Anemometer calibration at different air temperatures and air pressures

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## Revision History

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1 Introduction

An anemometer calibration is typically performed in a wind tunnel at a constant, prevailing air temperature and atmospheric pressure. This calibration is the basis for the wind speed measurements at meteorological met masts and therefore for the site assessment for potential wind farms. As the environmental parameters can influence the performance of the anemometer, an adequate anemometer for the specific site has to be chosen. Furthermore it is important to have a measure of the environmental influence on an accurate site assessment and wind turbine control.

Anemometers are assigned into different accuracy classes. In the latest IEC 61400-12-1 standard [1] there are different influence parameters which have to be investigated during the anemometer classification. The different classes cover different operational ranges of these influence parameters. Among these parameters are the air temperature and the air density.

In the IEC 61400-12-1 [1], it is assumed that a change in air temperature only influences the bearing friction. Higher air temperatures decrease the friction and therefore increase the rotational speed and vice versa.

In the IEC standard [1] are no further suggestions on how to evaluate a variation in air density. The air density is a function of air temperature and air pressure. To investigate the influence of a variation in air density, either the air temperature or the pressure can be altered. It is difficult to distinguish between the influence of changing air temperature and density if temperature variation is used to adjust the air density during the calibration. If both parameters, air temperature and air pressure, can be altered independently the most precise results will be obtained.

In standard wind tunnels air temperature and pressure can usually not be set deliberately. Therefore the impact of these environmental conditions cannot be estimated reliably. A special research wind tunnel of “Göttinger” layout has been developed with the ability to vary the ambient tunnel pressure and temperature independently.

This document describes a measurement methodology for calibration of cup anemometers, propeller anemometers and sonic anemometers in the variable air density wind tunnel of WindGuard Wind Tunnel Services. The calibration result is the indicated wind speed of the anemometer at different temperatures and/or different air pressure. The calibration results can be used to estimate the uncertainty for wind sensors at very low or high temperatures and/or at high altitudes (lower temperatures in combination with lower density). The results are also essential for the classification of anemometers according to IEC [1].

In the second chapter, former investigations on the influence of changing air temperature onto the bearing friction of cup anemometers are presented. In the third chapter, a technical description of the variable air density wind tunnel will be given, followed by the anemometer calibration procedure for varying air temperatures and air pressures. In the fourth chapter the uncertainty calculation is presented. In the end sample results for two different, commonly used and similar shaped cup anemometers with a frequency output are presented with a final conclusion.
2  Former investigations on temperature induced effects onto the anemometer output

Former investigations ([2], [3]) on temperature induced impacts on wind speed measurements with cup anemometers were performed by flywheel experiments in a climate chamber.

Figure 1 and Figure 2 illustrate the experimental set-up for the investigation of the bearing friction in a climate chamber with a flywheel test. The procedure assumes that the air resistance of the rotational disc is known. Still, a drag coefficient determined in 1934 by W. G. Cochran [4] is used, as there are no new reliable values for this coefficient. In the scope of a bachelor thesis [3] the flywheel test was done for different discs as well as for different surface roughness values. The results showed the possibility of quite high deviations.

![Figure 1: Experimental set-up for a flywheel test in a climate chamber, conducted by RISØ for the Characterisation and Classification of the RISØ P2546 Cup Anemometer in 2004 [2].](image1)

![Figure 2: Experimental set-up for a flywheel test in a climate chamber at WindGuard Wind Tunnel Services.](image2)

A similar procedure was used during the classification of the Thies First Class anemometer in 2003 to calculate the influence of varying air pressures and air temperatures [5]. A foil heater was used to solely increase the temperature of the bearing shaft, see Figure 3. To decrease the temperature of the bearing shaft a cooling device was constructed, see Figure 4.
Both procedures work with the idealized assumption that a change in air temperature only influences the bearing friction. Other possible temperature induced effects, like distortion of the rotor or changes of the aerodynamic properties are not considered. Wind tunnel tests with changing air temperature on the other hand also assess these effects and should therefore estimate the anemometer performance in a more realistic way.
3 Technical description of the variable air density wind tunnel

The variable air density wind tunnel of WindGuard Wind Tunnel Services has a closed-circuit design with a circular return flow. The wind tunnel is characterized by a particularly homogeneous flow at low turbulence level (<0.5 %). The wind tunnel is conceived mainly for investigation of anemometers at different total air pressure and air temperatures. The limits for the ambient conditions are given by the IEC 61400-12-1 [1]. On this basis, the following design criteria were laid out:

- Flow speed in the empty test section:
  - currently up to 16 m/s,
  - planned extension up to 25 m/s
- Air temperature range: -20 °C - +40 °C
- Air density range: 0.9 kg/m³ – 1.35 kg/m³
- Air pressure: 600 hPa – 1100 hPa

Based on these criteria and constraints, a suitable wind tunnel design is the closed-circuit configuration tunnel with a closed test section. A 0.8 m long test section with a cross sectional area of 0.5 m x 0.5 m was chosen. This provides an acceptable blockage ratio for the intended anemometer testing at different air densities. The tunnel has a contraction ratio of 3.3:1.

Figure 5 and Figure 6 show a photo of the variable air density wind tunnel at the WindGuard headquarters.

![Figure 5: Photo of the variable air density wind tunnel during the installation.](image-url)
Anemometer calibration at different air temperatures and air pressures

Figure 6: Photo of the variable air density wind tunnel of WindGuard Wind Tunnel Services.

The wind tunnel itself is comprised of a sheet metal construction with a closed test section that is hermetically sealed, thus enabling a variation of internal air pressure. Furthermore, the whole wind tunnel is placed in an isolated and temperature controlled chamber.

To achieve a high-quality flow, the settling chamber consists of a special honeycomb/screen arrangement of five screens and one honeycomb. Calculations were performed in order to determine the size of individual wind-tunnel components, the pressure variation and flow speed in different sections of the tunnel. These calculations were based on well proven values of diffuser angles, contraction ratios and pressure drop coefficients. Consequently, a fan unit was chosen to compensate the pressure loss and produce the desired wind speed at the test section.
3.1 Measuring system

In Figure 7 the measuring system is illustrated schematically. Two pitot static tubes deliver the reference flow speed. Furthermore, the air temperature and the humidity are monitored within the wind tunnel and also in the climatized room.

<table>
<thead>
<tr>
<th>Pos.</th>
<th>Sensor</th>
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<tbody>
<tr>
<td>1</td>
<td>Pitot static tube</td>
</tr>
<tr>
<td>2</td>
<td>Pitot static tube</td>
</tr>
<tr>
<td>3</td>
<td>El. Barometer</td>
</tr>
<tr>
<td>4</td>
<td>Pressure transducer</td>
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<td>5</td>
<td>Pressure transducer</td>
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<td>6</td>
<td>El. Thermometer</td>
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<td>El. Humidity</td>
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<td>El. Thermometer</td>
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<td>9</td>
<td>El. Humidity</td>
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<tr>
<td>10</td>
<td>Test item</td>
</tr>
<tr>
<td>11</td>
<td>Data acquisition system</td>
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</tbody>
</table>

![Figure 7: Schematic of the measurement setup.]

4 Calibration procedure

To reduce the measurement uncertainties, first the anemometer has to be calibrated at normal ambient conditions in an accredited wind tunnel of WindGuard Wind Tunnel Services. Subsequently a measurement in the variable air density wind tunnel is performed at nearly the same temperature and pressure prevailing during the first measurement. The anemometer itself serves as a transfer standard. With both calibrations done, a transfer factor for measurements in the variable air density wind tunnel can be determined.

The advantage of this procedure is that blockage effects are negligible. Only the uncertainties due to repeatability (type 'A') and the uncertainty of the basic calibration remain and have to be taken into account.

For this report, the following calibration procedure is used. However, this is not a standardized procedure.

During the calibration in the variable air density wind tunnel, the anemometer output is measured for flow speeds between 4 m/s and 15.5 m/s. For each measurement point adequate time is allowed to generate stable flow conditions. After this settling time, the flow speed is kept constant for a sampling interval of at least 30 s. The sampling frequency is at least 4 Hz. To cover rising and falling flow speeds the following sequence is chosen: 4, 8, 12, 15.5, 14, 10, 6 m/s.
4.1 Calibration procedure for varying air temperatures

After determining the transfer factor for the anemometer under investigation, the air temperature is decreased down to -20 °C and a calibration run is done. The air temperature is then increased in 5 °C steps up to the maximum air temperature of 40 °C, while the air pressure is kept constant. At each temperature the calibration is done as described above. To decrease the type ‘A’ uncertainty, the minimum duration of the sampling interval is 30 s. For each calibration run a linear regression analysis is performed, resulting in a calibration function with slope and offset for one particular air temperature.

4.2 Calibration procedure for varying air pressures

The calibration procedure for varying air pressures is done similar to varying temperatures. After the measurement for the determination of the transfer factor, the air pressure is increased in 50 hPa steps from 700 hPa up to 1100 hPa. To cover an air density of about 0.8 kg/m³ to 1.4 kg/m³, the measurements for different air pressures is done at a fixed air temperature of 10 °C. For each calibration run with variable ambient pressure a linear regression analysis is performed, resulting in a calibration function with slope and offset for each particular ambient air pressure.

It is possible to conduct surveys in any combination of pressure and temperature within the parameter range as describes in Chapter 3.
5 Measurement uncertainty

The measurement uncertainty $U_{DUT}$ for the procedure described in Chapter 4 is a combination of the measurement uncertainty of the device under test (DUT) $U_{WT}$ and of the standard error calculated from the $n > 10$ measurement repetitions.

$$U_{DUT} = \left( U_{WT}^2 + \left( \frac{\sigma}{\sqrt{n}} \right)^2 \right)^{0.5}; \quad k = 1$$

Where:

$U_{WT}$: Measurement uncertainty from the standard calibration of the device under test

$\sigma$: Standard deviation of the measurement

$n$: Amount of measurement repetition

The measurement uncertainty $U_{WT}$ from the calibration in the accredited wind tunnel of the device under test amounts to 0.05 m/s ($k=2$).

The sample results presented in Chapter 6 show relative changes for varying air temperatures and air pressures, therefore only type ‘A’ uncertainties are relevant. However, the uncertainty calculation must be applied if absolute calibrations at a certain air temperature and air pressure are performed.

6 Sample results

To illustrate the influence of air temperature and air pressure, some calibration results will be illustrated in this section.

Two different, commonly used and similar shaped cup anemometers with a frequency output from two different manufacturers were tested. Both anemometers contain roller bearings which support the spindle. To compare the results for both anemometers a ratio was calculated. This ratio represents the relation between measured wind speed (if the anemometer is not calibrated for different air temperature and air pressure) and the real wind speed. The ratio $k$ is calculated as follows:

$$k_{(T,p)} = \frac{f_{(T,p)}/v_{(T,p)}}{f_{(20°C,1000 \, hPa)}/v_{(20°C,1000 \, hPa)}}$$

Where:

$f_{(T,p)}$: Frequency output at wind speed $v_{(T,p)}$ for a certain air temperature $T$ and pressure $p$

$f_{(20°C,1000 \, hPa)}$: Frequency output at wind speed $v_{(20°C,1000 \, hPa)}$ for measurements at 20 °C air temperature and 1000 hPa air pressure
6.1 Calibration results for varying air temperatures

In Figure 8 the ratio for different air temperatures is illustrated.

![Figure 8: Ratio $k$ for anemometer A and B at varying air temperatures and wind speeds and at constant air pressure.](image)

The dashed lines with a triangular marker show the results for anemometer A at different wind speeds, the solid lines with a circular marker for anemometer B. As described above, the ratio is calculated by normalizing to the results at 20 °C. The influence of varying temperatures for both anemometers is quite different. Anemometer A has a decreasing ratio for decreasing temperatures whereas anemometer B has the opposite characteristic. Furthermore the influence of varying the air temperature is stronger at lower wind speeds.

If the basic calibration established at 20 °C is applied, anemometer A would undervalue the wind speed at low temperatures. Anemometer B on the other hand would indicate a too high wind speed at low temperatures. Air temperatures above 20 °C would lead to opposing results. Hence, the influence on anemometer B is stronger and would result in a slightly undervalued wind speed.
6.2 Calibration results for varying air pressures/air densities

In Figure 9 the ratio for different air densities and wind speeds is illustrated. The different air densities are obtained by varying the air pressure at a constant air temperature of 10 °C.

![Figure 9: Ratio k for anemometer A and B at varying air density and wind speeds and at constant air temperature.](image)

The dashed lines with a triangular marker show the results for anemometer A and the lines with a circular marker for anemometer B. As described, the ratio is calculated by normalizing to the results at 1000 hPa, corresponding to an air density of about 1.23 kg/m³. The influence of varying densities for both anemometers is almost similar. Both anemometers have a decreasing ratio for decreasing pressure. The influence is again stronger for lower wind speeds.

If the basic calibration established at 1000 hPa is applied, both would undervalue the wind speed at low densities and pressure respectively. The pressure can be assigned to an altitude above sea level with the so called barometric formula. A pressure of about 950 hPa, which corresponds to 1.16 kg/m³ in Figure 9, correlates to a height of about 500 m. Starting at moderate heights of about 500 m, the pressure difference would already influence the output of the anemometers.
7 Conclusion

The results presented in Chapter 5 clearly verify the influence of varying air temperature and air pressure on the cup anemometer performance. For the two tested cup anemometers, the influence is more pronounced at low wind speeds. While the results for varying air pressures are similar between the tested anemometers, the results for varying air temperatures are opposing. This demonstrates that a change in air temperature can have other effects than just an increase in bearing friction. Therefore it is not sufficient to evaluate the influence of varying temperature with the flywheel method. It is necessary to perform tests in which the whole anemometer is exposed to different temperatures.

Additionally, the results demonstrate the importance to consider air pressure as a primary influencing variable on cup anemometer measurements, rather than air density. Moreover, as the air density is dependent on air temperature and air pressure, the influence of the air density and air temperature on cup anemometer measurements can be very different. None of these aspects are covered in IEC 61400-12-1 [1].

If cup anemometers are used in subarctic climate regions or in higher altitudes, a standard calibration can lead to an under or over estimation of the wind speed. The magnitude may be in the order of several percent in wind speed, which is an even greater deviation in wind power.

Also the use of anemometers for the wind turbine control in these regions may result in a delayed start of power production, especially as the influence of air pressure and temperature is the highest for low wind speeds.

A correction procedure to adjust the indicated wind speed seems feasible. The correction algorithm may be developed considering air pressure, air temperature and wind speed. This correction function has to be individually developed for each anemometer type. Further discussion is needed on how to assess the impact of the air pressure and air temperature correction upon the associated uncertainty due to anemometer class number according to [1].
8 References


[2] T. Friis Pedersen, Characterisation and Classification of RISØ P2546 Cup Anemometer, Risø-R-1364(ed. 2)(EN), March 2004


