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**Technical report**

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# An investigation of wind tunnel blockage effects on cup anemometer calibrations

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# An investigation of wind tunnel blockage effects on cup anemometer calibrations

# Summary

An investigation of wind tunnel blockage effects on cup anemometer calibrations has been carried out. A slender anemometer body in combination with three rotors of different sizes have been calibrated in five different wind tunnels. Four wind tunnels were of the closed-test-section type and one wind tunnel of the open jet type. One of the closed tunnels had a significantly larger test section than the others and was used as a reference.

The smallest rotor was so small that blockage effects were negligible in the tunnels used and the large rotor so large that blockage effects were significant.

From each calibration of the three rotors the pulse frequency at 8 m/s was determined. The frequencies were normalised with the frequency for the smallest cup anemometer. The normalised frequencies were also normalised with the three frequencies from the largest wind tunnel in order to relate the frequencies to the "true" answer. These normalised figures were compared between the four tunnels.

The results were not as expected. The blockage effects in the three closed test sections were expected to be of similar magnitude and follow a common trend. The blockage effects in the open test section were expected to be lower in magnitude and of opposite sign.

The unexpected results could be explained by the test conditions. An important pre-requisite for a successful outcome of a test was that the flow influence from the presence of the test object should not influence the measurement of the reference wind speed. However due to budgetary limitations in the project it was not possible to use other set-ups than the standard set-up normally used . Significant influences, from the test object on the measurement of the tunnel reference wind speed, could therefore not be excluded.

Consequently, no general conclusions about blockage could be drawn. Provided that the frequency values from each tunnel are reliable, individual correction recommendations for each tunnel could be given.

The method is straight forward and easy to use. In spite of the fact that no general conclusions about blockage effects could be drawn, it can be assumed that the method works well provided that more efforts are put on the localization of the position to measure the undisturbed WT wind speed.

# 1 Contents

# 2 Introduction

It is a requirement [1] that cup anemometers used for wind turbine power performance measurements shall be calibrated. A calibration is usually carried out by exposing the cup anemometer to known wind speeds in a wind tunnel and the rotational speed, expressed as pulse frequency, from the anemometer is measured. The calibration results are usually expressed as slope and offset as a result from straight line fitting to the measured frequency and wind speed data sets.

The types of wind tunnels considered in this report are closed-measurement-section wind tunnels and an open-jet wind tunnel.

The dynamic pressure in the empty test section is calculated from pressure, measured in the settling chamber or elsewhere in the upstream part of the test section by means of Prandtl tubes, using a correction factor determined from a tunnel calibration.

The relationship from calibration is only valid for the empty test section and in the case of a blocking object in the test section the speed of the flow will be influenced. The closed measurement sections are surrounded by solid walls, which, in the case of an object blocking the flow, prevents it from freely expanding around the object. This will give rise to an actual increased wind speed.

In the case of a blocking object in the open jet test section the flow is free to expand and interact with the boundaries of still air around the jet. A blockage in an open jet test section will cause the actual wind speed to be reduced.

The objective of this project is to quantify blockage effects in wind tunnels.

# 3 Objectives

The primary objective is to assess the accuracy of wind speed measurements with cup anemometers. A secondary objective is to quantify blockage effects in wind tunnels and if possible improve or verify methods to correct for blockage when calibrating cup anemometers. This will be accomplished by:

- Calibrating cup-anemometers of different sizes in different wind tunnels
- Normalising and comparing the results

# 4 The test and evaluation procedure

A slender anemometer body in combination with cup rotors of different sizes where used. The tiniest rotor was sufficiently small for blockage effects to be negligible in the tunnels used. The biggest rotor was large enough for blockage effects to be significant.
Each of the three anemometer (rotor) set-ups was calibrated. The frequency output at 8 m/s was determined through a linear regression of frequency versus wind speed. The three frequency values thus obtained were normalised by the frequency output for the smallest rotor.
A basic assumption was that by relating the frequency output from the anemometer at a fixed wind speed the uncertainty of the relation between the different rotor sizes in one tunnel could be kept as small as possible.
The aim was not to search for an absolute calibration (i.e. the purpose was not to compare wind tunnels) because the blockage effects are probably much smaller than typical deviations between tunnels.
The selection of the position to measure the wind tunnel reference speed had to be made with greatest care. The speed measured in the selected position was to be influenced minimally by the presence of the anemometer. A new reference position, located further up-stream from the test object would eventually be necessary to find.
The uniformity of the flow within the rotor swept area was also essential. One way to check if horizontal gradients were present was to carry out the calibration procedure with the anemometer running both clock wise (CW) and counter clock wise (CCW).

The test and evaluation procedures are summarized below:

- Calibrate the anemometers repeatedly in the range 7-9 m/s
- Follow the calibration sequence 8, 7, 8, 9, 9, 8, 7 and 8 m/s
- Calibrate CW and CCW
- Do not apply blockage corrections
- Repeat calibrations of the reference anemometer
- Establish the average frequency output at 8 m/s from each set-up
- Normalise the frequencies with the reference (smallest rotor)
- Compare the results between tunnels

## 5 Cup-rotors of different sizes

A series of rotors of different sizes have been produced. The cups are conical in shape and the arm radii to cup diameters ratios are similar. The rotors are used together with a slender body.

Figure 1 - The cup anemometers lying on the front of a Volvo car provides an impression of the cup sizes. The largest rotor (on the left) could unfortunately not be used because it was too heavy and could jeopardize the anemometer shaft and bearings.

Table 1- Anemometer rotor dimensions

| Configu-ration | Outer radius [mm] | Radius to center of cup, R [mm] | Cup diameter, D [mm] | R/ D | Swept area rotor [m$^2$] | Swept area support+body [m$^2$] | Total [m$^2$] |
|---|---|---|---|---|---|---|---|
| Small Black (SB) | 74 | 47 | 54 | 0.86 | 0.0074 | 0.0090 | 0.0164 |
| Big Black (BB) | 174 | 105 | 139 | 0.75 | 0.0442 | 0.0090 | 0.0532 |
| Red (R)<br>Biggest Red not used | 271 | 167 | 207 | 0.81 | 0.1031 | 0.0090 | 0.1121 |

# 6 The wind tunnels

The main dimensions and type of wind tunnels used in this investigation are summarized in the table below:

Table 2 - Wind tunnel dimensions

| Tunnel | Width m | Height m | Cross section $m^2$ | Test section |
|---|---|---|---|---|
| FOI-LT5 | 0.9 | 0.68 | 0.61 | Closed |
| DEWI (Oldenburg) | 1.0 | 0.8 | 0.8 | Open |
| Gävle WT | 3.0 | 1.5 | 4.5 | Closed |
| IDR/UPM | 0.9 | 0.9 | 0.81 | Closed |
| CRES | 0.8 | 0.8 | 0.64 | Closed |

Details about how the reference wind speeds are measured are summarized in the table below:

Table 3 - Distance from rotor centre (tunnel centre) to reference point (Prandtl-tube-head) [m]

| Tunnel | windward | sideway | above/below center | radial | Note |
|---|---|---|---|---|---|
| FOI-LT5 | 0.833 | 0.45 | 0 | 0.95 | Only static pressure. Total pressure is measured further upstream in the settling chamber |
| DEWI | 0.7 | 0.4 | 0.3 | 0.86 | Prandtl-tube-head |
| Gävle WT | | | | | Wind speed determined by WT fan RPM |
| IDR/UPM | 0.2 | 0.25 | 0.15 | 0.35 | Prandtl-tube-head |
| CRES | 0.375 | 0.22 | 0.23 | 0.49 | Prandtl-tube-head |

# 7 Results

In the following chapters the results from calibration in different wind tunnels are presented together with appropriate graphs and photos.

## *7.1 FOI results*

The pictures below show the three rotors used mounted in FOI-LT5.

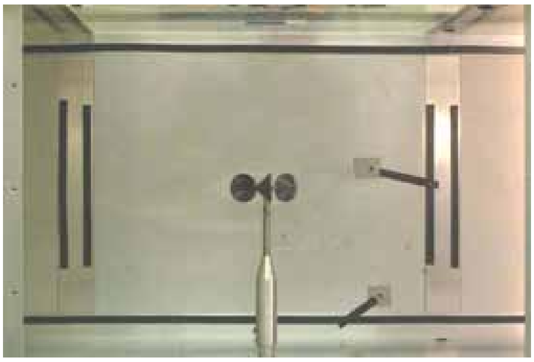

Figure 2 - Small Black rotating CW

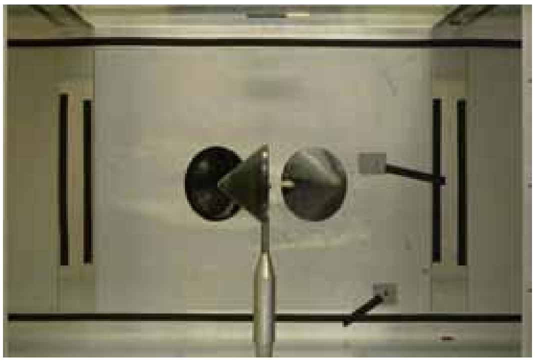

Figure 3 - Big Black rotating CW

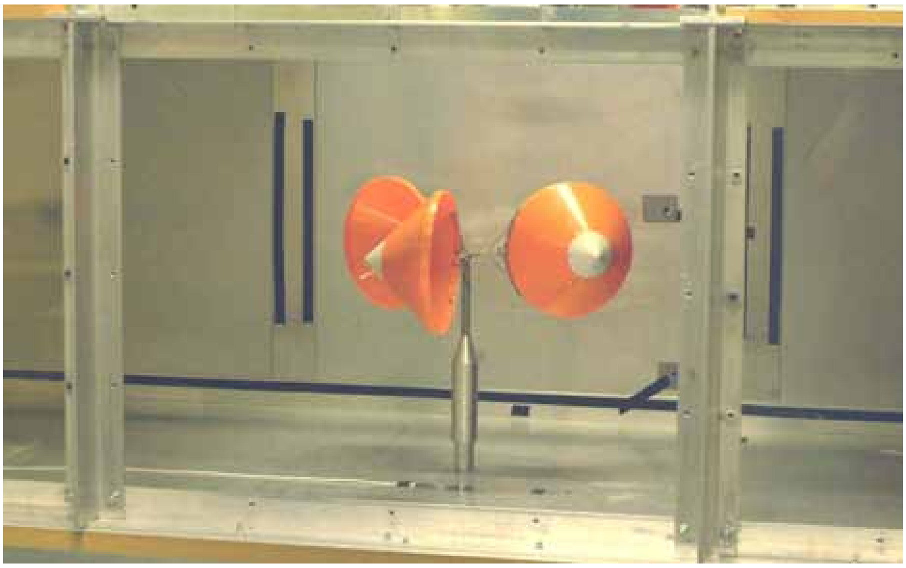

Figure 4 - Red rotating CW.

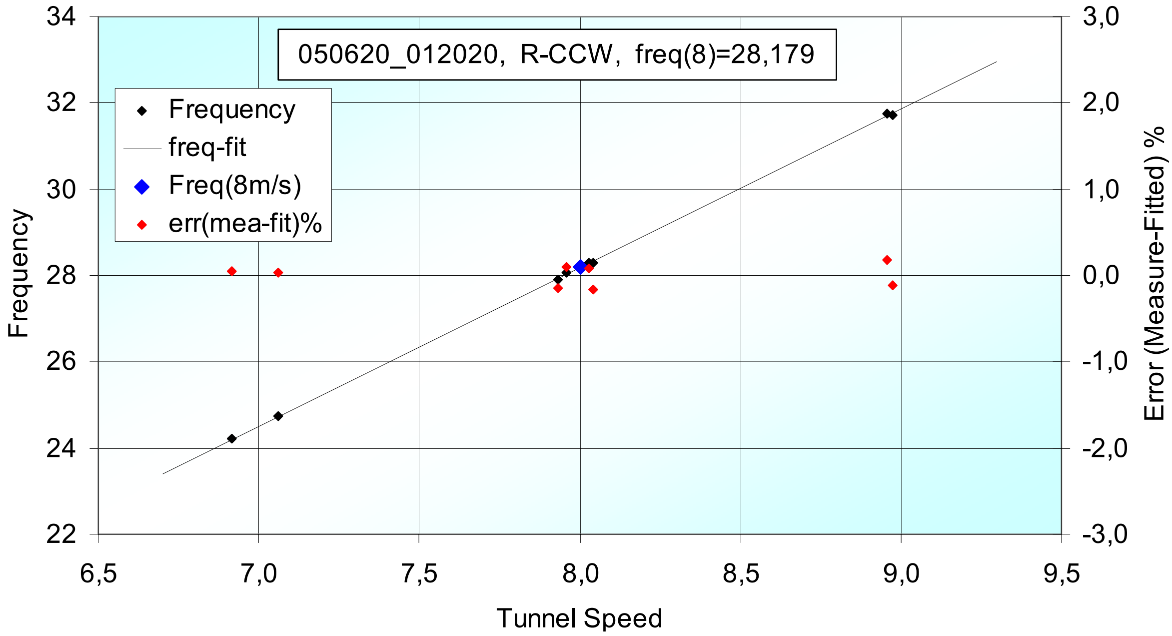


Figure 5 - The graph shows an example of result from the red configuration. The wind speed in LT5 can be set to approximate wind speeds and the measurement system measures the actual wind speed. The final result from this calibration is the frequency output at 8 m/s i.e. 28.179 Hz.

Table 4- The calibration results from tests in FOI-LT5

| Configurations | frequency at 8 m/s | Ratio CW/CCW | SB | BB | R |
|---|---|---|---|---|---|
| 050618_233434, SB-CW, freq(8)=98,272 | 98,272 | 1,0232 | 98,272 | | |
| 050619_001017, SB-CCW, freq(8)=96,046 | 96,046 | | 96,046 | | |
| 050619_004817, BB-CW, freq(8)=47,864 | 47,864 | 1,0283 | | 47,864 | |
| 050619_011953, BB-CCW, freq(8)=46,547 | 46,547 | | | 46,547 | |
| 050619_224755, SB-CW, freq(8)=98,686 | 98,686 | 1,0280 | 98,686 | | |
| 050619_231527, SB-CCW, freq(8)=96,000 | 96,000 | | 96,000 | | |
| 050620_004857, R-CW, freq(8)=28,820 | 28,820 | 1,0227 | | | 28,820 |
| 050620_012020, R-CCW, freq(8)=28,179 | 28,179 | | | | 28,179 |
| 050620_020246, SB-CW, freq(8)=98,241 | 98,241 | 1,0272 | 98,241 | | |
| 050620_023542, SB-CCW, freq(8)=95,639 | 95,639 | | 95,639 | | |
| | | | | | |
| | | Average | 97,147 | 47,205 | 28,500 |
| | | Normalised | 1 | 0,4859 | 0,2934 |

Note the 2.5% difference in frequency for CW and CCW direction of rotation. This is caused by a wind gradient across the projected test area. This effect is known and compensated for during normal cup anemometer calibrations.

### *7.2 DEWI results*

Table 5- The calibration results from the tests carried out by DEWI

| Configuration | f/Hz at 8 m/s | Ratio CW/CCW | SB | BB | Red |
|---|---|---|---|---|---|
| SB CW | 94,8850 | 0,9968 | 94,8850 | | |
| SB CCW | 95,1883 | | 95,1883 | | |
| BB CW | 44,8799 | 0,9955 | | 44,8799 | |
| BB CCW | 45,0841 | | | 45,0841 | |
| SB CW | 94,8505 | 0,9959 | 94,8505 | | |
| SB CCW | 95,2434 | | 95,2434 | | |
| RCW | 26,6284 | 0,9978 | | | 26,6284 |
| RCCW | 26,6868 | | | | 26,6868 |
| SB CW | 94,8166 | 0,9955 | 94,8166 | | |
| SB CCW | 95,2429 | | 95,2429 | | |
| | | Average | 95,0378 | 44,9820 | 26,6576 |
| | | DEWI norm. | 1 | 0,47331 | 0,28049 |

### *7.3 CRES results*

Table 6- The calibration results from the tests carried out by CRES

| Configuration | Frequency at 8m/s | Ratio CCW/CW | SB | BB | BR |
|---|---|---|---|---|---|
| Small black CW | 96.8230 | 1.0079 | 96.8230 | | |
| Small black CCW | 97.5866 | | 97.5866 | | |
| Big black CW | 46.2537 | 1.0122 | | 46.2537 | |
| Big black CCW | 46.8197 | | | 46.8197 | |
| Big red CW | 27.5274 | 1.0211 | | | 27.5274 |
| Big red CCW | 28.1075 | | | | 28.1075 |
| Small black CW2 | 96.7693 | 1.0047 | 96.7693 | | |
| Small black CCW2 | 97.2223 | | 97.2223 | | |
| Small black CW3 | 96.3990 | 1.0112 | 96.3990 | | |
| Small black CCW3 | 97.4789 | | 97.4789 | | |
| | | **Average** | 97.0465 | 46.5367 | 27.8175 |
| | | **Normalised** | **1.0000** | **0.4795** | **0.2866** |

### 7.4 IDR/UPM results

Table 7 - The calibration results from the tests carried out by IDR/UPM

| Configuration | frequency at 8 m/s | Ratio CW/CCW | SB | BB | R |
|---|---|---|---|---|---|
| Cupset SB CW Freq(8)=95,183 | 95,1826 | 0,9904 | 95,1826 | | |
| Cupset SB CCW Freq(8)=96,101 | 96,1011 | | 96,1011 | | |
| Cupset BB CW Freq(8)=45,358 | 45,3579 | 1,0089 | | 45,3579 | |
| Cupset BB CCW Freq(8)=44,957 | 44,9569 | | | 44,9569 | |
| Cupset BR CW Freq(8)=26,217 | 26,2173 | 0,9985 | | | 26,2173 |
| Cupset BR CCW Freq(8)=26,258 | 26,2579 | | | | 26,2579 |
| | | | | | |
| | | Average | 95,6419 | 45,1574 | 26,2376 |
| | | Normalised | 1 | 0,4722 | 0,2743 |

### 7.5 Gävle WT results

The Gävle wind tunnel at Gävle University is mainly used for building aerodynamics.


Figure 6 – The test section of the Gävle wind tunnel.


Figure 7 – The small black rotor.


Figure 8 – The big black rotor


Figure 9 – The largest red rotor in the Gävle WT. Blockage approx. 2.5%

Table 8 - The calibration results from the tests in the Gävle WT.

| Configuration | frequency at 8 m/s | Ratio CW/CCW | SB | BB | R |
|---|---|---|---|---|---|
| 130829_SB_CW, Freq(8)=94,416 | 94,416 | 0,9983 | 94,416 | | |
| 133607_SB_CCW, Freq(8)=94,572 | 94,572 | | 94,572 | | |
| 135830_BB_CW, Freq(8)=44,295 | 44,295 | 1,0024 | | 44,295 | |
| 141950_BB_CCW, Freq(8)=44,190 | 44,190 | | | 44,190 | |
| 144432_SB_CW, Freq(8)=94,499 | 94,499 | 0,9990 | 94,499 | | |
| 150420_SB_CCW, Freq(8)=94,598 | 94,598 | | 94,598 | | |
| 152653_R_CW, Freq(8)=26,224 | 26,224 | 1,0102 | | | 26,224 |
| 154811_R_CCW, Freq(8)=25,961 | 25,961 | | | | 25,961 |
| 160946_SB_CW, Freq(8)=94,439 | 94,439 | 0,9999 | 94,439 | | |
| 162953_SB_CCW, Freq(8)=94,452 | 94,452 | | 94,452 | | |
| | | | | | |
| | | Average | 94,496 | 44,243 | 26,092 |
| | | Normalised | 1 | 0,4682 | 0,2761 |

## 8 Comparisons

The normalized frequency ratios can now be compared between the tunnels. The comparison assumes as a first approximation that the blockage effects for the smallest anemometer is negligible in all tunnels. The comparison is also based on the assumption that the blockage effects are negligible for all rotor sizes in the large Gävle tunnel.

Table 9 –The final comparison between the tunnels.

| Wind Tunnel | Test cross section area m2 | SB 0,0164 1 | BB 0,0532 6 | R 0,1121 14 |
|---|---|---|---|---|
| Gavle | 4,5 | 1 | 0,4682 | 0,2761 |
| LT5 | 0,61 | 1 | 0,4859 | 0,2934 |
| DEWI | 0,80 | 1 | 0,4733 | 0,2805 |
| IDR | 0,81 | 1 | 0,4722 | 0,2743 |
| CRES | 0,64 | 1 | 0,4795 | 0,2866 |
| | | | | |
| LT5/Gavle | | 1 | 1,0378 | 1,0624 |
| DEWI/Gavle | | 1 | 1,0109 | 1,0158 |
| IDR/Gavle | | 1 | 1,0084 | 0,9935 |
| CRES/Gavle | | 1 | 1,0241 | 1,0379 |

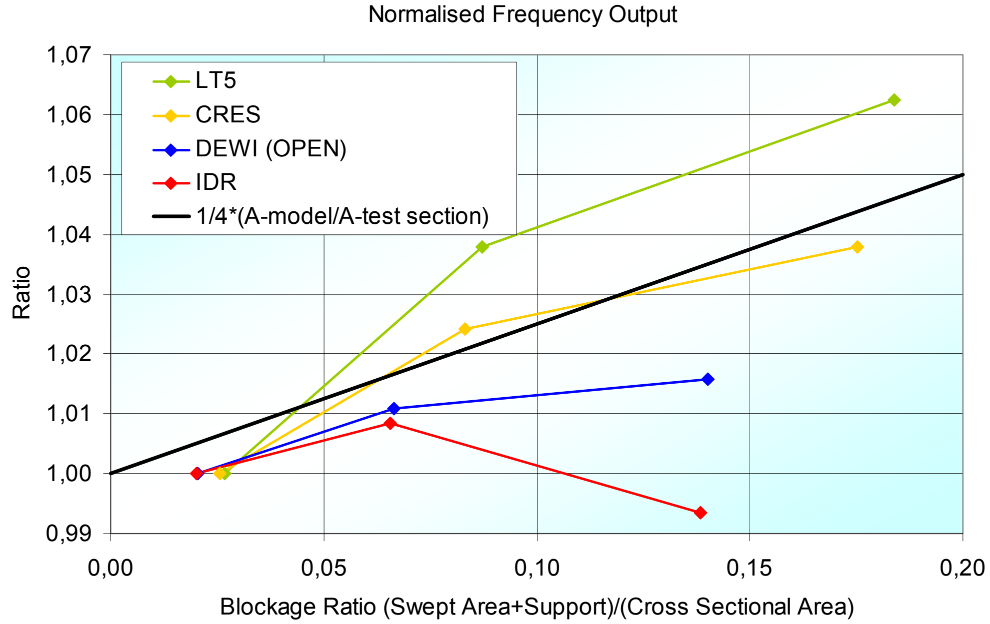


Figure 10 - A graphical representation of the values in Table 9 together with the formula given in the next chapter.

The black line in Figure 10 is a recommendation from [2]. The authors suggest "When all is lost as far as finding blockage corrections for some unusual shapes that needs to be tested in a tunnel, use the following formula"

$$\frac{WS + \Delta WS}{WS} = 1 + \frac{1}{4}\frac{Model\_frontal\_area}{Test\_section\_area} \qquad (1)$$

# 9 Conclusions and Discussion

The results presented in Figure 10 were not the expected. The blockage effects in the three closed test sections were initially assumed to be of similar magnitude and follow a common trend. The blockage effects in the open test section were expected to be lower in magnitude and of opposite sign.

The unexpected results could be explained by the test conditions. As outlined in section 4 an important pre-requisite for a successful outcome of the test was that the flow influence from the presence of the test object should not influence the measurement of the reference wind speed. However due to budgetary limitations in the project it was not possible to use other set-ups than the standard set-up. As can be seen from Table 3 the distance from the rotor centre to the wind speed measurement positions were in some cases very small compared to the outer dimensions of the test objects. Significant influences, from the test object on the measurement of the tunnel wind speed, could therefore not be excluded.

Hence, no general conclusions about blockage can be drawn. Provided that the frequency values from each tunnel and especially the reference tunnel (Gävle WT) are reliable, then individual correction recommendations for each tunnel can be given as:

- FOI should apply a correction which is about 30% larger than suggested by (1)
- If CRES applies a correction according to formula (1) a reasonably good correction will be obtained.
- The results suggests that DEWI should apply a correction which is about half as large as indicated by (1).
- In the setup used by IDR/UPM, the Prandtl tube seems to be located in a position such that blockage effects in measurements are compensated to some extent.

The method to calibrate anemometers of different sizes and normalize the results is straight forward and easy to use and in spite of the fact that no general conclusions about blockage effects could be drawn it is a belief that the method works well provided that more efforts are put on the localization of the position to measure the undisturbed WT wind speed.

# 10 References

[1] MEASNET; http://www.measnet.org/

[2] Rae, William. H. Jr, Pope Alan, "Low-Speed Wind Tunnel Testing", ISBN 0-471-87402-7

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The smallest rotor was so tiny that blockage effects were negligible in the tunnels used. The large rotor was sufficiently large for blockage effects to be significant.

The results were not the expected. The blockage effects in the three closed test sections were initially assumed to be of similar magnitude and follow a common trend. The blockage effects in the open test section were expected to be lower in magnitude and of opposite sign.

The unexpected results could be explained by the test conditions. Due to budgetary limitations in the project it was not possible to use other set-ups for measuring the reference wind speed than the standard set-up. Significant influences, from the test object on the measurement of the tunnel wind speed, could therefore not be excluded. Hence, no general conclusions about blockage could be drawn. Provided that the frequency values from each tunnel were reliable, then individual correction recommendations for each tunnel could be given:

The method to calibrate anemometers of different sizes and normalize the results is straight forward and easy to use and in spite of the fact that no general conclusions about blockage effects could be drawn it is a belief that the method works well provided that more efforts are put on the localization of the position to measure the undisturbed WT wind speed.

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