Measuring the air resistance as a function of the wind speed
– Measuring the wind speed with a pressure sensor and CASSY

Objects of the experiment
■ To verify that the aerodynamic drag increases with one object’s cross-sectional area.
■ To verify that the aerodynamic drag increases with the flow velocity.

Principles
The air resistance or aerodynamic drag $F$ is defined as the friction caused force component in direction of flow or against one object’s direction of movement:

$$F = c_w \cdot A \cdot \rho_d$$  \hspace{1cm} (I)

The drag coefficient $c_w$ is constant for low Mach numbers. The area $A$ denotes the maximal cross-sectional area of the object in direction of the flow. The dynamic pressure $\rho_d$ is depending on the flow velocity $v$:

$$\rho_d = \frac{\rho \cdot v^2}{2}$$  \hspace{1cm} (II)

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

In the experiment described here three resistance bodies (round disks) are placed in the air flow and the aerodynamic drag $F$ is measured for different flow velocities $v$.

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 $p_{\text{tot}}$ and the static pressure $p_s$:

$$p_d = p_{\text{tot}} - p_s$$  \hspace{1cm} (III)

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

$$v = \sqrt{\frac{2}{\rho} \left( p_{\text{tot}} - p_s \right)}$$  \hspace{1cm} (IV)

Remark: The experiment is closely related to P1.8.6.5 where the aerodynamic drag is determined depending on the object’s shape.
**Setup**

Assemble apparatus as shown in Fig 2. Place the pressure side of the suction and pressure fan facing towards the open aerodynamics working section. Ensure a clearance of approx. 1 m in front of the suction side and behind the open aerodynamics working section.

- Plug the pressure sensor $S$, ±70 hPa into Input A of Sensor-CASSY 2 (Fig. 2) or into the Mobile-CASSY (Fig. 4).
- 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 Prandtl pressure probe outlet for $p_{tot}$ (see Fig. 1).
- In the same way, connect pressure connection $p_2$ (bottom) of the pressure sensor $S$ to the $p_s$ outlet of the Prandtl pressure probe (see Fig. 1).

**Remark:** Not mixing up the connections of the hoses is crucial since the relative static pressure $p_s$ will be negative in the air stream.

- Make sure the precision metal rail is horizontal and exactly parallel to the direction of flow.
- Assemble the measurement trolley as shown in Fig. 2, using the smallest resistance body (round disk, $\varnothing$ 40 mm) first and place it on the precision metal rail. The 50 g counterweight is crucial for exact measuring results.
- Connect the sector dynamometer’s cord for the transfer of force to the hook of the measurement trolley so that the cord is approx. horizontal. Check if the cord wines closely around the spring casing with groove for the cord.
- Slide the measurement trolley away from the sector dynamometer so that the cord is almost stressed.

**Remark:** For further hints refer to instruction sheets 373 13, 373 041, 373 075 and 524 066.

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**Apparatus**

1. Suction and pressure fan .............................................. 373 041
2. Open aerodynamics working section ............................. 373 06
3. Prandtl pressure probe .................................................... 373 13
4. Sector dynamometer, 0.65 N ............................................. 373 14
5. Aerodynamics accessories .............................................. 373 071
6. Measurement trolley for wind tunnel .............................. 373 075
7. Sensor-CASSY 2 ................................................................. 524 013
8. Mobile-CASSY ................................................................. 524 009A
9. Pocket-CASSY 2 Bluetooth .............................................. 524 018
10. CASSY Lab 2 ................................................................. 524 220
11. Pressure sensor $S$, ±70 hPa ......................................... 524 066
12. Stand base, V-shaped, small .......................................... 300 02
13. Saddle base ................................................................. 300 11
14. Stand rod, 25 cm, 12 mm $\varnothing$ ................................. 300 41

**Safety notes**

Mind the safety notes in the instruction sheets 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.

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Fig. 2: 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

- **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:** For connecting sensors to Sensor-CASSY 2 can be found in the CASSY Lab 2 manual or on the web help.

- Reset the pressure sensor S by clicking in the “Settings” pane when “relative pressure $p_A$” 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 sector dynamometer shows more than 0.01 N for the aerodynamic drag $F$.

**Remark:** For minimizing measurement errors due to friction: Push the measurement trolley a little against the direction of flow. Release the measurement trolley again. When the sector dynamometer’s pointer stopped oscillating, first check if the cord is still in the groove of the spring casing. Repeat this step several times for estimating a good average value.

- Type the sector dynamometer’s value in the CASSY Lab 2 column for the aerodynamic drag $F$ (left side of the window).

- To record the belonging flow velocity $v$ with CASSY Lab 2 click shortly after reading off $F$.

- Slowly increase the speed of the suction and pressure fan until the flow velocity $v$ shows approx. 2 m/s more.

- Repeat the last steps until the sector dynamometer, 0.65 N comes close to its maximum.

- To record another resistance body click the drop down menu and select the next measurement series. Exchange the resistance body (round disks: Ø 40 mm, Ø 56 mm and Ø 80 mm) and repeat these steps.

**Remark:** For the reset button to appear in the “Settings” pane “relative pressure $p_A$” has to be marked in the submenu of “CASSY’s”. 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.

- Slowly increase the speed of the suction and pressure fan until the sector dynamometer shows more than 0.01 N for the aerodynamic drag $F$.

**Remark:** For minimizing measurement errors due to friction: Push the measurement trolley a little against the direction of flow. Release the measurement trolley again. When the sector dynamometer’s pointer stopped oscillating, first check if the cord is still in the groove of the spring casing. Repeat this step several times for estimating a good average value.

- **Load the settings in CASSY Lab 2.**

- Read off the belonging pressure $p_s$ shortly after reading off the aerodynamic drag $F$. Type both values in table “$F(p_s)$ manu.” (left side of the window). The flow velocity $v$ will be calculated automatically in table “$F(v)$”.

- Slowly increase the speed of the suction and pressure fan until the dynamic pressure $p_s$ is approx. 30% higher.

- Repeat the last steps until the sector dynamometer, 0.65 N comes close to its maximum.

- To record another resistance body click the drop down menu and select the next measurement series. Exchange the resistance body (rounded disks: Ø 40 mm, Ø 56 mm and Ø 80 mm) and repeat these steps.

**Remark:** To record more than the three prepared measurement series open “Measurement” in the menu bar and select “Append new Measurement Series”. Select table “$F(v)$” and click once. Open the “Settings” pane and mark “$F(v)$” in the submenu “Displays”. Push the button “Add new Curve” and select “$F#4$” in the drop down menu for “y-axis”. Do the same for “$F(p_s)$”.

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LD Physics Leaflets P1.8.6.4
Measuring example

Fig. 3: Aerodynamic drag $F$ as function of the dynamic pressure $p_d$ for the smallest resistance body (round disk, Ø 40 mm). The solid line corresponds to a fit of a straight line through origin: $y = B \times x$.

Fig. 5: Aerodynamic drag $F$ as function of the flow velocity $v$ for the smallest resistance body (round disk, Ø 40 mm). The solid curve corresponds to a fit of a norm parabola: $y = C \times x^2$.

Tab. 1: Dynamic pressure $p_d$, flow velocity $v$ and resulting aerodynamic drag $F$ for the smallest resistance body (round disk, Ø 40 mm).

<table>
<thead>
<tr>
<th>$p_d$ [hPa]</th>
<th>$v$ [m/s]</th>
<th>$F$ [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.205</td>
<td>5.8</td>
<td>0.02</td>
</tr>
<tr>
<td>0.354</td>
<td>7.7</td>
<td>0.04</td>
</tr>
<tr>
<td>0.605</td>
<td>10.0</td>
<td>0.08</td>
</tr>
<tr>
<td>0.953</td>
<td>12.6</td>
<td>0.13</td>
</tr>
<tr>
<td>1.380</td>
<td>15.2</td>
<td>0.21</td>
</tr>
<tr>
<td>1.694</td>
<td>16.8</td>
<td>0.28</td>
</tr>
<tr>
<td>2.203</td>
<td>19.2</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Fig. 4: Experimental setup with Mobile-CASSY.
Evaluation and Results

Fig. 6: Aerodynamic drag $F$ as function of the dynamic pressure $p_d$ for three resistance bodies (round disks: $\Theta 40 \text{ mm}$, $\Theta 56 \text{ mm}$, $\Theta 80 \text{ mm}$) with different cross-sectional areas. The solid lines correspond to a fit of straight lines through origin: $y = B \cdot x$.

$F(p_d) = B \cdot p_d$
$B = 0.462 \text{ N/hPa}$
$B = 0.255 \text{ N/hPa}$
$B = 0.154 \text{ N/hPa}$

Fig. 7: Aerodynamic drag $F$ as function of the flow velocity $v$ for three resistance bodies (round disks: $\Theta 40 \text{ mm}$, $\Theta 56 \text{ mm}$, $\Theta 80 \text{ mm}$) with different cross-sectional areas. The solid lines correspond to a fit of norm parabolas: $y = C \cdot x^2$.

When the cross-sectional area $A$ of the resistance body doubles the aerodynamic drag $F$ doubles, too (e.g.: In Fig. 6 at $p_d = 0.8 \text{ hPa}$ the best-fit functions cross approx. $0.1 \text{ N}$, $0.2 \text{ N}$ and $0.4 \text{ N}$):

$F \propto A$

Therefore the measuring results confirm equation (I).

Substituting the dynamic pressure $p_d$ in equation (I) leads to:

$F = c_w \cdot A \cdot \frac{1}{2} \cdot v^2 \quad (V)$

The aerodynamic drag $F$ increases with increasing flow velocity $v$. The relation appears to be quadratic. The best-fit functions are norm parabolas (Fig. 7):

$F \propto v^2$

Therefore the measuring results confirm equation (V).

Supplementary information

Furthermore, the function $F(A)$ may be determined by exchanging the three resistance bodies at one constant flow velocity $v$, respectively dynamic pressure $p_d$.

With the CASSY Lab 2 software it is possible to determine the function $F(A)$ for any flow velocity $v$ or dynamic pressure $p_d$ even if the measuring points were not recorded with one common flow velocity, respectively dynamic pressure $p_d$:

- Select one series of measurements by clicking on its first or last measuring point in the diagram pane for $F(p_d)$.
- Right click the selected measuring point, select `Fit Function` and click `Straight Line through Origin`.
- Drag with held left mouse button over all measuring points of the series. The selected fit function appears automatically.
- Right click on the created fit function, select `Set Marker` and click `Text (Alt+T)`. A text like `$A = 0.0156 \text{ N/hPa}$` will appear. At this point the cross-sectional area $A$ should not be confused with the mathematical scaling factor $A$. Renaming it to $B$ is recommended here.

- Repeat these steps for the other series of measurements.

This analysis delivered the mathematical scaling factor $B$ for each series of measurements.

From equation (I) follows that the mathematical scaling factor $B$ is defined here as

$B = c_w \cdot A$. \quad (VI)$

When the cross-sectional areas $A$ are known the drag coefficients $c_w$ can be calculated and hence the values for function $F(A)$ for any dynamic pressure $p_d$:

<table>
<thead>
<tr>
<th>$B$ (\text{N} \cdot \text{Pa}^{-1})</th>
<th>$A$ (\text{m}^2)</th>
<th>$c_w$</th>
<th>$\overline{c_w}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00462</td>
<td>0.0050</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>0.00252</td>
<td>0.0025</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>0.00156</td>
<td>0.0013</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8: Aerodynamic drag $F$ of round disks as function of the cross-sectional area $A$. The values were calculated from the fit functions of all three series of measurements for $p_d = 1 \text{ Pa}$.

The slope of $F(A)$ is $\overline{c_w} \cdot p_d$. When choosing $p_d = 1 \text{ Pa}$ (not hPa) the slope of $F(A)$ simplifies to $\overline{c_w}$.

Remark: The aerodynamic drag coefficient $c_w$ is directly determined in P1.8.6.5.