. 2.).

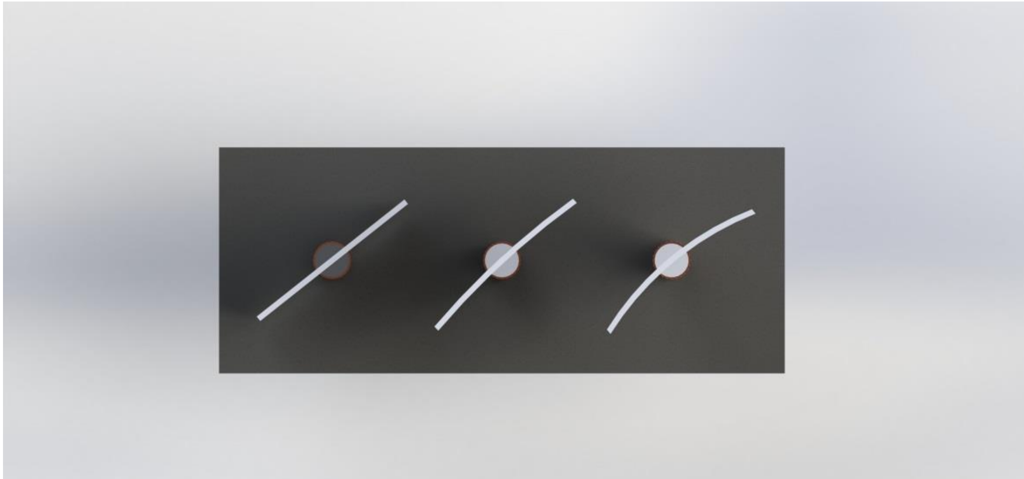
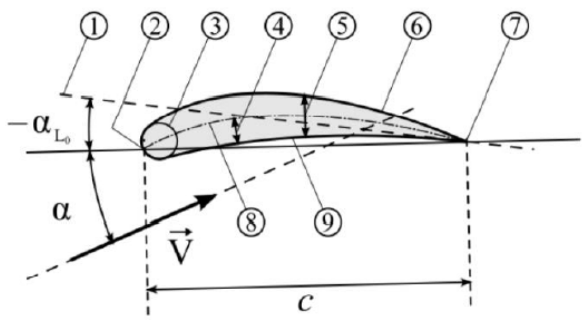


Fig. 4. Different plate geometries

3. Theory of the measurement

During the measurement, four different types of geometries can be measured: a simplified plate, a RAF6E airfoil geometry and two different cambered plates (*see Fig. 3. and Fig. 4.*). Their drag and lift coefficient will be investigated. All the four geometries can be considered simplified wings.

A typical airfoil geometry can be seen in *Fig. 5*. The simplified plate has significantly less parts.



1. húr (c)
2. belépő él
3. belépési sugár (Rb)
4. íveltség – a húr és a vázvonal távolsága (f)
5. vastagság (th)
6. szívott oldal
7. kilépő él
8. vázvonal – a két oldal közé rajzolható, érintő körök középpontjait összekötő vonal
9. nyomott oldal (Korenchy, 2009)

Fig. 5. Typical airfoil geometry. 1) chord (c), 2) leading edge, 3) leading edge radius (Rb), 4) curvature- the distance between the chord and the camber lines, 5) thickness, 6) suction side, 7) trailing edge, 8) camber, 9) pressure side

In *Fig. 5.* the direction of the relative velocity is $\vec{v}$, and its magnitude is v_∞. The angle of attack (α) is measured relative to the chord line. Since the pressure side of the RAF6E airfoil is flat, the angle of attack can be measured relative to the pressure side. In this case the chord length is equal with the length of the pressure side (c=100 mm). The chord length is the reference dimension of the airfoil section, the Reynolds number can be calculated based on this characteristic length.

$$Re = \frac{v \cdot c}{\nu}$$

For the simplified plate and the cambered plates, the chord length can be seen in *Fig. 6,* which is the characteristic length (or reference dimension) and also equal to the RAF6E chord length (the characteristic length is therefore c=100 mm in all cases).

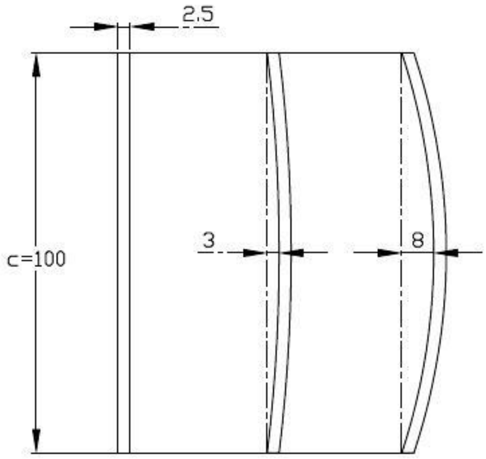


Fig. 6. Chord length of cambered plates

The aim of this measurement is to determine the drag and lift coefficient of simplified and cambered plates and the RAF6E airfoil. The following equations are needed:

$$c_f = \frac{F_f}{\frac{\rho}{2} \cdot v_\infty \cdot A_m}$$

$$c_e = \frac{F_e}{\frac{\rho}{2} \cdot v_\infty \cdot A_m}$$

The lift and drag coefficients are defined by the lift and drag force, the fluid density, the flow speed and the relevant cross-sectional area (A_m).

The relevant cross-sectional area in the case of an airfoil is the product of the chord length and the max thickness. The relevant area is constant for one typical airfoil geometry. Since the cambered plate and the simplified plate are also simplified wing geometries, the calculation of their relevant cross-sectional areas is done in the same manner.

Flow separation

Flow separation (*Fig. 7.*) occurs when the boundary layer travels far enough against an adverse pressure gradient that the speed of the boundary layer relative to the object falls almost to zero. The fluid flow becomes detached from the surface of the object. In the case of airfoils, the pressure field modification results in an increase in pressure drag, and if severe enough will also result in loss of lift as well as stall, both of which are undesirable. Flow separation measured at the department on a RAF6E airfoil and a simplified plate at $Re=10^5$ can be seen in Fig. 8. Two conclusions can be made from the diagrams. First, flow separation for the case of the RAF6E occurred at an angle of attack of 19 degrees (the lift coefficient decreased dramatically) and separation was realized in the case of a simplified flat plate. Second, the airfoil-shaped wing can create a higher lift coefficient than a flat plate. The flow separation can be visualized using smoke or with the help of threads.

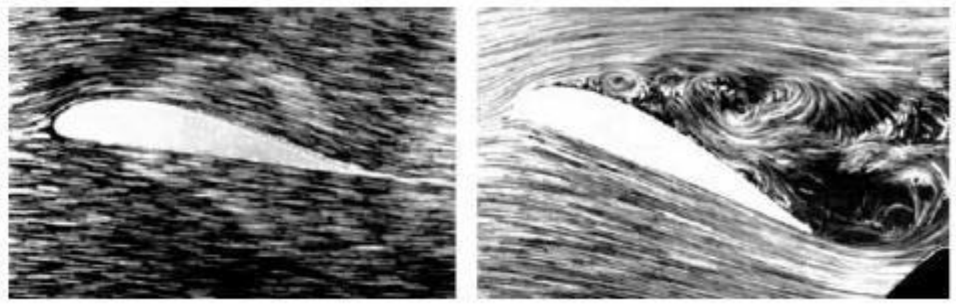


Fig. 7. Airfoil without flow separation (left) and with flow separation (right)

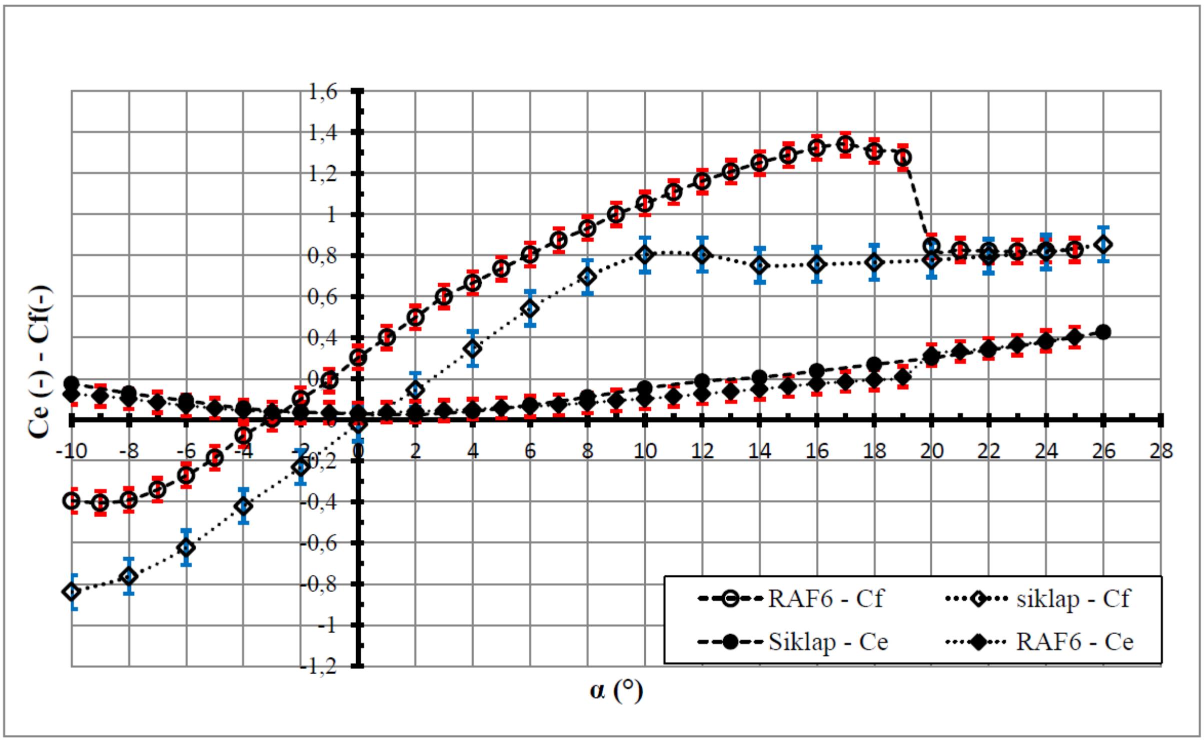


Fig. 8. Re=10^5, drag and lift coefficient, simplified flat plate and RAF6E

The flow separation always occurs at the same angle of attack if the flow parameters remain the same. If the flow parameters change, such as the airfoil surface quality or the Reynolds number, then the flow characteristics and hence the angle at which the flow separates will change (the flow separation will occur at higher or lower angle of attack). The RAF6E airfoil is very responsive for flows having Reynolds numbers under 10^5. Task C will therefore investigate the flow characteristics and separation characteristics as a function of Reynolds number. More information is available in the textbook, Lajos Tamás (2008) Az áramlástan alapjai, chapter 11.2.1.

4. Description of the measurement equipment

Wind tunnel

The various geometries will be placed in the small wind tunnel of our department (Blackbird 2. see *Fig. 9.*). Wind tunnel measurements on typical geometries, such as airfoils and cylinders can be performed with endplates, in order to ensure two-dimensional flow (see Lajos Tamás Áramlástan alapjai course book, chapter 11.1., page 516.). These end plates can be seen in the cross-sectional view of the wind tunnel.

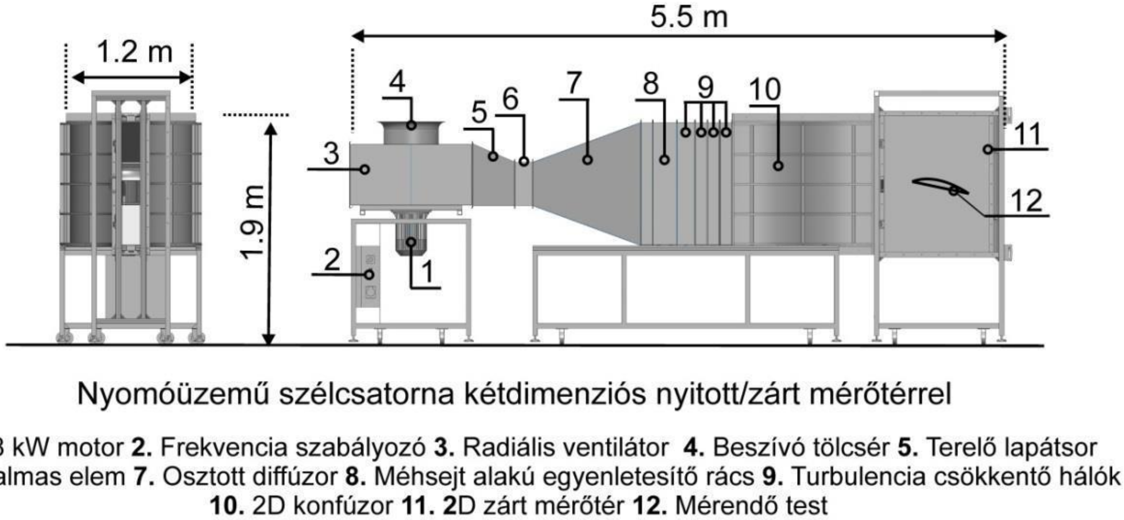


Fig. 9. Blackbird 2. wind tunnel. 1) 4.8 kW motor, 2) frequency convertor, 3) radial fan, 4) inlet bell mouth, 5) guide vanes, 6) elastic element, 7) split diffuser, 8) honeycomb flow conditioner, 9) turbulence reduction mesh, 10) 2D nozzle, 11) 2D closed measurement section, 12) measured body

Description of the wind tunnel:

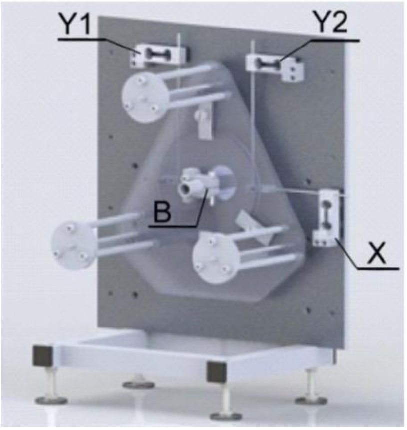
Maximum velocity: 21 m/s

Turbulent intensity: 0.8%

Cross-section of the test section: 1000x1000x152 mm

Force measurement

The multi axis (three-component) load cell, which was developed by the department, can be seen in *Fig. 10*. The load cell is fixed to the closed measurement section's back side (11). The drag force (acting opposite to the relative motion of the object moving with respect to the surrounding fluid) is measured by the **X**. load cell, the lift force (perpendicular to the oncoming flow direction) is measured by the **Y1** and **Y2** load cells. The resultant lift force can be calculated by taking the arithmetic mean. The measured body has to be fixed with the platform's clamping device (B) by placing the rod of the measured device through the hole of the wind tunnel and the clamping device and then fixing it (the door of the measurement section needs to be open during this procedure). **To ensure the measurement body's free motion, a 0.5 mm space needs to be left between the measured object and the wind tunnel wall using the spacers provided.**



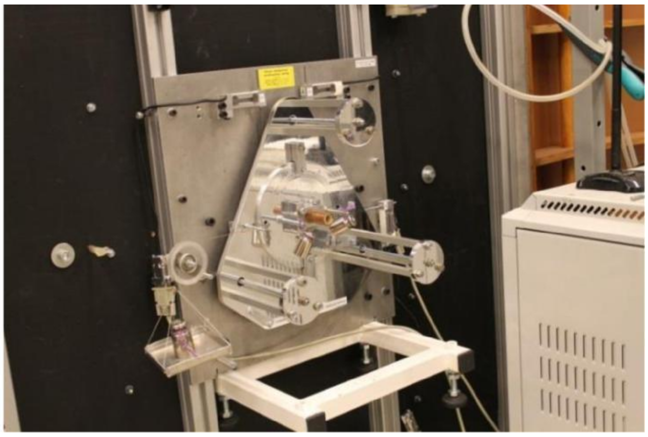


Fig. 10. Three-component load cell system

The first step of any measurement is to check the calibration of the load cell (*Fig. 10. right*). If it is incorrect, then the load cell has to be calibrated.


Fig. 11. Wind tunnel side which can be opened (left), back side of the wind tunnel (right)

The measurement setup can be seen in *Fig. 11*. The aim of the measurement is to determine the forces acting on the fixed body as a function of the angle of attack using the load cell system. The measurement will be carried out using the Pressure and Force 3.47 software developed by the Department (which is an executable program in Labview). The fluid velocity inside the measurement section will be measured using a Pitot-static probe (Prandtl probe) at every angle of attack. The pressures and forces need to be measured at approximately the same time. By doing so, the correct forces can be calculated along with the actual velocities, and the Reynolds number can also be kept constant. The measurement of the pressure can be made using a Setra digital pressure transducer. The data processing will be accomplished by the measurement software. The angle of attack can be set with an accuracy of 0.1 degrees (*Fig. 12.*). Be careful when rotating the airfoil in order to avoid overloading the load cell.

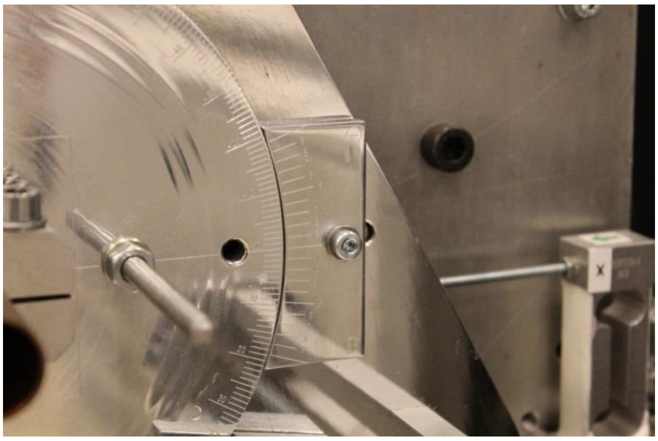


Fig. 12. Measuring the angle with an accuracy of 0.1 degrees

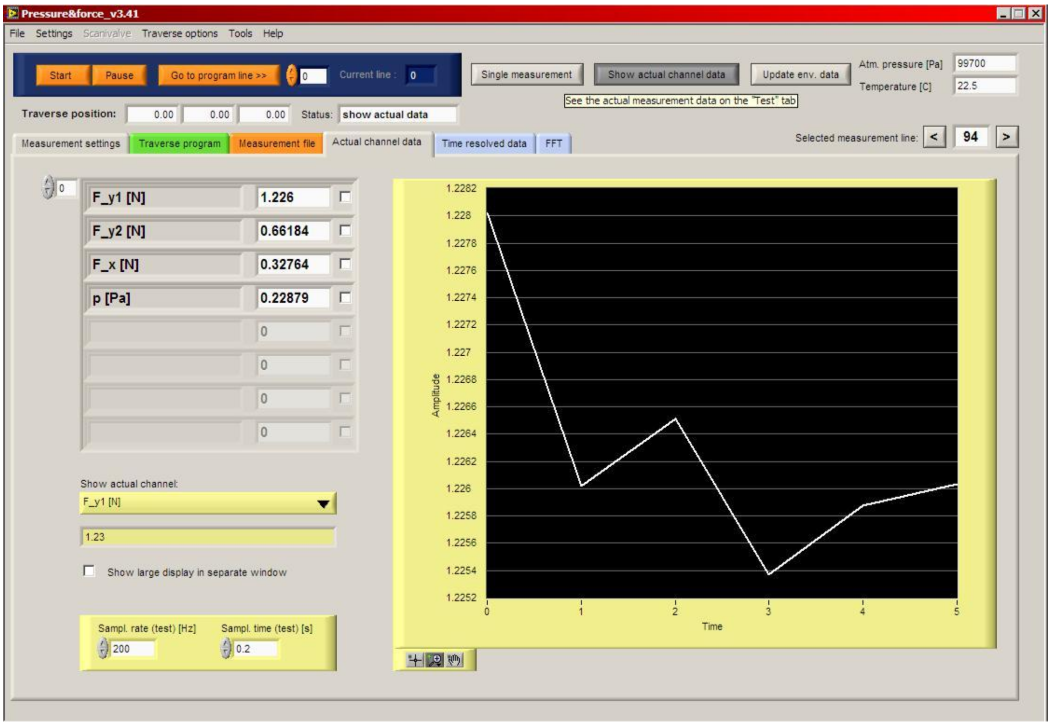
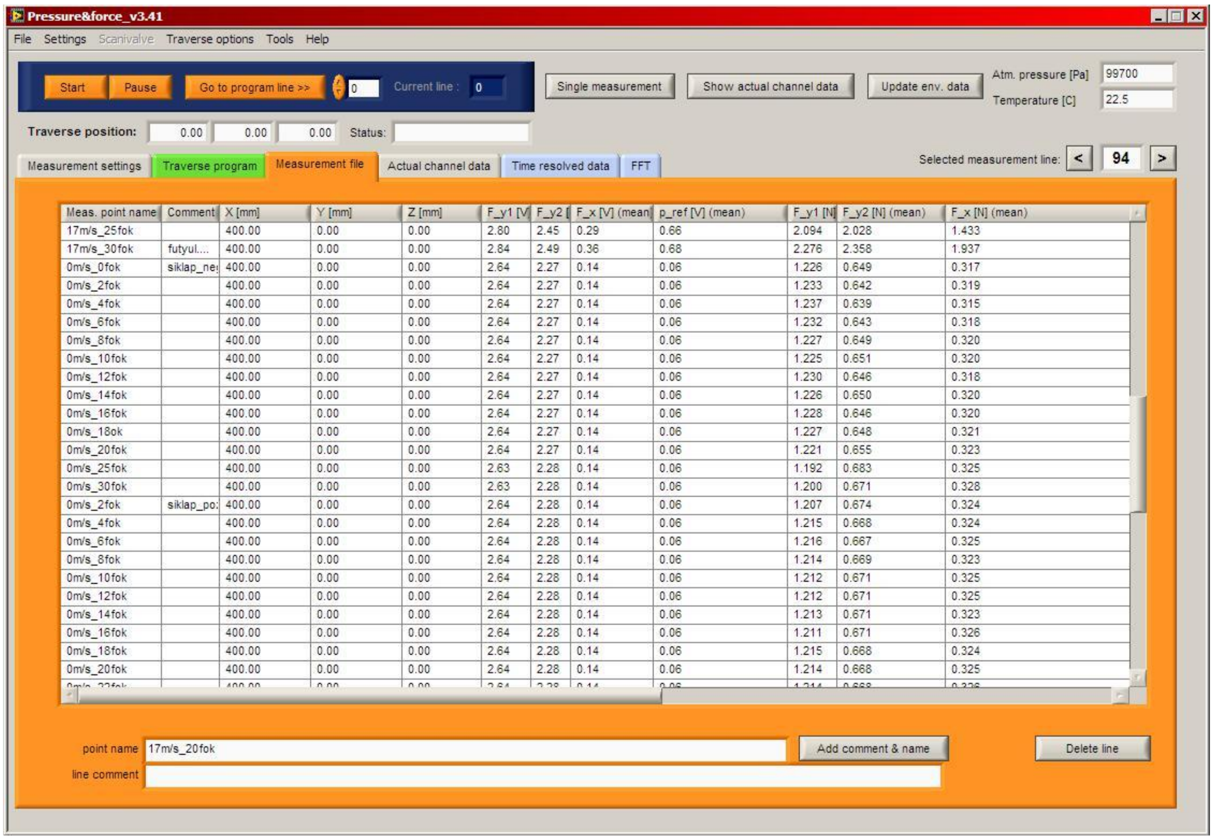


Fig. 13. GUI of the Labview software

During Task C, the measurement group needs to complete the measurement for various Re. Therefore, the dynamic pressure values associated with a given Re need to be set precisely. This can be done with the help of the software's *„Show actual channel data"* function, which shows the actual force and pressure values (see *Fig. 13.*). When the correct dynamic pressure has been set, turn off the *„Show actual data mode"* and perform the measurement of the current point with the help of the *„Single measurement"* button.



Meas. point name	Comment	X [mm]	Y [mm]	Z [mm]	F_y1 [V	F_y2 [	F_x [V] (mean	p_ref [V] (mean)	F_y1 [N	F_y2 [N] (mean)	F_x [N] (mean)
17m/s_25fok		400.00	0.00	0.00	2.80	2.45	0.29	0.66	2.094	2.028	1.433
17m/s_30fok	futyul....	400.00	0.00	0.00	2.84	2.49	0.36	0.68	2.276	2.358	1.937
0m/s_0fok	siklap_ne	400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.226	0.649	0.317
0m/s_2fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.233	0.642	0.319
0m/s_4fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.237	0.639	0.315
0m/s_6fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.232	0.643	0.318
0m/s_8fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.227	0.649	0.320
0m/s_10fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.225	0.651	0.320
0m/s_12fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.230	0.646	0.318
0m/s_14fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.226	0.650	0.320
0m/s_16fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.228	0.646	0.320
0m/s_18ok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.227	0.648	0.321
0m/s_20fok		400.00	0.00	0.00	2.64	2.27	0.14	0.06	1.221	0.655	0.323
0m/s_25fok		400.00	0.00	0.00	2.63	2.28	0.14	0.06	1.192	0.683	0.325
0m/s_30fok		400.00	0.00	0.00	2.63	2.28	0.14	0.06	1.200	0.671	0.328
0m/s_2fok	siklap_po	400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.207	0.674	0.324
0m/s_4fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.215	0.668	0.324
0m/s_6fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.216	0.667	0.325
0m/s_8fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.214	0.669	0.323
0m/s_10fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.212	0.671	0.325
0m/s_12fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.212	0.671	0.325
0m/s_14fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.213	0.671	0.323
0m/s_16fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.211	0.671	0.326
0m/s_18fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.215	0.668	0.324
0m/s_20fok		400.00	0.00	0.00	2.64	2.28	0.14	0.06	1.214	0.668	0.325

Fig. 14. Table from Labview

During the measurement, the measurement groups will record nearly 70 different data points, and every measurement point will be associated with a given angle. To make the identification of various data sets easier, comment each measurement point with the *„point name"* and *„line comment"* commands found in the *"Measurement file"* section. The comment can be saved with the *„Add comment & name"* button. The entire measurement file can be saved in .txt format, but it is recommended that each group write down their data on paper as well, in order to avoid possible data loss.

5. Evaluation of the results and error calculation

During the measurement the group will record 4 different quantities. The drag coefficient (c_d) can be calculated from the x component of the force. The lift coefficient (c_l) can be determined by the arithmetic mean of the two measured lift forces. The measurement groups have to set the geometry, the Re number, and the angle (i. angle) according to the measurement assignment and then calculate the drag and lift coefficients (c_d and c_l). After that, the results have to be presented as the function of the angle of attack (see *Fig. 1 and Fig. 8*).

Arrange the curves in joint diagrams in order to compare the different cases, such as the different Reynolds numbers and geometries. Determine at what angle the flow separation occurs in the case of the RAF6E and cambered plates. Specify the Re number dependence in the case of the RAF6E and investigate its effect on the flow separation. Determine the percentile difference between the RAF6E and the simplified geometries. Based on the measurement results, can the RAF6E be replaced by cambered plates?

Since we are only interested in the fluid forces acting on the body, we have to measure in case of zero velocity (0 m/s wind velocity) to determine force coming from the mass of the object. This zero-point measurement has to be subtracted from the measured forces for the relevant wind velocities. The zero-point measurement only needs to be done for the zero angles. The x and y forces can be calculated:

$$F_{xi} = f_{xi} - f_{x0}$$

$$F_{yi} = f_{yi1} - f_{y10} + f_{yi2} - f_{y20}$$

Where:

F_{xi} – drag force along x direction at the ith point
F_{yi} – lift force along y direction at the ith point
f_{xi} – force along x direction at the ith point
f_{x0} – force along x direction at the zero angle and zero velocity
f_{y1i} – force along y_1 direction at the ith point
f_{y2i} – force along y_2 direction at the ith point
f_{y10} – force along y_1 direction at the zero angle and zero velocity
f_{y20} – force along y_2 direction at the zero angle and zero velocity

An evaluation of the measurement uncertainty (measurement error) also needs to be conducted. In this measurement the absolute and relative errors need to be calculated for the drag and lift coefficients. This can be done using the following equations and values.

$$c_{di} = \frac{f_{xi} - f_{x0}}{\Delta p_i \cdot A_m}$$

$$c_{li} = \frac{f_{y1i} - f_{y10} + f_{y2i} - f_{y20}}{\Delta p_i \cdot A_m}$$

The pressure and force values are directly measured quantities. For calculating the drag coefficient, 1 measured pressure and 2 force values are used (3 values). For calculating the lift coefficient, 1 measured pressure and 4 force values are used (5 values). The density will drop out when simplifying the velocity equation, so there is no need to consider the atmospheric pressure and temperature measurement error during the drag and lift coefficient uncertainty calculations. The uncertainty must be presented in the lab report.

$$\delta c_{di} = \sqrt{\left(\frac{\partial c_{di}}{\partial f_{xi}} \cdot \delta f_x\right)^2 + \left(\frac{\partial c_{di}}{\partial f_{x0}} \cdot \delta f_x\right)^2 + \left(\frac{\partial c_{di}}{\partial \Delta p_i} \cdot \delta \Delta p\right)^2}$$

$$\delta c_{li} = \sqrt{\left(\frac{\partial c_{li}}{\partial f_{y1i}} \cdot \delta f_y\right)^2 + \left(\frac{\partial c_{li}}{\partial f_{y10}} \cdot \delta f_y\right)^2 + \left(\frac{\partial c_{li}}{\partial f_{y2i}} \cdot \delta f_y\right)^2 + \left(\frac{\partial c_{li}}{\partial f_{y20}} \cdot \delta f_y\right)^2 + \left(\frac{\partial c_{li}}{\partial \Delta p_i} \cdot \delta \Delta p\right)^2}$$

Measurement uncertainties:

$\delta f_x = \pm 0.15N$

$\delta f_y = \pm 0.12N$

$\delta \Delta p = \pm 2Pa$

The uncertainties must be included in the diagrams of the lab report (as seen in *Fig. 8.*).

References

[1] – Tamás Lajos: Áramlástan alapjai [2008]

[2] – Gurber Blahó: Folyadékok mechanikája [1973]

[3] – József Gruber: Ventilátorok [1968]

[3] – BMEGEÁTAG11: Error calculation

[4] – Benedek Károlyi: BSc thesis [2013]

[5] – Balázs Tokaji: MSc diploma thesis [2014]

TASK A.)

0. Measure the lab temperature and the atmospheric pressure.

1. Determine the lift and drag forces of the flat plate (**100x152mm**) and the **RAF6E airfoil** (**chord length = 100 mm**) as a function of the angle of attack. Perform the measurements in the Blackbird 2 wind tunnel with the help of the load cell system.

Measurements should be carried out for a -5 to +30 degree range of angle of attack, with a 1 degree increment (sum 70 measurement points). Set the Reynolds number to $Re=1.1*10^5$, the required flow velocity should be determined in this way.

Note: Do not forget to measure the forces as a function of the angle of attack in the case of zero velocity. This zero-point measurement has to be subtracted from the forces measured at certain wind velocities. The zero-point measurement only needs to be carried out at the zero angle.

2. Calculate the lift and drag coefficients from the measured lift and drag forces (F_d-F_l) for both cases (flat plate and RAF6E airfoil). The coefficients should be presented with the results being given in a graphical manner as a function of the angle of attack.

Note: Since the chord length and the wind velocity are the same for both cases, the results can be compared.

3. Uncertainty calculations should be made for the measurement results of the drag and lift coefficients, based on the assignment.

4. The various set-ups should be compared (simplified plate and RAF6E airfoil). The c_d-α and c_l-α being given in a graphical form. Point out the most advantageous and disadvantageous set-ups. Compare the results with useful references (from the measurement guideline or other sources).

5. Make suggestions for improving the measurement.

TASK B.)

0. Measure the lab temperature and the atmospheric pressure.

1. Determine the lift and drag forces of the flat plate (**100x152mm**) and the two cambered plates as a function of the angle of attack. Perform the measurements in the Blackbird 2 wind tunnel with the help of the load cell system.

Measurements should be carried out for a -20 to +30 degree range of angle of attack, with a 2 degree increment (sum 75 measurement points). Set the Reynolds number to $Re=1.1*10^5$, the required flow velocity should be determined in this way.

Note: Do not forget to measure the forces as a function of the angle of attack in the case of zero velocity. This zero-point measurement has to be subtracted from the forces measured at certain wind velocities. The zero-point measurement only needs to be carried out at the zero angle.

2. Calculate the lift and drag coefficients from the measured lift and drag forces (F_d-F_l) for both cases (flat plate and cambered plates). The coefficients should be presented with the results being given in a graphical manner as a function of the angle of attack.

Note: Since the chord length and the wind velocity are the same for both cases, the results can be compared.

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5. Make suggestions for improving the measurement.

TASK C.)

0. Measure the lab temperature and the atmospheric pressure.

1. Determine the lift and drag forces of the **RAF6E airfoil** (**chord length = 100 mm**) as a function of the angle of attack at three different Reynolds numbers. Perform the measurements in the Blackbird 2 wind tunnel with the help of the load cell system.

Measurements should be carried out for a -2 to +24 degree range of angle of attack, with a 1 degree increment (sum 78 measurement points). Set the Reynolds number to $Re=3.4*10^4$, $Re2=8*10^4$, $Re=1.1*10^5$, the required flow velocity should be determined in this way.

Note: Do not forget to measure the forces as a function of the angle of attack in the case of zero velocity. This zero-point measurement has to be subtracted from the forces measured at certain wind velocities. The zero-point measurement only needs to be carried out at the zero angle.

2. Calculate the lift and drag coefficients from the measured lift and drag forces (F_d-F_l) for both cases (flat plate and RAF6E airfoil). The coefficients should be presented with the results being given in a graphical manner as a function of the angle of attack.

3. Uncertainty calculations should be made for the measurement results of the drag and lift coefficients, based on the assignment.

4. The various set-ups should be compared (simplified plate and RAF6E airfoil). The c_d-α and c_l-α being given in a graphical form. Point out the most advantageous and disadvantageous set-ups. Compare the results with useful references (from the measurement guideline or other sources).

5. Make suggestions for improving the measurement.