

## Pressure curve on an airfoil profile – Measuring with a pressure sensor and CASSY

### Objects of the experiment

- To measure an airfoil profile's pressure curve for different angles of attack.
- To determine the static pressure difference's stake in the aerodynamic lift.
- To qualify the aerodynamic lift explanation due to the Bernoulli principle.
- To develop a critical distance to apparently secured knowledge.

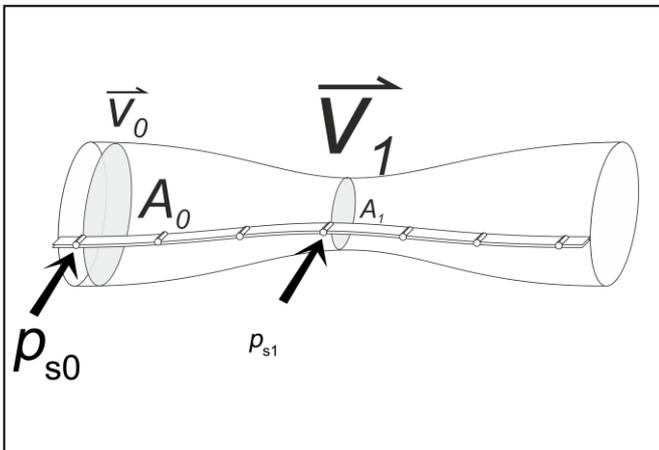
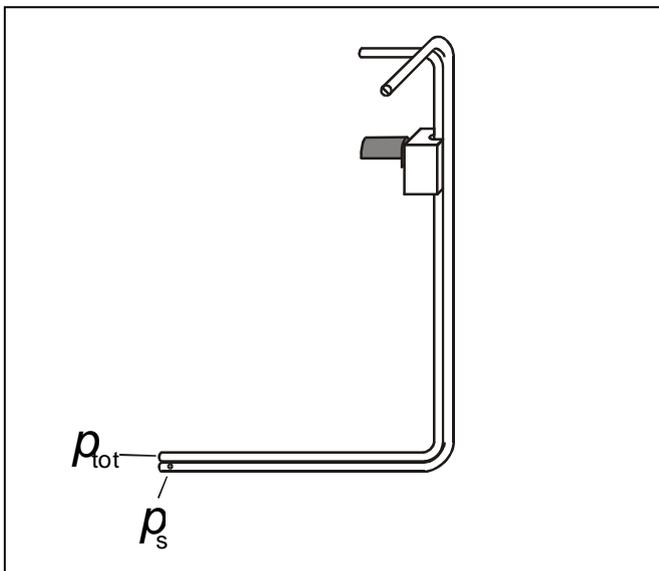


Fig. 1: Bernoulli principle: cross-sectional area  $A$ , flow velocity  $v$ , static pressure  $p_s$ . The font size indicates the absolute value of the physical quantity.

Fig. 2: Prandtl pressure probe for measuring the static pressure  $p_s$  and the total pressure  $p_{tot}$ .



### Principles

For a long time in physics books, the aerodynamic lift has been explained with a decrease in pressure due to the Bernoulli principle. In this experiment the stake of the static pressure difference  $\Delta p_s$  in the aerodynamic lift  $F$  is verified quantitatively.

Bernoulli's law states the relationship between static pressure  $p_s$  and flow velocity  $v$ . The following equation applies to a friction-free, horizontally flowing stream through a stationary flow tube between two points labeled with indices 0 and 1:

$$p_{s0} + \frac{\rho}{2} v_0^2 = p_{s1} + \frac{\rho}{2} v_1^2 \quad (I)$$

Density of the air:  $\rho = 1.2 \frac{\text{kg}}{\text{m}^3}$

The insufficient explanatory approach is phrased as follows: The air's longer path length on top of the airfoil results in a difference of static pressure  $\Delta p_s$ , which lifts up the airfoil.

Thus the theoretical aerodynamic lift  $F_T$  is defined via pressure and area:

$$F_T = A \cdot \Delta p_s \quad (II)$$

Area of the airfoil profile:  $A$

The flow velocity  $v$  is indirectly determined by a Prandtl pressure probe and a pressure sensor. Pointing in the direction of flow the Prandtl pressure probe measures the difference between the total pressure  $p_{tot}$  and the static pressure  $p_s$ :

$$p_d = p_{tot} - p_s \quad (III)$$

Therefore the flow velocity  $v$  can be determined by:

$$v = \sqrt{\frac{2}{\rho} \cdot (p_{tot} - p_s)} \quad (IV)$$

*Remark: The experiment is closely related to P1.8.7.1, where the airfoil's aerodynamic lift is measured directly. P1.8.5.4 and P1.8.7.4 are closely related, too.*

**Apparatus**

1 Suction and pressure fan.....	373 041
1 Open aerodynamics working section.....	373 06
1 Prandtl pressure probe .....	373 13
1 Airfoil model.....	373 70
1 Sensor-CASSY 2.....	524 013
or	
1 Mobile-CASSY.....	524 009A
or	
1 Pocket-CASSY 2 Bluetooth .....	524 018
1 CASSY Lab 2 .....	524 220
1 Pressure sensor S, ±70 hPa.....	524 066
1 Stand base, V-shaped, small.....	300 02

Additionally required: 1 PC with Windows XP or higher

**Safety notes**

Mind the safety notes in the instruction sheet of the suction and pressure fan.

Before removing the protective grid or the nozzle:

- Pull out the mains plug and
- wait for at least 30 seconds until the suction and pressure fan comes to a complete stop.

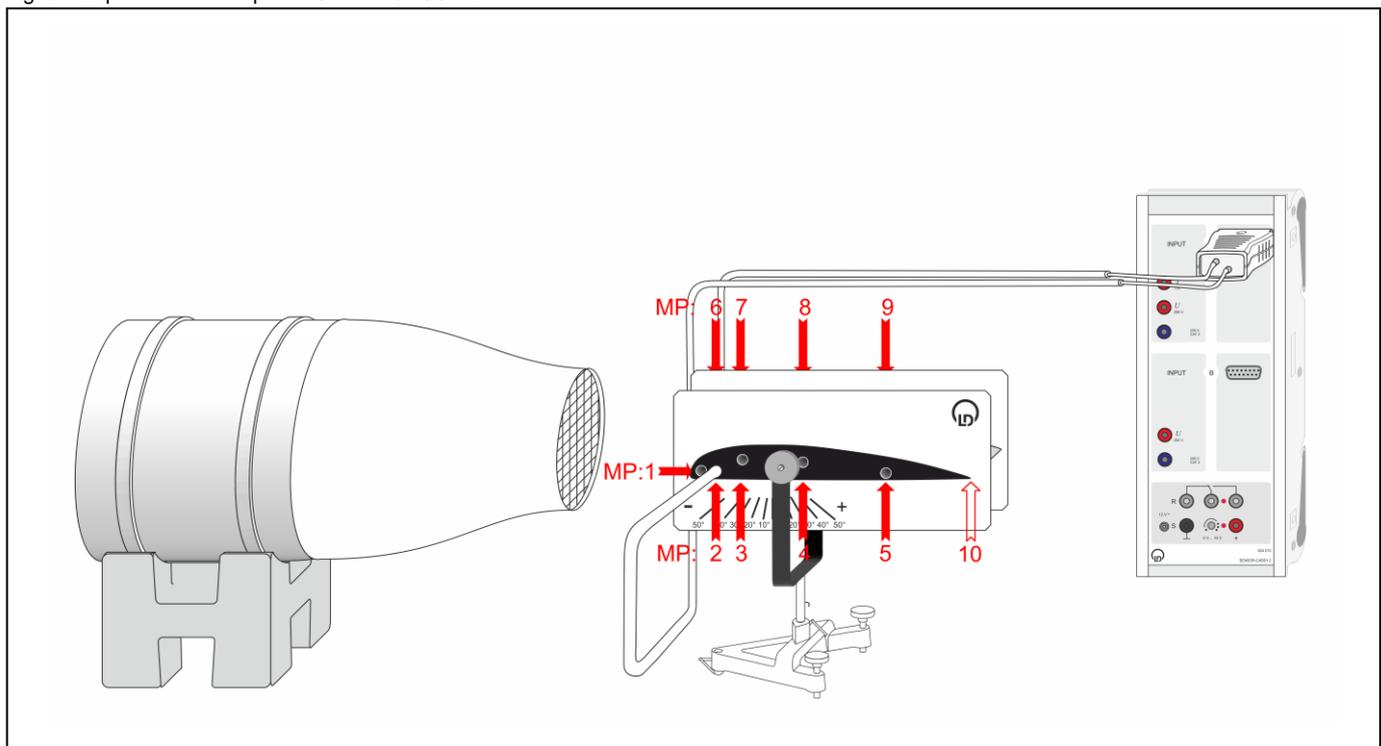
**Setup**

Assemble apparatus as in Fig. 3. Equip the suction and pressure fan with the big nozzle 150 mm Ø. Place the pressure side of the suction and pressure fan facing towards the airfoil model. Ensure a clearance of at least 1 m in front of the suction side and behind the airfoil model.

- Plug pressure sensor S, ±70 hPa into Input A of Sensor-CASSY 2 (Fig. 3) or into Mobile-CASSY (Fig. 6).
- Connect the 3 mm hose coming out of pressure connection  $p_1$  (top) of pressure sensor S to the 5 mm hose (delivered with the Prandtl pressure probe).
- Connect the other end of the 5 mm hose to the hose nipple and plug it into measuring point 6 of the airfoil model (see Fig. 3).
- In the same way, connect pressure connection  $p_2$  (bottom) of the pressure sensor S with measuring point 2 of the airfoil model (see Fig. 3).
- Position the airfoil model approx. 10 cm in front of the nozzle with a stand base, V-shaped and adjust the angle of attack  $\alpha = +10^\circ$ .

*Remark: Not mixing up the connections of the hoses is crucial since the static pressure difference  $\Delta p_s$  will be negative in the air stream. Further information in the instruction sheets 373 13 and 524 066.*

Fig. 3: Experimental setup with Sensor-CASSY 2.

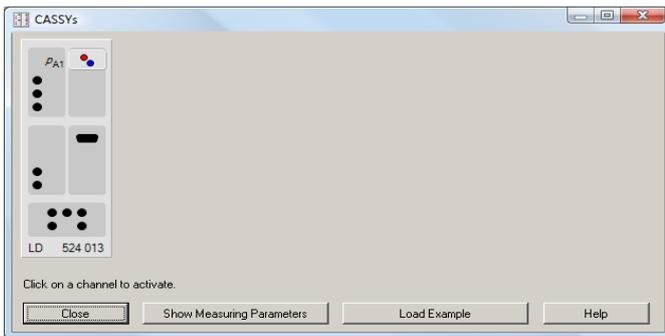


**Carrying out the experiment**

- If not yet installed, install the software CASSY Lab 2 and open the software.

**a) Measuring with Sensor-CASSY 2**

- [Load the settings in CASSY Lab 2.](#)
- The connected pressure sensor S should be displayed if Sensor-CASSY 2 is powered on and connected to the computer via the USB port.
- Activate the connected pressure sensor S at Input A by clicking .



Remark: Further details about connecting sensors to Sensor-CASSY 2 can be found in the CASSY Lab 2 manual or in the web help.

- Reset the pressure sensor S by clicking  in the "Settings" pane when "relative pressure  $p_{A1}$ " is marked.
- Set the suction and pressure fan to its minimum speed (i.e. left limit position of fan control) and only then switch it on.
- Slowly increase the speed of the suction and pressure fan until the flow velocity  $v$  reaches approximately 5,6 m/s. Therefore connect the hoses preliminary with the Prandtl pressure probe as shown in Fig. 4 and set  $\Delta p = 19$  Pa.

Remark: Detailed information for determining the flow velocity  $v$  are given in P1.8.5.6.

- Adjust the airfoil model's angle of attack to  $\alpha = +10^\circ$  and position it approx. 10 cm in front of the nozzle.
- At measuring points 1 and 10 (see Fig. 3) the difference in static pressure  $\Delta p_s$  is 0 Pa. For recording these values in CASSY Lab 2 connect both hoses to each other and click  (poss. zero with  in addition).
- Connect the hoses again with measuring points 2 and 6 of the airfoil model (as in Fig. 3) and set the belonging profile depth  $z$  with the slide bar  for channel z:

MP	1	2; 6	3; 7	4; 8	5; 9	10
$z$	0%	15%	24%	43%	72%	100%

- Record the static pressure difference  $\Delta p_s$  for measuring points 2 and 6, 3 and 7, ... 5 and 9 by clicking .
- For recording further angles of attack  $\alpha$  click the drop down menu  #1 and select the next series of measurements.

Remark: For the reset button  to appear in the "Settings" pane "relative pressure  $p_{A1}$ " has to be marked in the submenu of "CASSYs". It is recommended to press the reset button  before each series of measurements.

**b) Measuring with Mobile-CASSY**

Remark: To record the pressure values automatically, follow the instructions as described in a).

- Switch on Mobile-CASSY with the  key.
- Open the main menu by pressing the  key again.
- Select the submenu "Quantities" by using the arrow keys,  or , and enter the submenu using the right  key.
- Go to submenu "p" using the right  key.
- Choose "Compensate Offset" and set the pressure to zero by pushing the right  key.
- Press the  key and then the left  key to display the current pressure value.

Remark: It is recommended to zero the pressure values before each series of measurements. For further hints on using Mobile-CASSY (524 009A) refer to the instruction sheet.

- Set the suction and pressure fan to its minimum speed (i.e. left limit position of fan control) and only then switch it on.

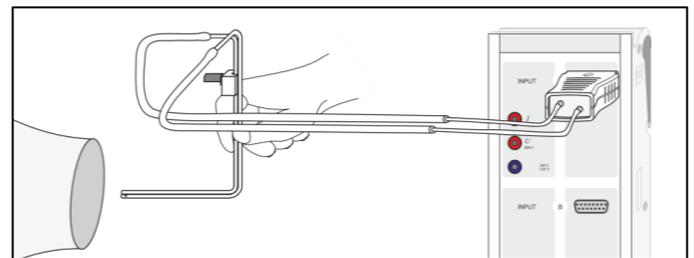


Fig. 4: Measuring the wind speed  $v$  with a Prandtl pressure probe and equation (IV).

- Slowly increase the speed of the suction and pressure fan until the flow velocity  $v$  reaches approximately 5,6 m/s. Therefore connect the hoses preliminary with the Prandtl pressure probe as shown in Fig. 4 and set  $\Delta p = 19$  Pa.

Remark: Detailed information for determining the flow velocity  $v$  are given in P1.8.5.6.

- Adjust the airfoil model's angle of attack to  $\alpha = +10^\circ$  and position it approx. 10 cm in front of the nozzle.
- [Load the settings in CASSY Lab 2.](#)
- At measuring points 1 and 10 (see Fig. 3) the difference in static pressure  $\Delta p_s$  is 0 Pa.
- Read off the difference in static pressure  $\Delta p_s$  for measuring points 2 and 6, 3 and 7, ... 5 and 9 and type the values in table " $p_s(z)$  [manu.]" together with the belonging profile depth  $z$  (see table on the left).
- For recording further angles of attack  $\alpha$  click the drop down menu  #1 and select the next series of measurements.

Remark: To record more than the prepared measurement series open "Measurement" in the menu bar and select  "Append new Measurement Series". Select table " $\Delta p_s(z)$ " and click  once. Open the  "Settings" pane and mark " $\Delta p_s(z)$ " in the submenu "Displays". Push the button "Add new Curve" and select " $\Delta p_s\#6$ " in the drop down menu for "y-axis".

**Measuring example**

The profile depth  $z$  corresponds with the airfoil's measuring points. At the airfoil's leading edge ( $z = 0\%$ ) and the tailing edge ( $z = 100\%$ ) the difference in static pressure  $\Delta p_s$  equals 0 Pa.

	$\frac{\alpha}{^\circ}$	20	10	0	-10	-20
MP	$z$	$\frac{\Delta p_s}{\text{Pa}}$				
1	0 %	0	0	0	0	0
6-2	15 %	27	16	4	-15	-14
7-3	24 %	27	20	12	-1	-4
8-4	43 %	10	7	5	2	-5
9-5	72 %	4	3	2	2	-4
10	100 %	0	0	0	0	0

Tab. 1: Static pressure difference  $\Delta p_s$  between downside and upside of the airfoil model for six different profile depths  $z$  and five angles of attack  $\alpha$ .

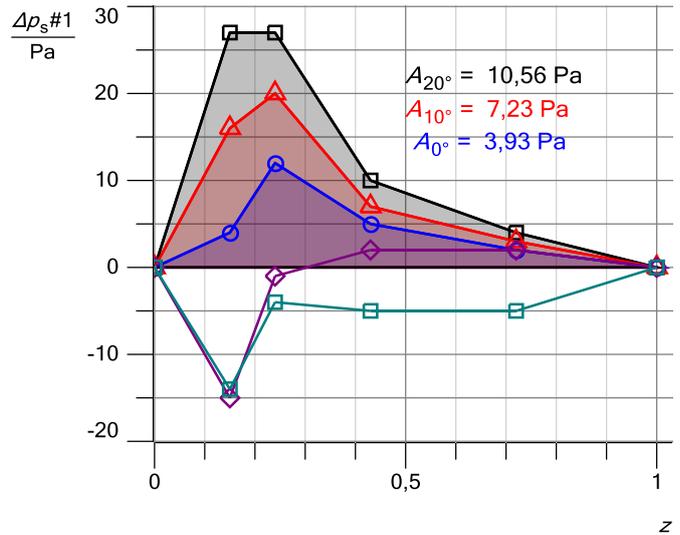
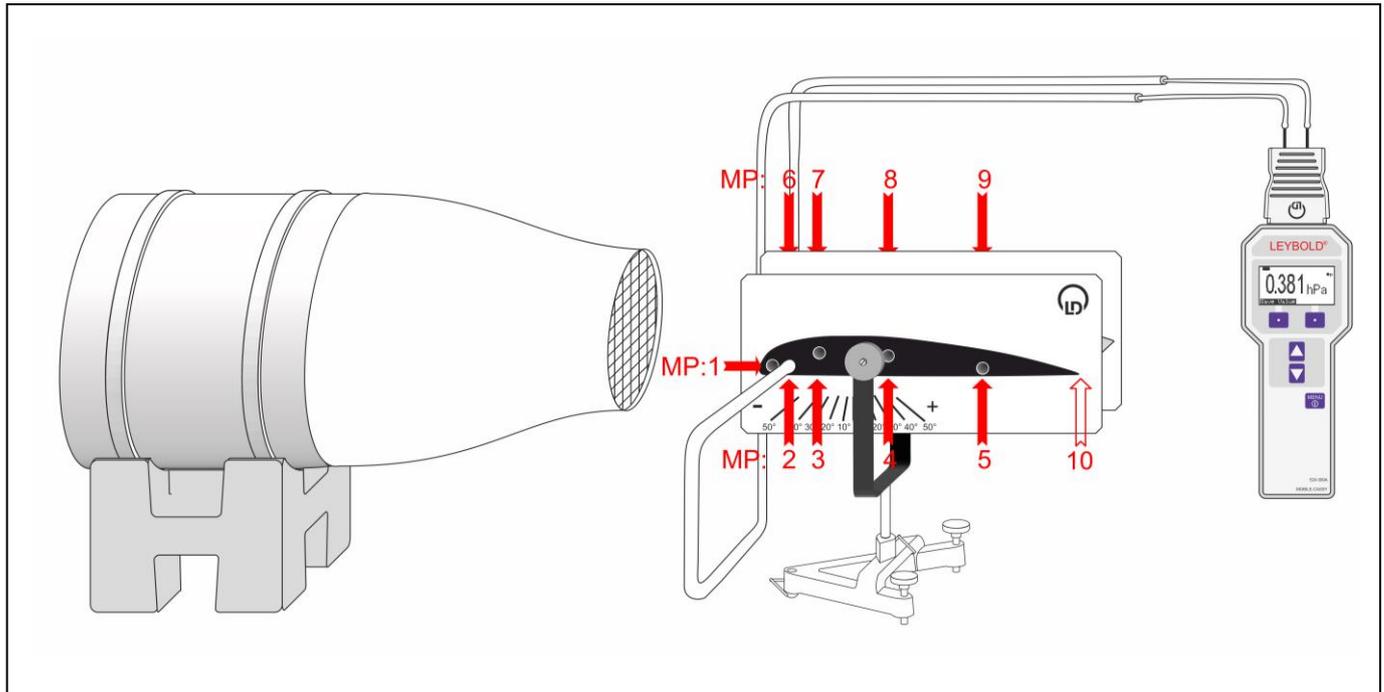


Fig. 5: Static pressure difference  $\Delta p_s$  as function of profile depth  $z$ .

*Remark: CASSY Lab 2 can determine the area below the graph of  $\Delta p_s(z)$  automatically: Right click on one measuring point in the  $\Delta p_s(z)$  diagram, select **dx** "Calculate Integral" and click **▲** „Area to x-Axis“. Drag the left mouse button over all measuring points of the series.*

*If the first or last measuring point of one measuring series is covered by others, first select an outstanding measuring point and drag the integral in one direction. Then double click the same measuring point again and drag the integral into the other direction.*

Fig. 6: Experimental setup with Mobile-CASSY.



**Evaluation and results**

The area  $A_{10^\circ}$  below the graph of  $\Delta p_s(z)$  can be determined with CASSY Lab 2 automatically or calculated manually. E.g. for an angle of attack  $\alpha = +10^\circ$ :

$$A_{10^\circ} = \int_0^{100\%} \Delta p_s(z) dz = 7.23 \text{ Pa} = 7.23 \frac{\text{N}}{\text{m}^2}$$

Multiplying  $A_{10^\circ}$  with the airfoil model's width  $b$  and depth  $z$  (in meters, not %!) and considering the angle of attack  $\alpha = +10^\circ$  results in the theoretical aerodynamic lift  $F_T$ :

$$F_T = A_{10^\circ} \cdot b \cdot z \cdot \cos(\alpha)$$

According to this Bernoulli principle based theory an airfoil as in P1.8.7.1 (similar shape, width  $b = 0.14 \text{ m}$ , depth  $z = 0.22 \text{ m}$ ) should produce an aerodynamic lift of:

$$F_T = 7.23 \frac{\text{N}}{\text{m}^2} \cdot 0.14 \text{ m} \cdot 0.22 \text{ m} \cdot \cos(10^\circ) = 0.2 \text{ N}$$

In contrast to this theory the measured aerodynamic lift  $F_M$  for the airfoil in P1.8.7.1 amounts to 2.1 N at an angle of attack  $\alpha = +10^\circ$  (see Tab. 2):

$$F_M = 2.1 \text{ N}$$

$\frac{v}{\frac{\text{m}}{\text{s}}}$	5.6							
$\frac{\alpha}{^\circ}$	0	2	4	6	8	10	12	14
$\frac{F_M}{\text{N}}$	0.5	0.7	1.1	1.5	1.7	2.1	2.3	2.5

Tab. 2: Measuring results from P1.8.7.1. Measured aerodynamic lift  $F_M$  and angle of attack  $\alpha$  at flow velocity  $v = 5.6 \text{ m/s}$ .

The difference in static pressure  $\Delta p_s$  explains only approx. 10% of the measured aerodynamic lift!

**Supplementary information**

Often in this context, the lower pressure on the upside of the airfoil is wrongfully explained with rejoining airstreams at the tailing edge and the air's longer path length. This insufficient explanation survived even though Alexander Lippisch had already published contradictory pictures of pulsed smoke trails around airfoils in the early years of aviation. This pictures show that the two airstreams do not rejoin with each other:

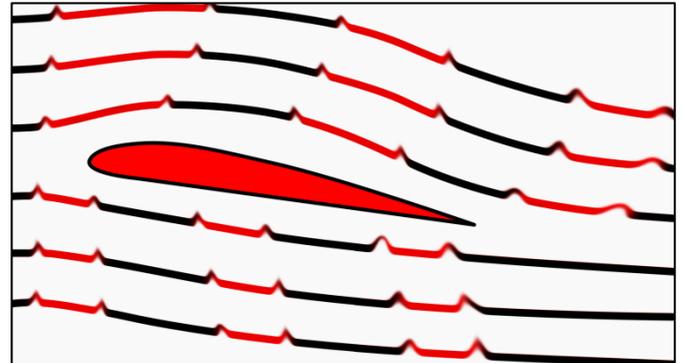


Fig. 7: Pulsed smoke trails around an airfoil, schematically.