Precision of Cup Anemometers – A Numerical Study

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Abstract

Cup anemometers are often used for the measurement of wind speed because they offer many practical advantages like simple and robust construction, simplicity of speed measurement and low maintenance requirements. However, cup anemometers have got disadvantages, too. These are on the one hand the inertia of the anemometer in case of gusts of wind and on the other hand the uncertainty whether the data delivered are faulty in case of oblique inflow.

This contribution addresses questions concerning the behaviour of rotating cup anemometers in case of changing direction of inflow by means of numerical simulation (CFD). Numerical results which were validated by experimental data are presented and discussed.

Keywords: three-arm cup anemometers, wind speed measurement, oblique inflow

Definition of task

Usually, cup anemometers are rugged, versatile wind speed sensors providing an excellent price-to-performance ratio. In technical applications, they are often used for a measurement of the horizontal component of wind speed. Typically cup anemometers have got three cups. In rear cases they have got four cups, too.

The advantages of cup anemometers can be seen in their simple and solid construction as well as in the simplicity of speed measurement by optical or electro-magnetic pulse generation.

The flow rate of air perpendicular to the rotation axis of the anemometer follows directly from the measured number of signals per time unit. Due to low maintenance requirements three-arm cup anemometers are preferably used for long-term measurements at hardly accessible locations as e.g. the top of cablecars, cranes and wind turbines.

However, there are downsides of three-arm cup anemometers, too. These are the inertia of three-arm cup anemometers as well as the deviation of the measurands in case of oblique inflow.

Due to its inertness a cup anemometer can not react without slippage in case of wind gusts. That means three-arm cup anemometers are not appropriate sensors for the measurement of transient wind speeds.
In addition, owing to their design and construction, only the wind perpendicular to the rotational axis of the anemometer can be determined. However, empirical evidence suggests that in case of oblique inflow the measuring values determined are incorrect.

Therefore, we had made it to our aim to analyse the flow conditions on a rotating three-arm cup anemometer both in perpendicular and in oblique inflow by numerical simulations. Additionally, our foremost goal was to validate the results from numerical simulations by experimentally determined data.
Since the method of experimentally determining required comparative data under laboratory conditions has already been described in detail in a paper by *Winkel, Paschen, Jensch* (2007), some assumptions for the numerical modelling are explained in more detail and selected results from numerical simulation referring to the anemometer in Fig. 1 are presented and discussed as an example.

Fig.1: *Thies First Class*

Methodological approach for flow simulation

Modern numerical simulation techniques are used increasingly and with great success to solve phenomenological questions about complex fluid-structure interactions. Numerical analyses allow detailed insights into flow processes, which mostly can not be fig.d out satisfactorily in an experiment. However, theory is still subject to some uncertainties; in this respect experimental considerations become necessary for the calibration of numerical flow simulations as well.
Experience has shown that the synthesis of experimental and theoretical methods of investigation helps to get qualitatively and quantitatively reliable results. Hence the numerical simulation, for example, helps to make statements about transient flow phenomena on an anemometer hardly accessible by measuring devices or about the torque characteristic in case of oblique inflow. However, the knowledge of individual, easy-to-measure characteristics at selected locations in a flow field *G* at a time *t* is required.

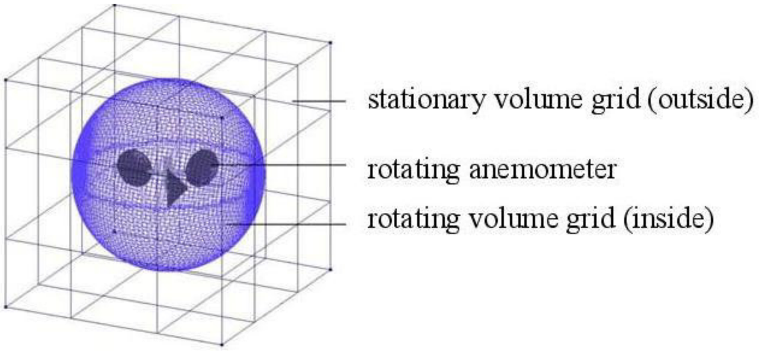

Fig. 2: Volume grids used for numerical simulation

The correct rotational speed is found if the corresponding sum of all moments $Mi (v,n)$ acting along the axis of rotation equals 'zero' over a full rotation of the cup anemometer, i.e., $\Sigma Mi (v,n) = 0$. The summary torque typically results from the effect of the aerodynamic load on the cup anemometer and the friction work of the anemometer axis.

The determination of this state of equilibrium can not explicitly be done due to the complexity of fluid-structure interactions on the cup anemometer. For these investigations the following approach was applied: For a given inflow velocity and a selected number of rotations *n* after CFD simulations the aerodynamic moment was determined acting at the cup anemometer.

It had to be taken into account that the anemometer torque even at a constant inflow depends on the instantaneous orientation of the cup anemometer to the flow, i.e., the torque oscillates around a mean value in the course of one full revolution. This has been done by determining and afterwards averaging the anemometer torque for a total of 120 angular settings (≡ sampling points). The angular distance between two grid points was 3 degrees in each case (0.04248 rad).

The following Fig. 3 examplarily shows the approach and calculation results for the anemometer *Thies First Class* exposed to an inflow of $v = 8$ m/s.

Assuming that the friction moment is only a negligible share of the total moment, the rotation speed of the anemometer v_{rot} can directly be determined from Fig. 3. Then by definition applies

$M_{res} (v, v_{rot}) \approx M_{aerodyn.} (v, v_{rot}) = 0.$

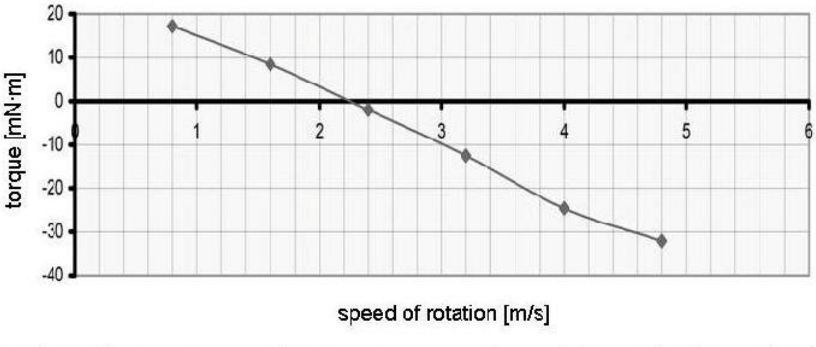

Fig.3: Thies First Class – averaged torque $M_{aerodyn.} (v, v_{rot})$ for an inflow velocity $v = 8$ m/s

The rotational speed v_{rot} determined for different inflow velocities v has been compared with the experimentally determined calibration curve at horizontal inflow to the anemometer. This comparison shows a good correspondence for this anemometer, see Fig. 4. The rotational speed v_{rot} determined in this way now completes all boundary conditions required for simulating the flow around the anemometer.

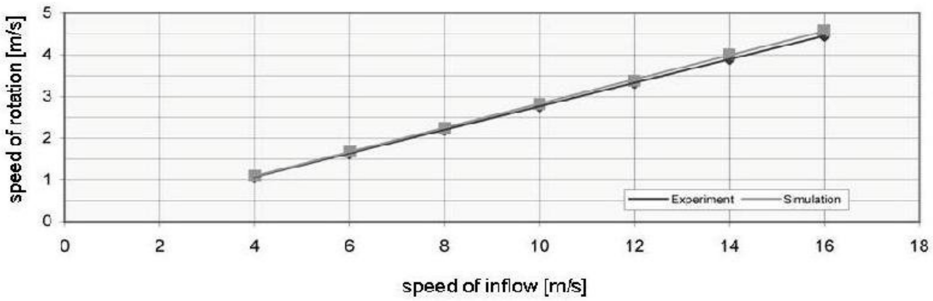

Fig. 4: Calibration curve of the three-arm cup anemometer *Thies First Class*

Results for horizontal inflow

There are various ways to visually present the calculated results. In the given case the authors restrict to a two-dimensional representation of the flow field in the horizontal plane, which at the same time represents the plane of symmetry of the cups. Whereas Fig. 5 gives a more qualitative impression of the flow field near the anemometer cups, Fig. 6 provides a quantitative assessment of the same flow field. In particular, Fig. 6 shows that the single anemometer cups are exposed to clearly divergent flow conditions within one revolution. The cup pointing downwards receives an almost undisturbed inflow, while the right cup follows in the nearly complete wake of the anemometer cup (left) rushing ahead.

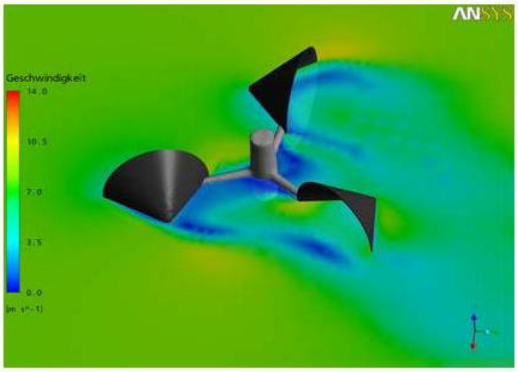

Fig. 5: Thies First Class – anemometer, representation of the velocity distribution on a plane

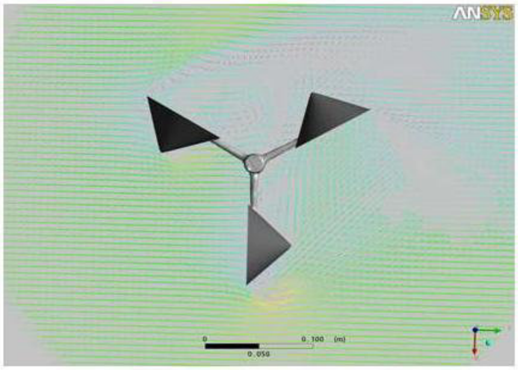

Fig. 6: Thies First Class – anemometer, representation of the surrounding flow by means of velocity vectors

Methodological approach at oblique inflow and simulation results

With respect to the axis of rotation of the anemometer the velocity vector of the inflow can be decomposed into a normal and a tangential component. In the following, however, we speak of a horizontal and a vertical velocity component of inflow. It is assumed, that the anemometer axis is aligned perpendicular to the earth's surface.

In the beginning we have stated, that three-arm cup anemometers are used to measure the horizontal wind component. In the open field, as e.g. on a measurement platform or on the gondola of a wind turbine, the anemometer is naturally always affected by more or less severe turbulences and up- and downdrafts. In case of up- and downdrafts the cup anemometer is exposed to an asymmetrical flow with respect to its horizontal plane. The consequence of this oblique inflow for the resulting rotational speed of the anemometer is widely unknown. It is also unknown, whether different geometric designs of cups lead to different measuring results in oblique inflow.

In order to solve these questions, i.e. to quantify the off-axis response of three-arm cup anemometers, the numerical analyses presented above have been extended to the case of oblique inflow. For this purpose a so-called tilt angle α has been introduced. It is formed by the vector of the inflow and the horizontally aligned plane of the cup. By definition, the tilt angle is negative, i.e. $\alpha < 0$, if the vertical component of the inflow comes from above to the plane of the cup. Accordingly, the angle is positive, i.e. $\alpha > 0$, when the inflow comes from below.

As part of the numerical investigations the angle has been varied in the range from $30^\circ \leq \alpha \leq 0^\circ$. The speed of the cup anemometer n considering the flow velocity v and the tilt angle α results from the moment equilibrium $\Sigma M_i(v,n,\alpha) = 0$. From this moment equilibrium in turn the peripheral speed or the speed of the anemometer follows.

In case the three-arm cup anemometer induces exclusively aerodynamic resistance and the friction work in the bearings of the anemometer is still negligible, the calibration curve shown in Fig. 4 can also be used for determining the horizontal component of the wind speed. When doing so, it must be possible to indicate from the determined speed directly to the horizontal component of the wind speed.

The results in Fig. 7 illustrate, however, that this assumption is true only for small angles of attack in the range of $-15^\circ \leq \alpha \leq 15^\circ$. (In order to validate the simulation results with the experimentally determined results, the horizontal component of the anemometer has been normalized with the amount of the resulting wind speed.)

In case of a tilt angle of $|\alpha| > 15^\circ$, numerically and experimentally determined speed of the anemometer lead to excessive horizontal wind speeds. These results match closely with measuring data of Wind Sensor P2546-OPR Anemometer which were published by *Renewable NRG Systems* in 2013. Unfortunately, the results for tilt angles $a > 15^\circ$ were not presented in this classification report.

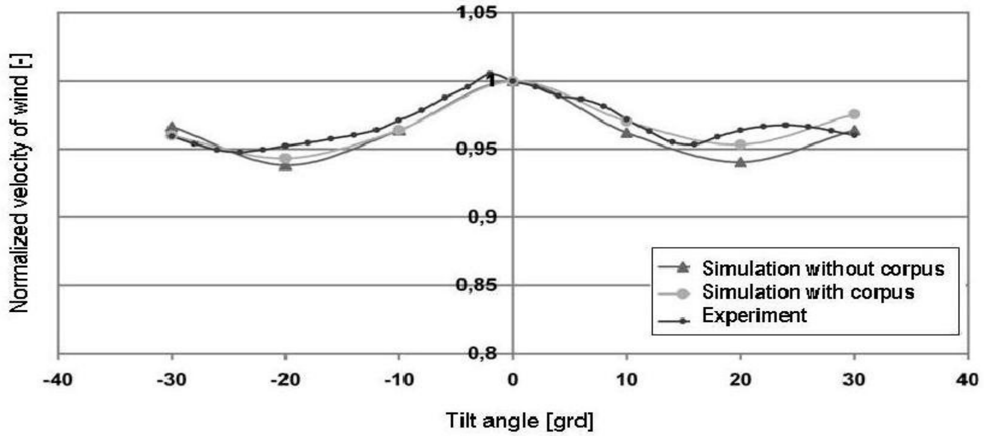

Fig. 7: Normalized velocity of wind against the tilt angle - comparison of numerical and experimental data of a *Thies First Class - Anemometer*

It also obvious, that the simulation results with and without consideration of the anemometer corpus differ from each other in case of positive angles of attack. The explanation for these results follows directly from Fig. 8, where the three-arm cup anemometer is of type *Vector*:

1. The oblique inflow to the cup anemometer induces not only different flow velocities on the upper and lower edge of the cups. It must be assumed that around each of the cups a circulation is formed leading to aerodynamic lift. With a correspondingly large tilt angle a horizontal lift component is created measurably increasing the aerodynamic moment $M(v,n)$ and thus leading to higher speeds.
2. In oblique inflow due to updrafts the anemometer corpus creates a wake field, which comes into the range of the cup anemometer at a correspondingly large α. This wake directly affects the flow around the cup anemometer and in this way the aerodynamic moment $M(v,n)$. In case of oblique inflow due to fall winds this effect is not to be found according to expectations.
3. The numerical results presented here (with anemometer corpus) only slightly deviate from the measured data. Small deviations could still disappear by further measures of optimization. The direct comparison of both simulation results (calculations with and without anemometer corpus) makes is possible to recognize the influence of the anemometer corpus on the rotational speed of the anemometer and in this way on the measured wind speed.

Summary and Outlook

We have successfully developed a mathematical model for simulating the flow around various three-arm cup anemometers, which stands the comparison with experiments.

Previous numerical investigations clearly show, that numerical flow analyses of three-arm cup anemometers are very useful to detect fluid-structure interactions occurring at all and to explain special flow effects.

The effects of individual - mainly constructive - parameters of anemometers by different manufacturers could be largely resolved in relation to the surrounding flow field. However, we do not want to give a presentation of detailed results here. The results of numerical simulations show deviations compared to the experiments with anemometers exposed to oblique inflow. The causes for this are not completely clarified so far.

Maybe the numerical simulation of anemometers in oblique inflow requires even finer computational grids in order to better resolve particularly flow effects in the wake of the threearm cup anemometers. With the fineness of the generated net, however, the computational effort increases disproportionately. To keep the computing time on a reasonable level, the parallel calculation on computers in a network proved to be very effective. However, even this approach was limited.

Due to the high computational effort for the time being some tests had to be shelved. Among these studies are:

- Consideration of other flow velocities; we mainly concentrated on an inflow of 8 m / s;
- Refinement of the generated nets in certain areas in order to identify physical effects more in detail;
- Optimization of the net's mesh size to reduce the number of nodes in order to minimize the computational efforts;
- Simplification of the numerical models by leaving out of certain details of the geometries, which are not relevant for the calculation or are of little influence on the flow around;
- further studies on the increment of the rotation; so far the time step has been chosen in a way that the anemometer turns by 3° per time step considered;
- comparative studies on the behaviour of several three-arm cup anemometer construction types exposed to oblique inflow;
- control of the process for finding the exact rotation speed of the anemometer at a given flow velocity using a specially written program.

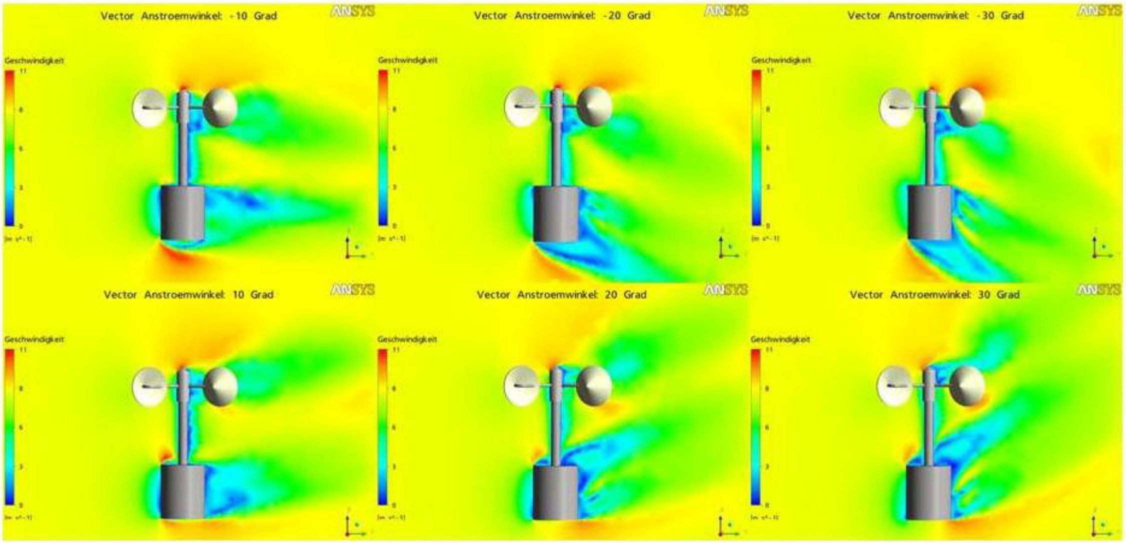

Fig. 8: Simulation of oblique inflow for a *Vector Anemometer*

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