

INTERNATIONAL STANDARD

NORME INTERNATIONALE



Wind energy generation systems –

Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments

Systèmes de génération d'énergie éolienne

Partie 50-1: Mesurages du vent – Application d'instruments météorologiques montés sur mât, nacelle et nez de rotor



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2022 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de l'IEC ou du Comité national de l'IEC du pays du demandeur. Si vous avez des questions sur le copyright de l'IEC ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de l'IEC de votre pays de résidence.

IEC Secretariat
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Discover our powerful search engine and read freely all the publications previews. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22 300 terminological entries in English and French, with equivalent terms in 19 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

A propos de l'IEC

La Commission Electrotechnique Internationale (IEC) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications IEC

Le contenu technique des publications IEC est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Recherche de publications IEC -

webstore.iec.ch/advsearchform

La recherche avancée permet de trouver des publications IEC en utilisant différents critères (numéro de référence, texte, comité d'études, ...). Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

IEC Just Published - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications IEC. Just Published détaille les nouvelles publications parues. Disponible en ligne et une fois par mois par email.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Découvrez notre puissant moteur de recherche et consultez gratuitement tous les aperçus des publications. Avec un abonnement, vous aurez toujours accès à un contenu à jour adapté à vos besoins.

Electropedia - www.electropedia.org

Le premier dictionnaire d'électrotechnologie en ligne au monde, avec plus de 22 300 articles terminologiques en anglais et en français, ainsi que les termes équivalents dans 19 langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (IEV) en ligne.

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 50-1: Wind measurement – Application of meteorological mast, nacelle and
spinner mounted instruments**

**Systèmes de génération d'énergie éolienne
Partie 50-1: Mesurages du vent – Application d'instruments météorologiques
montés sur mât, nacelle et nez de rotor**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.180

ISBN 978-2-8322-5937-5

**Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.**

CONTENTS

FOREWORD.....	6
INTRODUCTION.....	8
1 Scope.....	9
2 Normative references	9
3 Terms and definitions	10
4 Symbols, units and abbreviated terms	11
5 General	16
6 Classification of cup and sonic anemometry	16
6.1 General.....	16
6.2 Classification classes.....	17
6.3 Influence parameter ranges	17
6.4 Classification of cup and sonic anemometers	17
6.5 Reporting format	19
7 Assessment of cup and sonic anemometry	19
7.1 General.....	19
7.2 Measurements of anemometer characteristics	19
7.2.1 Measurements in a wind tunnel for tilt angular response characteristics of cup anemometers	19
7.2.2 Wind tunnel measurements of directional characteristics of cup anemometers.....	21
7.2.3 Wind tunnel measurements of cup anemometer rotor torque characteristics	21
7.2.4 Wind tunnel measurements of step responses of cup anemometers	22
7.2.5 Measurement of temperature induced effects on anemometer performance	23
7.2.6 Wind tunnel measurements of directional characteristics of sonic anemometers.....	24
7.3 A cup anemometer classification method based on wind tunnel and laboratory tests and cup anemometer modelling	25
7.3.1 Method	25
7.3.2 Example of a cup anemometer model	25
7.4 A sonic anemometer classification method based on wind tunnel tests and sonic anemometer modelling.....	32
7.5 Free field comparison measurements.....	32
8 Wind tunnel calibration procedure for anemometers	32
8.1 General requirements	32
8.2 Requirements for the wind tunnel.....	33
8.3 Instrumentation and calibration setup requirements	35
8.4 Calibration procedure.....	35
8.4.1 General procedure for cup and sonic anemometers	35
8.4.2 Procedure for the calibration of sonic anemometers.....	36
8.4.3 Determination of the wind speed at the anemometer position	36
8.5 Data analysis	37
8.6 Uncertainty analysis.....	37
8.7 Reporting format	38
8.8 Example uncertainty calculation.....	39

9	In-situ comparison of anemometers	42
9.1	General.....	42
9.2	Prerequisite	42
9.3	Analysis method	42
9.4	Evaluation criteria	43
10	Mounting of instruments on the meteorological mast.....	45
10.1	General.....	45
10.2	Single top-mounted anemometer.....	46
10.3	Side-by-side top-mounted anemometers	47
10.4	Side-mounted instruments	49
10.4.1	General	49
10.4.2	Tubular meteorological masts	49
10.4.3	Lattice meteorological masts	51
10.4.4	Flow distortion correction of side-mounted anemometers.....	56
10.5	Lightning protection	56
10.6	Mounting of other meteorological instruments	56
10.7	Data acquisition system	57
11	Uncertainty of wind speed measurement	57
11.1	Category B uncertainties: Wind speed – Introduction	57
11.2	Category B uncertainties: Wind speed – Hardware.....	57
11.3	Category B uncertainties: Wind speed – Meteorological mast mounted sensors.....	57
11.3.1	General	57
11.3.2	Pre-calibration	58
11.3.3	Post-calibration	58
11.3.4	Classification	58
11.3.5	Mounting	59
11.3.6	Lightning finial	60
11.3.7	Data acquisition.....	60
11.4	Category B uncertainties: Method – Cold climate	60
11.5	Combining uncertainties.....	60
11.5.1	General	60
11.5.2	Combining uncertainties in the wind speed measurement ($u_{V,i}$).....	61
11.5.3	Combining uncertainties in the wind speed measurement from cup or sonic anemometer ($u_{VS,i}$)	61
12	Reporting.....	61
Annex A	(informative) Wind tunnel calibration procedure for wind direction sensors.....	63
A.1	General requirements	63
A.2	Requirements of the wind tunnel	63
A.3	Instrumentation and calibration setup requirements	64
A.4	Calibration procedure.....	65
A.5	Data analysis	66
A.6	Uncertainty analysis.....	66
A.7	Reporting format.....	67
A.8	Example of uncertainty calculation.....	68
A.8.1	General	68
A.8.2	Measurement uncertainties generated by determination of the flow direction in the wind tunnel	68

A.8.3	Uncertainty contribution by uncertainties in the determination of the geometrical centreline α_{CL} (wind tunnel centreline)	68
A.8.4	Contribution by uncertainties in the determination of flow direction α_{dir}	68
Annex B (informative)	Mast flow distortion correction for lattice masts	73
Annex C (informative)	Nacelle instrument mounting	76
C.1	General.....	76
C.2	Preferred method of anemometer's mounting	76
C.3	Preferred position of anemometer	76
Annex D (informative)	Spinner anemometers	78
Bibliography		79
Figure 1	Tilt angular response $V_{\alpha}/V_{\alpha=0}$ of a cup anemometer as a function of flow angle α compared to cosine response	21
Figure 2	Wind tunnel torque measurements $Q_A - Q_F$ as a function of angular speed ω of a cup anemometer rotor at 8 m/s	22
Figure 3	Example of bearing friction torque Q_F as function of temperature for a range of angular speeds ω	24
Figure 4	Example of rotor torque coefficient C_{QA} as a function of speed ratio λ derived from step responses with κ_{low} equal to -5,5 and κ_{high} equal to -6,5	27
Figure 5	Classification deviations of example cup anemometer showing a class 1,69A (upper) and a class 6,56B (lower)	30
Figure 6	Classification deviations of example cup anemometer showing a class 8,01C (upper) and a class 9,94D (lower)	31
Figure 7	Definition of volume for flow uniformity test	34
Figure 8	Example valid control anemometer direction sector for a single top-mounted anemometer on a triangular lattice meteorological mast.....	44
Figure 9	Example valid control anemometer direction sector for a single top-mounted anemometer on a tubular meteorological mast.....	45
Figure 10	Example of a top-mounted anemometer and requirements for mounting	47
Figure 11	Example of alternative top-mounted primary and control anemometers positioned side-by-side and wind vane and other instruments on the boom.....	48
Figure 12	Iso-speed plot of local flow speed around a cylindrical meteorological mast	50
Figure 13	Centreline relative wind speed as a function of distance R_d from the centre of a tubular meteorological mast and meteorological mast diameter d	51
Figure 14	Representation of a three-legged lattice meteorological mast.....	51
Figure 15	Iso-speed plot of local flow speed around a triangular lattice meteorological mast with a C_T of 0,5	52
Figure 16	Centreline relative wind speed as a function of distance R_d from the centre of a triangular lattice meteorological mast of leg distance L_m for various C_T values.....	53
Figure 17	3D CFD derived flow distortion for two different wind directions around a triangular lattice meteorological mast ($C_T = 0,27$)	55
Figure A.1	Example of calibration setup of a wind direction sensor in a wind tunnel.....	65
Figure B.1	Example of mast flow distortion	73
Figure B.2	Flow distortion residuals versus wind direction.....	75
Figure C.1	Mounting of anemometer on top of nacelle	77

Table 1 – Influence parameter ranges (10 min averages) of classes A, B, C, D and S.....	18
Table 2 – Tilt angle response of example cup anemometer	28
Table 3 – Friction coefficients of example cup anemometer	29
Table 4 – Miscellaneous data related to classification of example cup anemometer	29
Table 5 – Example of evaluation of anemometer calibration uncertainty.....	39
Table 6 – Estimation method for C_T for various types of lattice mast.....	54
Table A.1 – Uncertainty contributions in wind directions sensor calibration	71
Table A.2 – Uncertainty contributions and total standard uncertainty in wind direction sensor calibration	72

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –**Part 50-1: Wind measurement – Application of meteorological mast,
nacelle and spinner mounted instruments**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC 61400-50-1 has been prepared by IEC technical committee 88: Wind energy generation systems. It is an International Standard.

This first edition of IEC 61400-50-1 is part of a structural revision that cancels and replaces the performance standards IEC 61400-12-1:2017 and IEC 61400-12-2:2013. The structural revision contains no technical changes with respect to IEC 61400-12-1:2017 and IEC 61400-12-2:2013, but the parts that relate to wind measurements, measurement of site calibration and assessment of obstacle and terrain have been extracted into separate standards.

The purpose of the re-structure was to allow the future management and revision of the power performance standards to be carried out more efficiently in terms of time and cost and to provide a more logical division of the wind measurement requirements into a series of separate standards which could be referred to by other use case standards in the IEC 61400 series and subsequently maintained and developed by appropriate experts.

The text of this International Standard is based on the following documents:

Draft	Report on voting
88/902/FDIS	88/916/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 61400 specifies procedures and methods which ensure that wind measurements using cup or sonic anemometers mounted on meteorological masts or wind turbine nacelles/spinners are carried out and reported consistently and in accordance with best practice. This document does not define the purpose or use case of the wind measurements. However, as this document forms part of the IEC 61400 series of standards, it is anticipated that the wind measurements carried out in accordance with this standard will be used in relation to some form of wind energy testing or resource assessment.

The main clauses of this document are not mutually dependent. Therefore, it is possible that a user will refer to only certain of the main clauses rather than all clauses to adapt this document to their specific use case. However, the main clauses are presented in a logical sequence that could be applied in practice.

The technical content of this document could previously be found in IEC 61400-12-1:2017 and IEC 61400-12-2:2013.

NOTE A technical correction to the value of the tolerance of the anemometer mounting tube has been made in 10.2.

Due to the increasing complexity of these source documents, IEC TC 88 decided that a re-structuring of the IEC 61400-12 series of standards into a number of more specific parts would allow more efficient management and maintenance going forward. This document has been created as part of that re-structuring process. The requirements on wind measurement specific to the use cases described in IEC 61400-12-1:2017 and IEC 61400-12-2:2013 (for example, the required location of the meteorological mast relative to the test turbine and the height of wind measurement relative to hub height) remain within the new editions of IEC 61400-12-1 and IEC 61400-12-2.

WIND ENERGY GENERATION SYSTEMS –

Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments

1 Scope

IEC 61400-50 specifies methods and requirements for the application of instruments to measure wind speed (and related parameters, e.g. wind direction, turbulence intensity). Such measurements are required as an input to some of the evaluation and testing procedures for wind energy and wind turbine technology (e.g. resource evaluation and turbine performance testing) described by other standards in the IEC 61400 series. This document is applicable specifically to the use of wind measurement instruments mounted on meteorological masts, turbine nacelles or turbine spinners which measure the wind at the location at which the instruments are mounted. This document excludes remote sensing devices which measure the wind at some location distant from the location at which the instrument is mounted (e.g. vertical profile or forward facing lidars). This document specifies the following:

- a) the classification parameters for cup and sonic anemometers such that the uncertainty in wind speed measurement for a specific type and model of anemometer exposed to a certain class of environmental conditions can be assessed;
- b) the procedure and requirements for classifying cup and sonic anemometers as, for example, part of the type testing of a specific anemometer model and type;
- c) the procedures and requirements for wind tunnel calibration of anemometers;
- d) an additional or alternative method of checking the consistency of the calibration of an anemometer in the field by carrying out an in-situ comparison with another anemometer;
- e) the requirements for the mounting of anemometers and other instruments on meteorological masts;
- f) the assessment of wind speed measurement uncertainty;
- g) reporting requirements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2533:1975, *Standard atmosphere*

ISO 3966, *Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1

accuracy

closeness of the agreement between the result of a measurement and a true value of the measurand

3.2

data set

collection of data sampled over a continuous period

3.3

distance constant

indication of the response time of an anemometer, defined as the length of air that shall pass the instrument for it to indicate 63 % of the final value for a step input in wind speed

3.4

flow distortion

change in air flow caused by obstacles, topographical variations, or other wind turbines that results in the wind speed at the measurement location being different from the wind speed at the wind turbine location

3.5

hub height

<of a wind turbine> height of the centre of the swept area of the wind turbine rotor above the ground at the tower

Note 1 to entry: For a vertical axis wind turbine the hub height is defined as the height of the centroid of the swept area of the rotor above the ground at the tower.

3.6

measurement period

period during which a statistically significant database has been collected for the use case

Note 1 to entry: A power performance test is an example of a use case.

3.7

measurement sector

sector of wind directions from which data are selected for the use case

Note 1 to entry: A measured power curve is an example of a use case.

3.8

obstacle

obstruction that blocks the wind and creates distortion of the flow

Note 1 to entry: Buildings and trees are examples of obstacles.

3.9

power performance

measure of the capability of a wind turbine to produce electric power and energy

3.10**standard uncertainty**

uncertainty of the result of a measurement expressed as a standard deviation

3.11**wind measurement equipment**

meteorological mast-mounted instruments or remote sensing device

3.12**wind shear**

change of wind speed with height

3.13**wind shear exponent**

α

exponent of the power law defining the variation of wind speed with height

Note 1 to entry: This parameter is used as a measure of the magnitude of wind shear and can be otherwise useful. The power law equation is:

$$v_{zi} = v_h \left(\frac{z_i}{H} \right)^\alpha \quad (1)$$

where

v_h is the hub height wind speed;

H is the hub height (m);

v_{zi} is the wind speed at height z_i ;

α is the wind shear exponent.

4 Symbols, units and abbreviated terms

Symbol	Description	Unit
A	swept area of the wind turbine rotor	m ²
B	barometric pressure	Pa
$B_{10\text{min}}$	measured air pressure averaged over 10 min	Pa
C_h	pitot tube head coefficient	
C_{QA}	generalized aerodynamic torque coefficient	
C_T	thrust coefficient	
c	sensitivity factor of a parameter (the partial differential)	
$c_{B,i}$	sensitivity factor of air pressure in bin i	W/Pa
$c_{d,i}$	sensitivity factor of data acquisition system in bin i	
c_{index}	sensitivity factor of index parameter	
$c_{k,i}$	sensitivity factor of component k in bin i	
$c_{T,i}$	sensitivity factor of air temperature in bin i	W/K
$c_{V,i}$	sensitivity factor of wind speed in bin i	Ws/m
$c_{\rho,i}$	sensitivity factor of air density correction in bin i	Wm ³ /kg

Symbol	Description	Unit
d	meteorological mast diameter	m
e	eccentricity	
$F(V)$	Rayleigh cumulative probability distribution function for wind speed	
$F_{a,\gamma}(a,\gamma, \bar{U})$	tilt and yaw response function for the sonic anemometer	
$f(k_b, k_i, k_p, \bar{v}_p, \dots)$	correction function due to interference between the anemometer including its mounting tube and the wind tunnel flow	
H	hub height of wind turbine	m
h	height of obstacle	m
I	inertia of cup anemometer rotor	kg·m ²
$K_{B,t}$	barometer sensitivity	N/m ² V
$K_{B,s}$	barometer gain	
$K_{B,d}$	barometer sampling conversion	
$K_{T,t}$	temperature transducer sensitivity	K/A
$K_{T,s}$	temperature transducer gain	A/V
$K_{T,d}$	temperature transducer sampling conversion	
$K_{p,t}$	pressure transducer sensitivity	
$K_{p,s}$	pressure transducer gain	
$K_{p,d}$	pressure transducer sampling conversion	
k	class number	
k_b	blockage correction factor	
k_c	wind tunnel calibration factor	
k_f	wind tunnel correction factor to other tunnels (only used in uncertainty estimate)	
k_i	correction factor due to interference between the anemometer (including mounting tube) and test section enclosure, also including flow effects due to mounting tubes extending through the enclosure	
k_n	class number of anemometer sample number n ($n = 1, \dots, 5$ or more)	
k_p	correction factor due to interference caused by the anemometer (including mounting tube) on the velocity measured by the pitot tube	
k_ρ	humidity correction to density	
L_m	distance between adjacent legs of lattice meteorological mast	m
L	distance between the wind turbine and the wind measurement equipment	m
M	number of uncertainty components in each bin	
M_A	number of category A uncertainty components	
M_B	number of category B uncertainty components	
m	slope of the regression relating V_{control} to $V_{\text{primary_est}}$	

Symbol	Description	Unit
m	slope of the regression between V_1 and V_2	
N	number of bins	
N_h	number of hours in one year $\approx 8\,760$	h
N_i	number of 10 min data sets in wind speed bin i	
N_j	number of 10 min data sets in wind direction bin j	
n	number of samples within sampling interval	
n_h	number of available measurement heights	
P_w	vapour pressure	Pa
p	axial run-out deviation	
Q_A	aerodynamic torque	N·m
Q_F	friction torque	N·m
R	rotor radius	m
r_a	effective radius of angle measurement	
R_0	gas constant of dry air (287,05)	J/kg·K
R_d	distance to meteorological mast centre	m
R_w	gas constant of water vapour (461,5)	J/kg·K
REWS	rotor equivalent wind speed	
RSD	remote sensing device	
r	correlation coefficient	
s	category A standard uncertainty component	
s_A	category A standard uncertainty of tunnel wind speed time series	
$s_{k,i}$	category A standard uncertainty of component k in bin i	
s_i	combined category A uncertainties in bin i	
S	meteorological mast solidity	
T	absolute temperature	K
TI	turbulence intensity	
T_{10min}	measured absolute air temperature averaged over 10 min	K
t	time	s
U	wind speed	m/s
U_d	centreline wind speed deficit	m/s
U_{eq}	equivalent horizontal wind speed	m/s
U_i	wind speed in bin i	m/s
U_j	wind speed in bin j	
U_{sonic}	sonic anemometer	
U_t	threshold wind speed	m/s
$\vec{U}$	instantaneous wind vector	
u	category B standard uncertainty component	

Symbol	Description	Unit
$u_{B,i}$	category B standard uncertainty of air pressure in bin i	Pa
$u_{c,i}$	combined standard uncertainty of the power in bin i	W
$u_{dVS,i}$	uncertainty component of data acquisition of the wind speed signal	
u_i	combined category B uncertainties in bin i	
u_{index}	category B standard uncertainty of index parameter	
$u_{k,i}$	category B standard uncertainty of component k in bin i	
$u_{M,cc,i}$	influence of measurement in cold climate on the classification of the anemometers	
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	m/s
$u_{VHW,i}$	uncertainty on the hardware used and is one of $u_{VS,i}$, $u_{VR,i}$ or $u_{REWS,i}$	
$u_{VM,i}$	uncertainty related to the method applied	
$u_{VS,class,i}$	uncertainty related to the classification of the sensors	
$u_{VS,igt,i}$	uncertainty related to the flow distortion from lightning finial	
$u_{VS,mnt,i}$	uncertainty related to the mounting of the sensors	
$u_{VS,precal,i}$	uncertainty relating to the pre-calibration	
$u_{VS,postcal,i}$	uncertainty related to the post-calibration	
$u_{v2,i}$	wind speed uncertainty assessment	
$u(t)$	measured wind speed by the cup anemometer at time t using the ordinary calibration function	
u_t	tunnel wind speed	
Δu	difference between wind tunnel wind speed and the indicated wind speed of the cup anemometer, at the beginning of the step response measurement, at time t_0	
V	wind speed	m/s
V_{ave}	annual average wind speed at hub height	m/s
V_{control}	wind speed of the control anemometer	
$V_{\text{control},i}$	wind speed of the control anemometer in bin i	
V_i	normalized and averaged wind speed in bin i	m/s
V_n	normalized wind speed	m/s
$V_{n,i,j}$	normalized wind speed of data set j in bin i	m/s
$V_{\text{primary},i}$	wind speed of the primary anemometer in bin i	
$V_{\text{primary_est}}$	estimated primary anemometer wind speed	
$V_{10\text{min}}$	measured wind speed averaged over 10 min	m/s
V_1	wind speed from sensor one	
V_2	wind speed from the second sensor	
v	transversal wind speed component	m/s

Symbol	Description	Unit
$\bar{v}$	average wind speed at the anemometer position	m/s
$\bar{v}_p$	average wind speed at the reference position	
v_{eq}	measured equivalent wind speed	m/s
WD	wind direction	
WME	wind measurement equipment	
w	vertical wind speed component	m/s
w_i	weighting function to define deviation envelope	
α	wind shear exponent from power law	°
α	pitot static tube head coefficient	
α	angle to be measured (calibration value)	
α_{CL}	wind tunnel centreline	
$\alpha_{Digital}$	uncertainty by digital output signal	
α_{dir}	uncertainties in the determination of flow direction	
$\alpha_{incl.1}$	influence of the angle between the axes of rotation	
α_{item}	uncertainty by mounting the wind direction sensor	
$\alpha_{incl.2}$	uncertainty by possible malposition of the wind direction sensor	
α_{sensor}	uncertainties in the calibration of the reference yawing sensor	
α_{set}	aligning the centreline with the north marking of the wind direction sensor	
α_{Ω}	uncertainty by the determination of the ohmic resistance of a wind direction sensor	
ε_i	deviation in m/s for influence parameter combination i	
$\varepsilon_{max,i}$	maximum deviation for any wind speed bin i in the wind speed range	m/s
θ	disturbed sector	°
κ	von Karman constant 0,4	
λ	speed ratio	
λ_0	speed ratio for $C_{QA} = 0$	
ρ	air density	kg/m ³
τ	the time constant to be determined for the step response (τ_{low} for step response from below and τ_{high} for step response from above)	
ρ_0	reference air density	kg/m ³
ρ_{10min}	derived air density averaged over 10 min	kg/m ³
$\sigma_{P,i}$	standard deviation of the normalized power data in bin i	W
σ_{10min}	standard deviation of parameter averaged over 10 min	
$\sigma_u/\sigma_v/\sigma_w$	standard deviations of longitudinal/transversal/vertical wind speeds	
Φ	relative humidity (range 0 % to 100 %)	

Symbol	Description	Unit
ω	angular speed	s^{-1}
Δp_{ref}	mean differential pressure	

5 General

This document defines methods and requirements for carrying out wind measurements using instruments such as anemometers (cup and ultrasonic) mounted on meteorological masts, wind turbine nacelles (Annex C) and wind turbine spinners (Annex D). Requirements for calibration, classification and mounting are described. Wind measurements carried out in accordance with this document are useable for many purposes in the field of wind energy (e.g. power performance measurement, site assessment, load measurement, noise measurement) as described in other standards in the IEC 61400 series. The specific standard relating to the intended use case of the wind measurements should be referred to for limitations and additional requirements (e.g. height of measurement relative to turbine hub height in the case of power performance measurements). For wind measurements carried out using ground-mounted remote sensing devices (e.g. lidar and sodar), refer to IEC 61400-50-2 [1]¹. Although the wind measurements defined in this document relate mainly to the measurement of wind speed, an example of a procedure defining the calibration of wind direction sensors is provided in Annex A.

6 Classification of cup and sonic anemometry

6.1 General

Cup and sonic anemometers are wind measurement instruments that can be used in a wide range of wind energy related measurements. In order to transfer traceability they shall be calibrated in a wind tunnel in accordance with Clause 8. Wind tunnel calibrations are performed under controlled environmental conditions with a smooth and low turbulent flow. However, during measurements and operation in the field, these instruments are subject to turbulent flow and environmental conditions that can deviate significantly from wind tunnel calibration conditions. The field conditions can significantly influence the instrument characteristics and cause the instrument output to deviate from wind tunnel calibrations. If the ranges of the influence parameters during field operation are determined, then the systematic deviations can be analysed and the deviations in instrument output can be put into a classification scheme.

Known influence parameters on cup anemometer measurements are turbulence, air temperature, air density, and average upflow angle. Known influence parameters on sonic anemometer measurements are wind direction, upflow angle, and air temperature. These influence parameters shall be considered in the classification. Other environmental parameters can influence the instruments. If such influence parameters are known to give systematic deviations, the influence shall be analysed and included in the classification scheme. Furthermore, the combined effect of all influence parameters shall be assessed. The systematic deviations due to influence parameters shall be analysed in accordance with the procedures described in Clause 7 resulting in a classification specification of the type of anemometer. At least five samples of the anemometer type shall be assessed. Modification of an anemometer type that can influence the output requires a new assessment. Change in geometry of the anemometer type, measurement principle, software algorithm for calculation of the output, software settings, or supporting structure geometry, requires a new assessment.

The classification method only considers normal operation of the sensors. The method does not consider, for example, wear, malfunctioning or icing.

¹ Numbers in square brackets refer to the Bibliography.

6.2 Classification classes

The classification of an anemometer type is divided into five classes dependent on the purpose. Classes A, B, C and D are based on predefined terrain and climate ranges, see Table 1. Classes A and C shall be used for terrain that meets the requirements in IEC 61400-12-5 and in type A terrain in IEC 61400-12-3. Classes B and D shall be used for terrain that does not meet the requirements in IEC 61400-12-5. Classes B and D could be used in terrain type B in IEC 61400-12-3. If information about the influence parameter ranges during the measurements are available then class S may be used.

Class S is a special class, where the influence parameter ranges may be defined by the user, see Table 1. This can be for a special climate, for example cold climate conditions. Class S can also be used for uncertainty estimate for a measurement campaign where the influence parameter ranges are determined during the measurements. Class S may be used for measurements in type A, B and C terrain, see IEC 61400-12-3. The classification number k shall be used in determination of the wind speed operational characteristics uncertainty, as listed in 11.3.4. IEC 61400-12-5 provides an assessment of the terrain to evaluate if the flow distortion due to the terrain will be significant. For classification of cup and sonic anemometers, this terrain assessment supports the definition of the classification classes A, B, C and D.

Class A: Associated with terrain that meets the requirements of IEC 61400-12-5 and with general influence parameter ranges for this type of terrain.

Class B: Associated with terrain that does not meet the requirements of IEC 61400-12-5 and with general influence parameter ranges for this type of terrain.

Class C: Same as class A but with temperatures down to $-20\text{ }^{\circ}\text{C}$.

Class D: Same as class B but with temperatures down to $-20\text{ }^{\circ}\text{C}$.

For terrain or climate that deviates from classes A to D, a class S climate may be specified.

Class S: Associated with conditions that deviate from class A, B, C or D. In this class, the user defines the influence parameter ranges. This may be due to special or user defined terrain or climate conditions.

6.3 Influence parameter ranges

The minimum required influence parameter ranges of cup and sonic anemometer classification are listed in Table 1.

6.4 Classification of cup and sonic anemometers

The classification of an anemometer is specified by the amount of systematic deviations from calibrated values (calibration in accordance with Clause 8) where the systematic deviations are determined for values varying within the influence parameter ranges. For a sonic anemometer and for directional sensitive cup anemometers, a reference direction that is used for calibrations in accordance with Clause 8 shall be defined for the instrument type. The systematic deviations shall be derived for all values that are relevant for the class determination between minimum and maximum values for each parameter. The class number k_n of an anemometer sample number n shall be determined as the maximum systematic deviation from the wind tunnel calibration value, weighted with a wind speed function ε_i :

$$k_n = 100 \cdot \max |\varepsilon_i / w_i| \quad (2)$$

where

k_n is the class number of anemometer sample number n ($n = 1, \dots, 5$ or more);

w_i is a weighting function in m/s that defines the deviation envelope, see Equation (3);

ε_i is the deviation in m/s for influence parameter combination i .

NOTE A class number of 1 corresponds to 1 % at 10 m/s but more than 1 % below 10 m/s and less than 1 % above 10 m/s.

The weighting function w_i averages the influence of absolute and relative deviations:

$$w_i = 5 \text{ m/s} + 0,5 \cdot U_i \quad (3)$$

where

U_i is the wind speed in m/s for influence parameter combination i .

Table 1 – Influence parameter ranges (10 min averages) of classes A, B, C, D and S

Parameter	Class A Terrain meets requirements in IEC 61400-12-5 Range	Class B Terrain does not meet requirements in IEC 61400-12-5 Range	Class C Terrain meets requirements in IEC 61400-12-5 Range	Class D Terrain does not meet requirements in IEC 61400-12-5 Range	Class S ^a Special class with user defined ranges Range
Wind speed, V (m/s)	4 to 16	4 to 16	4 to 16	4 to 16	4 to 16
Turbulence intensity	0,03 to (0,12 + 0,48/ V)	0,03 to (0,12 + 0,96/ V)	0,03 to (0,12 + 0,48/ V)	0,03 to (0,12 + 0,96/ V)	User defined
Turbulence ^b structure $\sigma_u/\sigma_v/\sigma_w$	1/0,8/0,5 ^c	1/0,8/0,5 ^c	1/0,8/0,5 ^c	1/0,8/0,5 ^c	User defined or 1/0,8/0,5 ^c
Air temperature (°C)	0 to 40	–10 to 40	–20 to 40	–20 to 40	User defined
Air density (kg/m ³)	0,9 to 1,35	0,9 to 1,35	0,9 to 1,35	0,9 to 1,35	User defined
Average upflow angle (°)	–3 to 3	–15 to 15	–3 to 3	–15 to 15	User defined
Wind direction ^d (°)	Cups and sonics: 0 to 360°	Cups and sonics: 0 to 360°	Cups and sonics: 0 to 360°	Cups and sonics: 0 to 360°	Cups: 0 to 360° Sonics: user defined

^a The influence parameter ranges determined during a specific measurement campaign include some parameters that are measured as part of the measurement: wind speed, turbulence, air temperature, air density. The upflow angle can be determined by mounting a bi-vane or three-dimensional sonic anemometer on the meteorology mast.

^b For generation of artificial wind, see for example 7.4.

^c A non-isotropic Kaimal turbulence spectrum with turbulence length scale 350 m.

^d If a cup anemometer is directionally sensitive (should be investigated on at least one sample), then directivity shall be included in the classification. For sonic anemometers directivity shall always be included in the classification, but for class S the wind direction range may be defined by the user.

For the five anemometer samples being tested for classification, the class is determined by the average of the k values plus half the range divided by $\sqrt{3}$ assuming a rectangular distribution (see Equation (4)).

$$k = \frac{1}{5} \sum_{n=1}^5 k_n + \frac{k_{\max} - k_{\min}}{2} \cdot \frac{1}{\sqrt{3}} \quad (4)$$

A classification, referring to a certain class, is expressed by kA , kB or kS , for example 1,7A or 2,5S. The operational characteristics standard uncertainty (see 11.3.4) of a cup or sonic anemometer can be derived from the classification assuming a rectangular uncertainty distribution, in which case the standard uncertainty to be used in the wind speed uncertainty assessment is:

$$u_{v2,j} = (0,05 \text{ m/s} + 0,005 \cdot U_j) \cdot k / \sqrt{3} \quad (5)$$

An example of a classification is described in Clause 7.

6.5 Reporting format

Reporting of the classification of the wind speed sensor shall specify all relevant details of the sensor, including all settings. Documentation of the class of a sonic anemometer shall specify the programmed configuration for which the classification is valid.

Relevant documentation shall be provided with detailed information on the procedures followed, the measurements performed as background for the classification, and documentation of the facilities and instruments used.

7 Assessment of cup and sonic anemometry

7.1 General

Assessment of anemometry for classification shall be derived from traceable wind tunnel tests, other laboratory tests and associated modelling of anemometer characteristics. A thorough assessment method should also include verification field tests.

An assessment of a type of cup or sonic anemometer shall include verified procedures to determine the influence of the following basic characteristics (also note Table 1):

- a) tilt angular response characteristics;
- b) yaw angular response characteristics;
- c) temperature induced effects on the anemometer performance.

Additionally, for cup anemometers the following characteristics shall be assessed:

- d) dynamic effects due to rotor torque characteristics.

Subclause 7.2 describes procedures for measuring anemometer characteristics. Subclause 7.3 describes a method for classification of cup anemometers with an example and 7.4 describes a method for classification of sonic anemometers. An actual assessment shall be based on the methodologies in 7.3 and 7.4, but could also be based on other assessment methods, as long as they include verified procedures to incorporate the influence of the parameters in Table 1. Subclause 7.5 presents a method for field comparison of anemometers.

7.2 Measurements of anemometer characteristics

7.2.1 Measurements in a wind tunnel for tilt angular response characteristics of cup anemometers

The tilt angular response is the measured wind speed at inclined flow angles relative to the measured wind speed at non-inclined flow. The tilt angular response of a cup anemometer shall be measured in a wind tunnel that fulfils the requirements described in Clause 8. Additionally, it shall be documented that the wind tunnel is sufficient in height for obtaining accurate tilt response characteristics.

The behaviour of an anemometer is strongly influenced by the free space around and especially underneath and above the anemometer. It is important that the tilting mechanism is designed in such a way that the centre of the sensing part of the anemometer is fixed but free to rotate, and the bottom plate of the wind tunnel shall be closed in order to prevent adverse flow effects. Therefore, no translatory motion can be performed by the rotor, instead only an inclination of the rotor plane is realized.

The tilt angle response may be measured with two alternative methods, one using a sweep and the other using fixed positions.

The determination of the anemometer's response to quasi-statically inclined flow should be performed with the help of an automatic tilt angle device installed in the wind tunnel. During the measurements, the anemometer is slowly tilted back and forth with a very slow sweep rate (less than $0,05^\circ/\text{s}$) so the influence on the results due to the angular speed can be neglected. Sweeps may only be used if the wind speed in the wind tunnel is kept within 0,5 % of the nominal wind speed for all tilt angles.

At non-inclined flow the tilt angle shall be fixed and measurements shall be performed for 300 seconds to ensure that sufficient data is collected for the zero bin ($\pm 0,5^\circ$). This zero bin data is used for normalization of the tilt angular response.

Recording of tilt angle, wind tunnel wind speed and anemometer output shall be made simultaneously and averaged. It can be meaningful to incorporate a finer resolution of the bin-averaging algorithm to account for higher gradients in the tilt angle response around zero degrees.

The tilt angular response should alternatively be determined by stepwise fixed position measurements, where the response at each angle is determined by Clause 8 wind tunnel calibration at selected nominal wind speeds in the wind speed range.

Measurement matrix recommendations:

- a) definition of flow angle: positive for upwards flow on cup rotor;
- b) tilt angle range and steps: at least -30° to $+30^\circ$ (for example $\pm 0^\circ$, $\pm 1^\circ$, $\pm 2^\circ$, $\pm 3^\circ$, $\pm 4^\circ$, $\pm 6^\circ$, $\pm 8^\circ$, ..., $\pm 30^\circ$);
- c) wind speed range and steps: 4 m/s to 16 m/s (for example 4 m/s, 8 m/s, 12 m/s and 16 m/s);
- d) bin averaging range for the sweep method: bin width max. 2° .

An example of tilt angular response (including the "ideal" cosine shape) is shown in Figure 1.

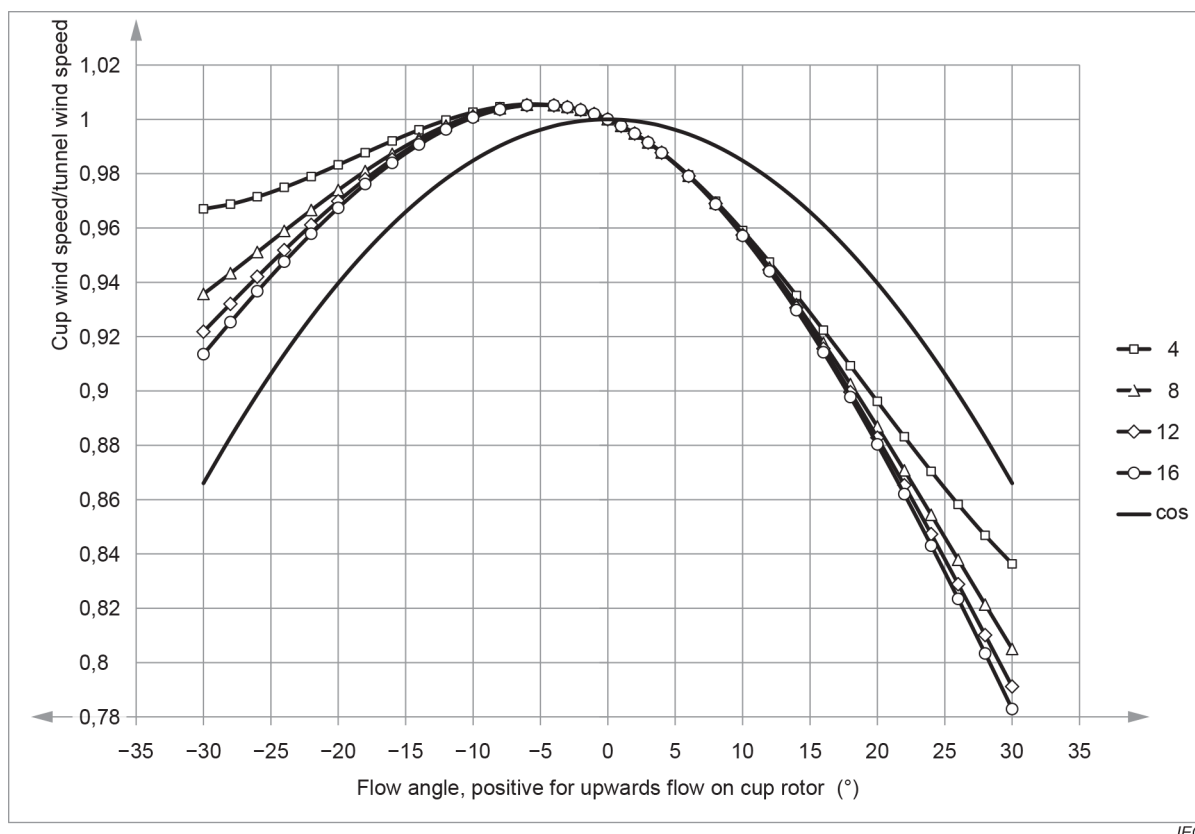


Figure 1 – Tilt angular response $V_\alpha/V_{\alpha=0}$ of a cup anemometer as a function of flow angle α compared to cosine response

7.2.2 Wind tunnel measurements of directional characteristics of cup anemometers

The design of certain cup anemometers (asymmetric housing shape, asymmetric cable entries, etc.) can have an adverse effect on the anemometer wind speed signal with respect to the horizontal flow direction and the reference direction used for calibration (yaw sensitivity). This effect is not desired since it usually cannot be corrected for. It can contribute substantially to the total uncertainty in the wind speed measurement. Yaw sensitivity measurements shall be conducted at wind speeds of 4 m/s, 8 m/s, 12 m/s, and 16 m/s.

7.2.3 Wind tunnel measurements of cup anemometer rotor torque characteristics

The dynamic response of a cup anemometer to wind is governed by Equation (6), where I is the mass moment of inertia, ω is the angular velocity, t is time, Q_A is the aerodynamic rotor torque and Q_F is the torque due to friction (mainly in bearings).

$$I \frac{d\omega}{dt} = Q_A - Q_F \quad (6)$$

The net torque, $Q_A - Q_F$, on the cup anemometer rotor, and thus the rotor torque characteristics, can be measured in a wind tunnel.

The aerodynamic torque can be measured by forcing the rotor to turn at off-equilibrium specific angular speeds while measuring the torque with a torque sensor.

The aerodynamic rotor torque on the cup anemometer is equal to the reaction torque on the shaft, measured with the torque sensor, minus friction torque. Measurements close to the equilibrium angular speed should be very accurate and detailed. An example of a torque measurement, where the wind tunnel speed was kept constant at 8 m/s and the rotational speed of the rotor was varied, is shown in Figure 2.

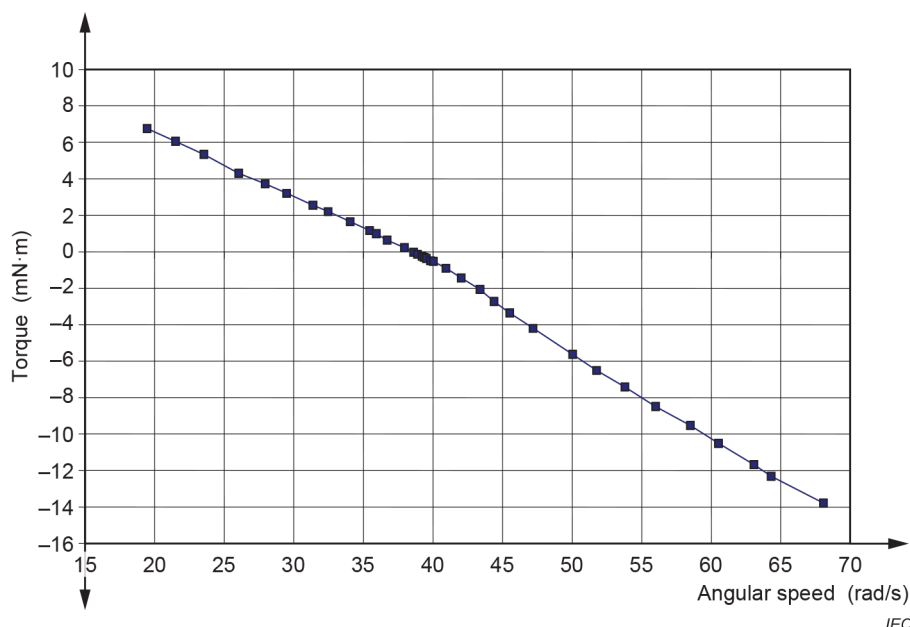


Figure 2 – Wind tunnel torque measurements $Q_A - Q_F$ as a function of angular speed ω of a cup anemometer rotor at 8 m/s

7.2.4 Wind tunnel measurements of step responses of cup anemometers

The rotor torque characteristics may alternatively be measured with a step response method in a wind tunnel. This method is less precise than the method in 7.2.3 because linear torque characteristics on either side of the equilibrium speed ratio (torque coefficient equal to zero, see 7.3.2) shall be assumed.

A step response is a method where a cup anemometer, in a wind tunnel of constant flow speed, is forced to an off-equilibrium rotational speed, above or below the equilibrium wind speed, where the recovery to equilibrium angular speed is monitored. The recovery region close to equilibrium is the important part of the recovery. It is recommended to use the data from the recovery region between 50 % and 98 % of the equilibrium rotor speed during the acceleration tests, and between 150 % and 102 % during the deceleration tests when fitting the torque coefficient lines.

The method to force the anemometer to operate off-equilibrium can be made by attaching a thin shaft to the top of the cup anemometer rotor, and extending it through a hole in the tunnel wall to a motor. The rotational speed is controlled by the motor, which is mechanically disengaged from the rotor when the measurement of the acceleration or deceleration is to start.

Alternatively, the off-equilibrium state can be achieved by applying one or more jets of compressed air to the one or the other side of the cup anemometer rotor. However, the upstream wind in the tunnel shall not be disturbed.

The off-equilibrium starting states should be well outside the rotational range for the analysis (50 % to 150 % of equilibrium rotor speed) to ensure the excitation device is not influencing the data used for fitting.

In case the torque characteristics can be expressed by a linear relationship on either side of torque equilibrium (torque equal to zero) then the step response can be expressed with Equation (7):

$$u(t) = u_t - \Delta u \cdot \exp\left(\frac{t-t_0}{\tau}\right) \quad (7)$$

where

- $u(t)$ is the measured wind speed by the cup anemometer at time t using the ordinary calibration function;
- u_t is the tunnel wind speed;
- Δu is the difference between wind tunnel wind speed and the indicated wind speed of the cup anemometer, at the beginning of the step response measurement, at time t_0 ;
- t is the time;
- τ is the time constant to be determined for the step response (τ_{low} for step response from below and τ_{high} for step response from above).

In fitting the data to the two unknown constants τ and t_0 , it is useful to reformulate equation and to use linear regression to determine the time constant τ :

$$\ln\left(\frac{u_t - u(t)}{\Delta u}\right) = \frac{t - t_0}{\tau} \quad (8)$$

An example of using the step response method results to determine the linear torque from the time constants is further described in 7.3.2.

7.2.5 Measurement of temperature induced effects on anemometer performance

7.2.5.1 General

Temperature induced effects influencing the anemometer performance shall be assessed.

7.2.5.2 Measurement of friction torque in a cup anemometer

The temperature dependent effects due to bearing friction shall be assessed by a flywheel test in a climate chamber [2].

Friction torque measurements shall be made by replacing the cup anemometer rotor with a flywheel, and by measuring the deceleration from a rotational speed corresponding to 20 m/s. There are two torques acting on the rotor: friction torque in the bearings and air friction torque on the flywheel (which shall be subtracted from the measured torque). There can be friction torque due to other causes than bearing friction, for example friction due to signal generation. Such torque shall be included in the friction torque measurements. The tests shall be performed at temperatures from -20 °C to $+40\text{ °C}$ at least with a 5 °C graduation. For each temperature, the friction can be expressed with a second order polynomial with three constants F_0 , F_1 and F_2 .

$$Q_F = F_0 + F_1\omega + F_2\omega^2 \quad (9)$$

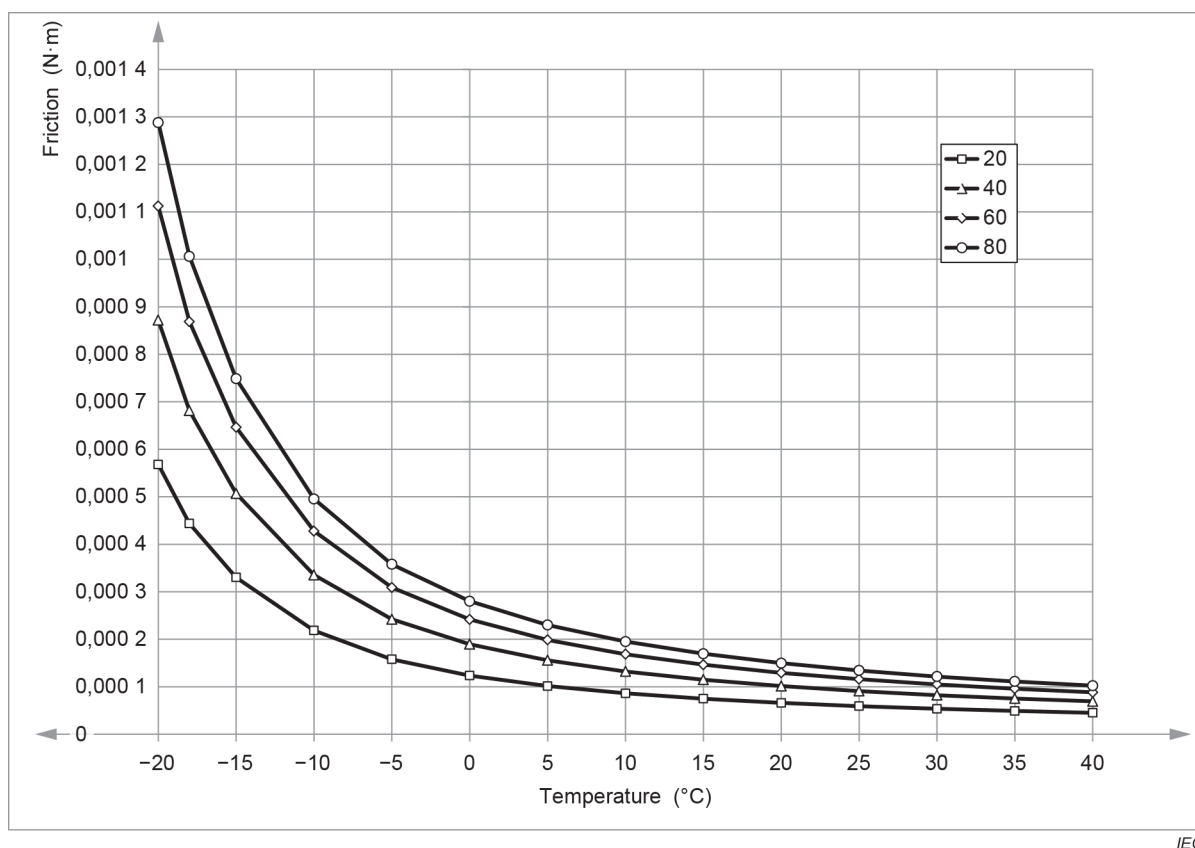


Figure 3 – Example of bearing friction torque Q_F as function of temperature for a range of angular speeds ω

7.2.5.3 Wind tunnel tests at different temperature and wind speeds

Influence of temperature effects on a whole anemometer (cup anemometers as well as sonic anemometers) can be verified with climate wind tunnel tests. The tests shall be performed at temperatures according to Table 1 from -20 °C to $+40\text{ °C}$ at a 5 °C graduation. The tests shall be conducted at 4 m/s , 8 m/s , 12 m/s and 16 m/s . The wind speed deviations from the standard calibration of the anemometer can then be determined. The findings of the wind tunnel tests shall not be biased by undesired effects (e.g. the accretion of rime upon the anemometer rotor). The results should be compared to simulated values calculated with the cup anemometer model in 7.3.2.

7.2.6 Wind tunnel measurements of directional characteristics of sonic anemometers

The directional influence on the output of sonic anemometers shall be measured in a wind tunnel that fulfils the requirements described in Clause 8.

The determination of the anemometer's response to quasi statically inclined and/or yawed air flow shall be performed with the help of an automatic tilt and yaw angle device installed in the wind tunnel. During the measurements, the anemometer is positioned in a fixed tilt angle. The yaw direction can be specified for fixed yaw positions with measurements for 30 s averages, or it can be yawed continuously with a sweep rate of about $1^\circ/\text{s}$.

NOTE The use of fixed yaw directions improves measurement accuracy while the use of a slow sweep rate method is an advantage to reveal the detailed changes that can occur.

The yawing shall be performed for the pre-defined measurement sector of the sonic anemometer. The tilt angle of the sonic anemometer shall be fixed for the following tilt angles: 0° , $\pm 2^\circ$, $\pm 5^\circ$, $\pm 10^\circ$, $\pm 15^\circ$, $\pm 20^\circ$, $\pm 30^\circ$. Tilt angles should be added or omitted if there is clear evidence that they are needed or unneeded. The measurements shall be performed for the wind speeds: 4 m/s, 8 m/s, 12 m/s, and 16 m/s. For each direction the deviation of the indicated wind speed of the sonic anemometer from the ordinary calibration at the reference direction shall be derived.

7.3 A cup anemometer classification method based on wind tunnel and laboratory tests and cup anemometer modelling

7.3.1 Method

The classification method shall use an appropriate cup anemometer model to determine deviations due to influence parameters according to Table 1. The cup anemometer model shall be verified to be able to include all the influence parameters properly. The method shall be based on the wind tunnel and laboratory measurements described in 7.2. Furthermore, the method shall use an artificial wind generator in order to generate three-dimensional time domain input wind data for the cup anemometer model. The deviations ε_i shall be determined from the differences between the 10 min horizontal wind speed input averages from the artificial wind generator and the 10 min cup anemometer model response averages.

7.3.2 Example of a cup anemometer model

7.3.2.1 General

The example cup anemometer model is a physical model that simulates cup anemometer response in time domain, see references [2] and [3]. Some physical properties of the cup anemometer shall be measured and used throughout the assessment. These are: rotor inertia I , frontal area of one cup A and radius R from shaft centre to the centre of the cups.

The response of the cup anemometer to the three-dimensional wind shall be derived from a torque equilibrium differential equation, where the torque on the rotor consists of aerodynamic torque minus friction torque (right hand side of equation), see Equation (6).

From the differential equation the angular speed of the cup anemometer ω is found, and using the wind tunnel calibration values, the response from the resulting aerodynamic torque and friction torques due to wind variations is determined. The aerodynamic torque Q_A is a function of the instantaneous wind vector $\vec{U} = \{u, v, w\}$ as determined by the artificial wind generator. From the wind vector, the upflow angle and the scalar of the wind vector are determined:

$$\alpha = \arctan\left(\frac{w}{\sqrt{u^2 + v^2}}\right) \quad (10)$$

$$|\vec{U}| = \sqrt{u^2 + v^2 + w^2} \quad (11)$$

An equivalent horizontal wind speed is found by multiplying the scalar of the wind vector with the angular response measured in wind tunnel for the instantaneous upflow angle:

$$U_{eq} = F_\alpha(\alpha, |\vec{U}|) \cdot |\vec{U}| \quad (12)$$

Here $F_\alpha(\alpha, |\vec{U}|)$ is the tilt angular response of the cup anemometer as shown in Figure 1.

The aerodynamic torque can be expressed by a generalized torque curve which has been verified to be valid for all wind speeds and all rotational speeds [2]:

$$Q_A = \frac{1}{2} \rho A R U_{eq}^2 C_{QA}(\lambda) \quad (13)$$

where

- ρ is the air density;
- A is the cup area of one cup;
- R is the radius to a cup;
- U_{eq} is the equivalent horizontal wind speed;
- C_{QA} is the generalized aerodynamic rotor torque coefficient.

The generalized aerodynamic rotor torque coefficient is derived from the wind tunnel torque measurements in 7.2.3 or 7.2.4, where U_{eq} in this case is substituted by the tunnel wind speed:

$$C_{QA} = C_{QA}(\lambda) = \frac{Q_Q}{\frac{1}{2} \rho A R U_{eq}^2} \quad (14)$$

The generalized aerodynamic rotor torque coefficient is a function of the speed ratio:

$$\lambda = \frac{\omega R}{U_{eq} - U_t} \quad (15)$$

where

U_t is a threshold wind speed (derived as the remaining calibration offset when the friction influence has been subtracted; if friction is zero the threshold wind speed is equal to the calibration offset).

In case the rotor torque coefficient can be characterized by two linear curves on either side of the torque equilibrium then two corresponding time constants can be determined by wind tunnel step response measurements, see 7.2.4 and [4]. The linear torque characteristics can then be determined from the τ values, for low- and high-speed ratios, from Equation (16):

$$\kappa = -\frac{2I(u_0 + \Delta u - U_t)}{\rho A R^2 (u_0 + \Delta u)^2 \tau} \quad (16)$$

The generalized aerodynamic rotor torque coefficient can then be expressed by:

$$\text{for } \lambda \leq \lambda_0 : C_{QA} = \kappa_{low}(\lambda - \lambda_0) \text{ and for } \lambda > \lambda_0 : C_{QA} = \kappa_{high}(\lambda - \lambda_0) \quad (17)$$

where

λ_0 is the speed ratio for $C_{QA} = 0$.

An example of the rotor torque coefficient is shown in Figure 4.

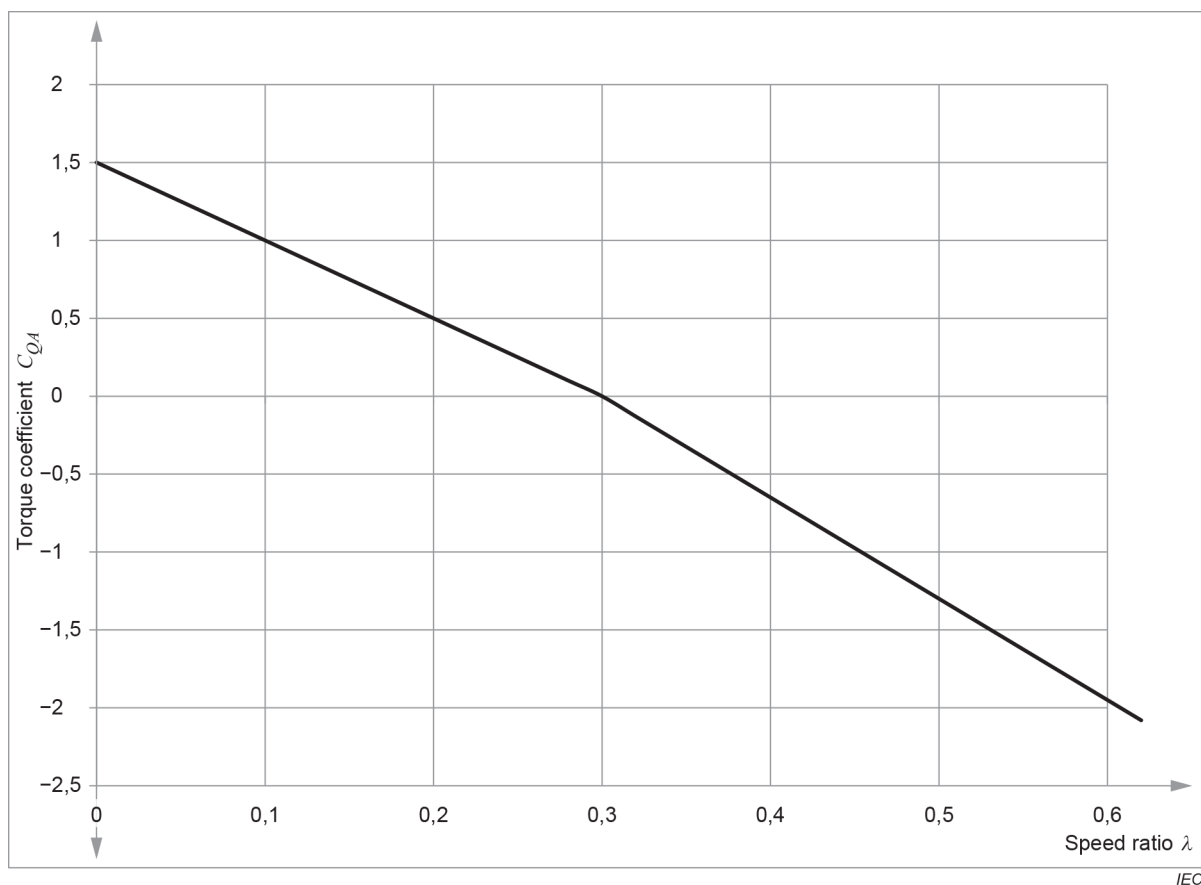


Figure 4 – Example of rotor torque coefficient C_{QA} as a function of speed ratio λ derived from step responses with κ_{low} equal to $-5,5$ and κ_{high} equal to $-6,5$

The friction torque is a function of the temperature and the rotational speed as found from the friction measurements in 7.2.5.2:

$$Q_F = Q_F(T, \omega) \quad (18)$$

7.3.2.2 Influence parameter range variations and example class determination

The influence parameter ranges shall be varied by using a turbulence model that generates artificial three-dimensional 10 min time series wind speeds with a sample speed of at least 10 Hz. Exposing the cup anemometer model to such artificial winds, the responses of the cup anemometer are derived and the deviations from the horizontal wind speed of the artificial winds are found. The deviations for all combinations of the influence parameter ranges can be derived by a Monte Carlo process. The deviations determine the class as expressed in Equation (2). An example of classification of a cup anemometer is shown in Figure 5 and with the characteristics shown in Figure 3 and Figure 4 and with the data presented in Table 2 and Table 3. Other data related to the classification are shown in Table 4.

Deviations for classes A, B, C and D of all influence parameters are shown in Figure 5 and Figure 6. The resulting classes are 1,69A, 6,56B, 8,01C and 9,94D.

Table 2 – Tilt angle response of example cup anemometer

Wind speed, V (m/s)	4	8	12	16
Angle, α (deg)	$V_{\alpha}/V_{\alpha=0}$	$V_{\alpha}/V_{\alpha=0}$	$V_{\alpha}/V_{\alpha=0}$	$V_{\alpha}/V_{\alpha=0}$
–30	0,967 005	0,935 689	0,921 815	0,913 545
–28	0,968 769	0,943 307	0,932 028	0,925 304
–26	0,971 484	0,951 098	0,942 067	0,936 683
–24	0,974 941	0,958 908	0,951 805	0,947 569
–22	0,978 933	0,966 583	0,961 111	0,957 850
–20	0,983 253	0,973 974	0,969 863	0,967 413
–18	0,987 695	0,980 930	0,977 934	0,976 148
–16	0,992 055	0,987 304	0,985 199	0,983 945
–14	0,996 131	0,992 948	0,991 538	0,990 698
–12	0,999 722	0,997 717	0,996 829	0,996 301
–10	1,002 628	1,001 468	1,000 954	1,000 648
–8	1,004 651	1,004 057	1,003 793	1,003 637
–6	1,005 594	1,005 344	1,005 233	1,005 166
–4	1,005 262	1,005 188	1,005 155	1,005 136
–3	1,004 558	1,004 526	1,004 513	1,004 505
–2	1,003 462	1,003 452	1,003 448	1,003 446
–1	1,001 951	1,001 950	1,001 949	1,001 949
0	1,000 000	1,000 000	1,000 000	1,000 000
1	0,997 595	0,997 594	0,997 593	0,997 593
2	0,994 750	0,994 740	0,994 736	0,994 734
3	0,991 490	0,991 458	0,991 445	0,991 437
4	0,987 838	0,987 764	0,987 731	0,987 712
6	0,979 458	0,979 208	0,979 097	0,979 030
8	0,969 803	0,969 209	0,968 945	0,968 789
10	0,959 068	0,957 908	0,957 394	0,957 088
12	0,947 450	0,945 445	0,944 557	0,944 029
14	0,935 147	0,931 964	0,930 554	0,929 714
16	0,922 359	0,917 608	0,915 503	0,914 249
18	0,909 287	0,902 522	0,899 526	0,897 740
20	0,896 133	0,886 854	0,882 743	0,880 293
22	0,883 101	0,870 751	0,865 279	0,862 018
24	0,870 397	0,854 364	0,847 261	0,843 025
26	0,858 228	0,837 842	0,828 811	0,823 427
28	0,846 801	0,821 339	0,810 060	0,803 336
30	0,836 325	0,805 009	0,791 135	0,782 865

Table 3 – Friction coefficients of example cup anemometer

Temperature (°C)	F_0 (N·m)	F_1 (N·m·s)	F_2 (N·m·s ²)
–20	2,000E-04	2,000E-05	–8,000E-08
–18	1,563E-04	1,563E-05	–5,714E-08
–15	1,163E-04	1,163E-05	–4,000E-08
–10	7,692E-05	7,692E-06	–3,077E-08
–5	5,556E-05	5,556E-06	–2,222E-08
0	4,348E-05	4,348E-06	–1,739E-08
5	3,571E-05	3,571E-06	–1,429E-08
10	3,030E-05	3,030E-06	–1,212E-08
15	2,632E-05	2,632E-06	–1,053E-08
20	2,326E-05	2,326E-06	–9,302E-09
25	2,083E-05	2,083E-06	–8,333E-09
30	1,887E-05	1,887E-06	–7,547E-09
35	1,724E-05	1,724E-06	–6,897E-09
40	1,587E-05	1,587E-06	–6,349E-09

Table 4 – Miscellaneous data related to classification of example cup anemometer

Classification list	Value
Cup diameter	75 mm
Cup area A	0,004 417 87 m ²
Radius to cup centre R	65 mm
Rotor inertia I	0,000 2 kg·m ²
Equilibrium speed ratio λ_0	0,3
Calibration temperature	20 °C
Calibration barometric pressure	101 3 hPa
Calibration air density ρ	1,203 821 kg/m ³
Calibration turbulence intensity	0,003
Calibration turbulence structure	Isotropic $\sigma_u/\sigma_v/\sigma_w = 1/1/1$
Calibration coefficients A and B	0,679 55 and 0,258 70
Calibration friction coefficients F_0 , F_1 and F_2 at 20 °C	see Table 3 for 20 °C
Torque coefficient slopes κ_{low} and κ_{high}	–5,0 and –6,5

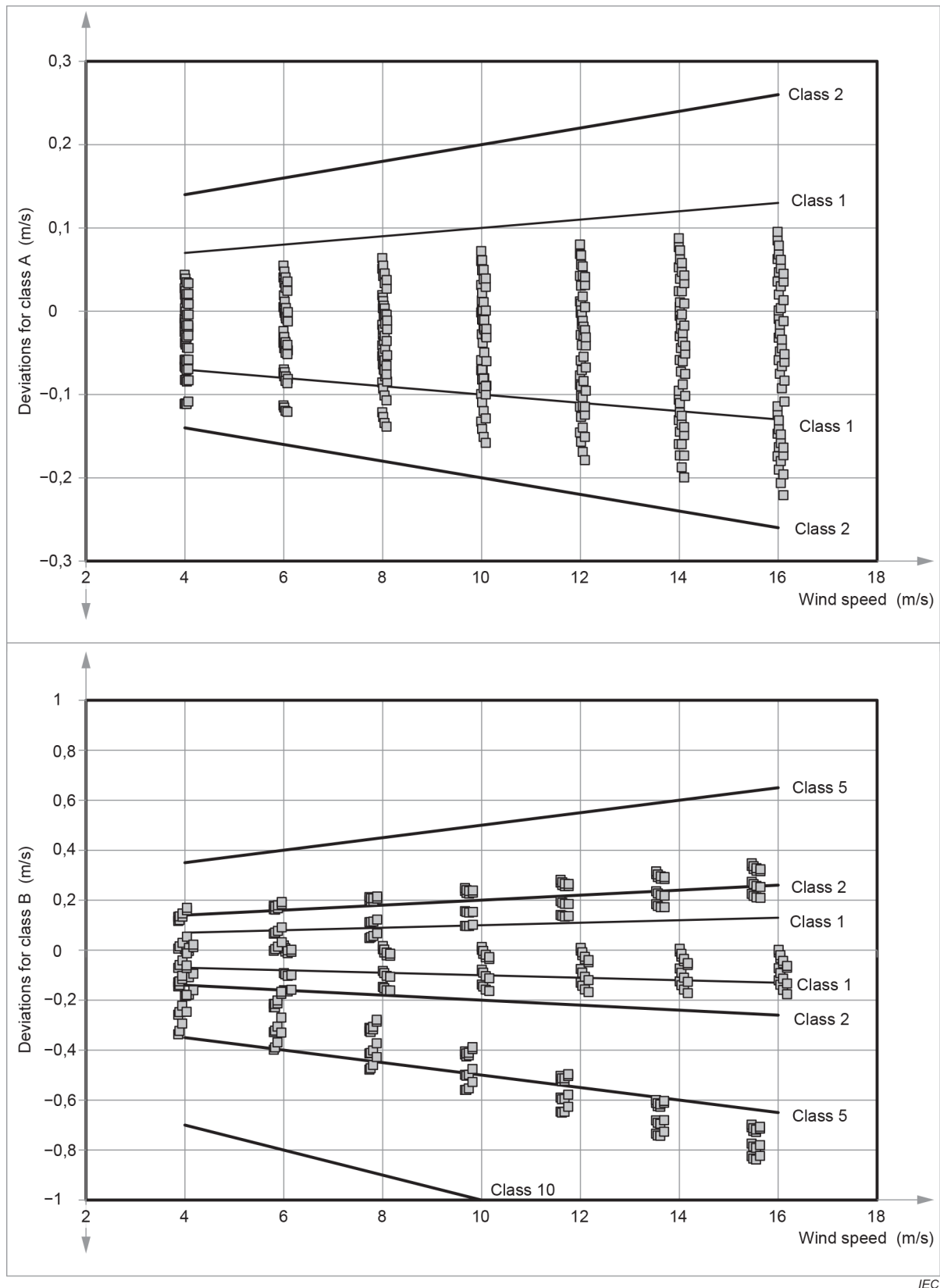


Figure 5 – Classification deviations of example cup anemometer showing a class 1,69A (upper) and a class 6,56B (lower)

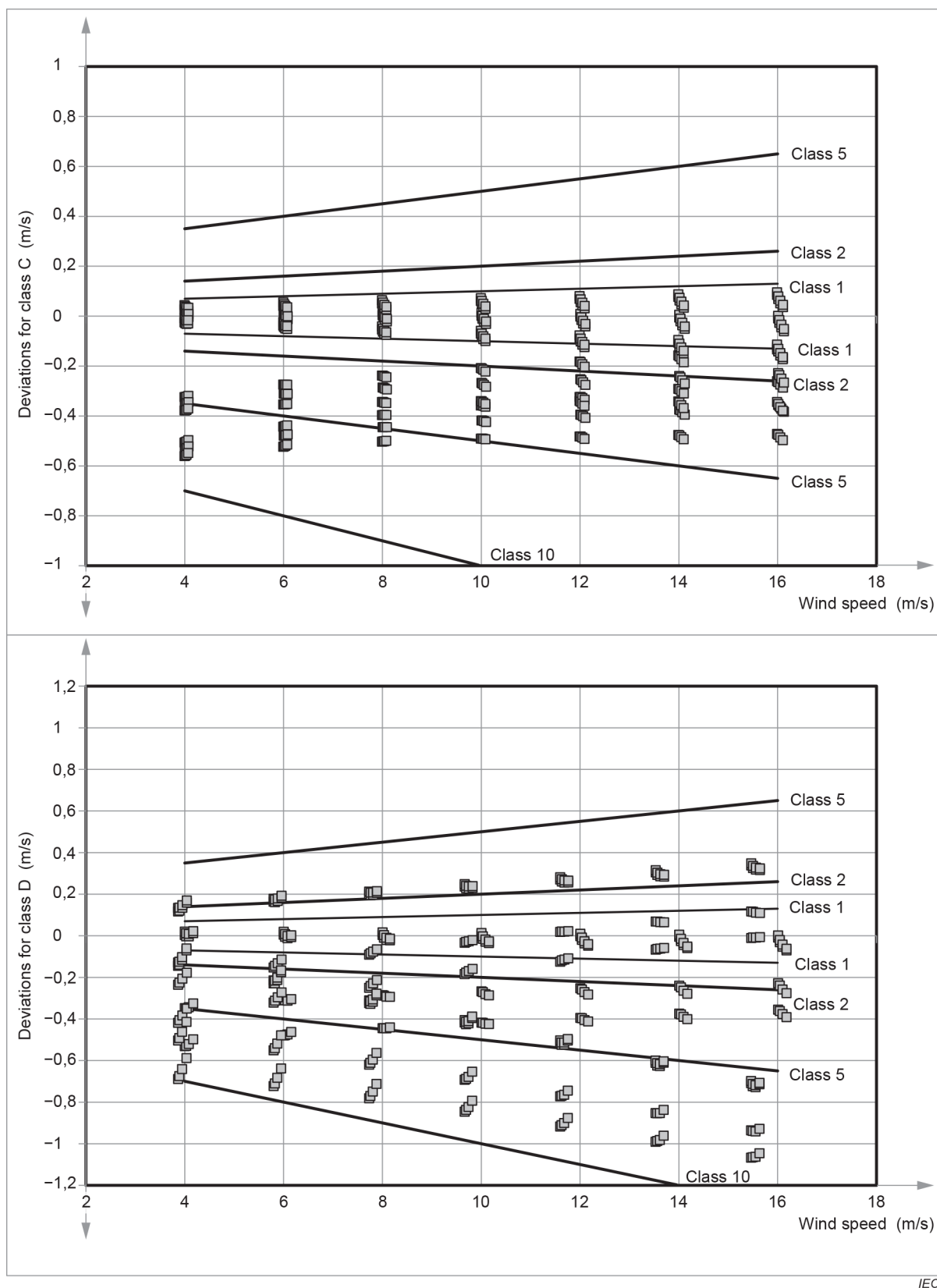


Figure 6 – Classification deviations of example cup anemometer showing a class 8,01C (upper) and a class 9,94D (lower)

7.4 A sonic anemometer classification method based on wind tunnel tests and sonic anemometer modelling

The classification method uses a sonic anemometer model to determine deviations due to influence parameters. The method is based on wind tunnel and laboratory measurements as described in 7.2.6 and 7.2.5.3. Furthermore, the sonic anemometer classification method uses an artificial wind generator similar to the one for the cup anemometer model, see 7.3.2, in order to generate three-dimensional time domain input wind data for the sonic anemometer model.

The response of the sonic anemometer is a function of the instantaneous wind vector $\vec{U} = \{u, v, w\}$ as determined by the artificial wind generator. From the wind vector, the upflow angle and the scalar of the wind vector are determined by Equations (10) and (11). The response is then determined by interpolation in the measured data from the wind tunnel measurements:

$$U_{\text{sonic}} = F_{\alpha,\gamma}(\alpha, \gamma, |\vec{U}|) \cdot |\vec{U}| \quad (19)$$

where

$F_{\alpha,\gamma}(\alpha, \gamma, |\vec{U}|)$ is the tilt and yaw response function for the sonic anemometer.

Deviations are determined from differences between sonic anemometer model responses and artificial wind data averages, see 7.3.2.2. The relevant influence parameters are tilt and yaw angular responses and temperature induced effects.

7.5 Free field comparison measurements

In a free field comparison measurement, two anemometers can be compared. The comparison measurement can be used to verify that the methods being used in classification of the instruments are consistent, see 7.3 and 7.4. The comparison of anemometers requires that both anemometers are calibrated in the same wind tunnel. The setup in the field should be made in accordance with the mounting procedures for two top-mounted anemometers as described in 10.3, using the maximum distance between them. A 3D ultrasonic anemometer (u , v , and w calibrated) shall be mounted on a boom below the two sensors to measure the environmental influence parameter ranges (flow angle, turbulence, turbulence spectrum), for a class S measurement campaign classification analysis. Additionally, air temperature shall be measured on the same boom for determination of the temperature range, and air pressure shall be measured for determination of the air density range. Time traces of the 3D sonic anemometer shall be recorded, while 10 min average measurements in a relatively small sector perpendicular to the boom are acceptable for the two anemometers under comparison. An acceptable database (at least 180 h) shall be collected for a wind speed range of 4 m/s to 16 m/s and a range of turbulence intensities (for instance from 0,04 to 0,14). Comparison of two anemometers should then be made by deriving a class S classification of the two anemometers from laboratory tests, and comparing these with the field measurements.

8 Wind tunnel calibration procedure for anemometers

8.1 General requirements

The general requirements for the calibration of anemometers are summarized as follows.

- a) The calibration of the anemometer shall be carried out in a wind tunnel that is suitable for the calibration of anemometers.

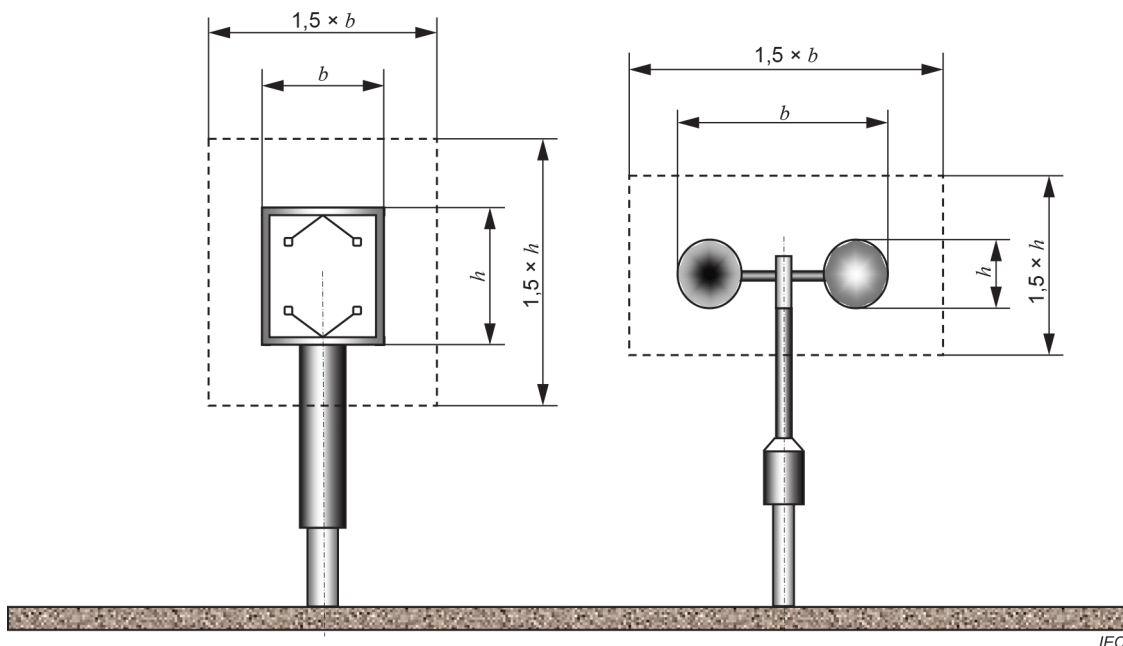
- b) All transducers and measuring equipment relevant for the calibration of anemometers shall have calibrations traceable to international standards. Calibration certificates and reports shall contain all relevant traceability information (e.g. including details of accreditations where available).
- c) The reference wind speed shall be measured with a pitot static tube that shall be of NPL type with ellipsoidal head in accordance with ISO 3966. The pitot-static tube shall be calibrated for appropriate wind speed ranges, and shall be documented. The reference wind speed may alternatively be measured by LDA (laser Doppler anemometry) with well documented uncertainties.
- d) Consistency of the experimental setup shall be verified by at least daily comparative calibrations of the facility's "quality control anemometer".
- e) Flow quality shall be verified as required in 8.2.
- f) The repeatability of the calibration shall be verified as required in 8.2.
- g) Anemometer calibration shall be supported by a thorough assessment of calibration uncertainty, carried out in accordance with ISO/IEC Guide 98-3:2008.

8.2 Requirements for the wind tunnel

The presence of the anemometer shall not substantially affect the flow field in the wind tunnel. During measurements the anemometer will to some extent be influenced by wind tunnel blockage and boundary effects. The blockage area ratio (BR) – defined as the ratio of the anemometer projected area, perpendicular to flow direction, (including its mounting system and projected area of a spinning rotor) to the total test section area – shall not exceed 0,05. Blockage effects shall always be accounted for in accordance with 8.4.3.

It is recommended that the wind tunnel test section has a height of at least 1,0 m and a width of at least 1,0 m.

The flow in the cross-sectional area, where the anemometer will be located, shall be uniform. Flow uniformity should be measured using velocity sensing devices, i.e. pitot tubes, hot wires or laser Doppler velocimetry, to measure flow profiles in longitudinal, transversal and vertical directions. Over the calibration wind speed range, the maximum difference in the mean velocity between any two points inside the measurement volume shall be less than 0,2 %. The mean value shall be calculated during at least five minutes and the measurement volume shall cover the active volume of the anemometer with 50 % margin in all directions as shown in Figure 7. Uniformity shall be tested over a period of at least five minutes for wind speeds of approximately 4 m/s, 8 m/s, 12 m/s and 16 m/s each.



The volume will also extend $1,5 \times b$ in depth (along the flow).

Figure 7 – Definition of volume for flow uniformity test

The stability of the flow shall be measured in the middle of the volume of which uniformity was verified. The flow can be considered stable if ten consecutive 30 second means are within 0,5 % of their average value.

Cup anemometers are very sensitive to horizontal wind gradients. Different horizontal wind gradients can be seen depending on pollution of nets and smoothing devices. Therefore, it is useful to check the horizontal wind gradient by using two identical pitot tubes. They shall be placed at the exact position where the anemometer will be placed with their heads spanning approximately the area covered by the cup anemometer's rotating cups. A set of measurements shall be made and the linear regression between the dynamic pressures measured by the two pitot tubes shall be calculated. The difference in wind speed shall be less than 0,2 % over a period of at least five minutes. The influence due to the presence of the anemometer type to be calibrated (including mounting tube) on the flow speed measured by the pitot tube shall be verified to be less than $\pm 0,2$ %.

The axial turbulence intensity in wind speed at the anemometer's position shall be below 2 %. The turbulence intensity shall include longitudinal wind speed fluctuations with frequencies of up to 10 Hz. The data for turbulence measurements shall be acquired for a duration of 60 s per wind speed at a sampling rate of at least 20 Hz. Turbulence assessment shall be performed for at least the flow speeds 7 m/s, 10 m/s and 13 m/s with a device that is suitable to measure wind speed fluctuations with a cut-off frequency of at least 20 Hz. Deviations from the above requirements shall be assessed through suitable tests and be considered in the uncertainty evaluation.

The wind tunnel calibration factor, which gives the relation between the conditions at the reference measurement position and those at the anemometer position, shall be appraised using pitot tubes for a speed range of 4 m/s to 16 m/s.

The calibration setup shall undergo a detailed examination of the repeatability of anemometer calibrations. The calibration facility shall designate reference anemometers of representative size for use in these tests. The standard deviation and maximum deviation of the quality control anemometer output in the calibration speed range should be less than 0,2 % and 0,6 %, respectively, of the mean value.

8.3 Instrumentation and calibration setup requirements

Dedicated external signal conditioning equipment such as frequency to voltage converters, etc. shall be calibrated in isolation from the anemometer, so allowing the anemometer's calibration to be derived and reported in isolation from the signal conditioning equipment.

The resolution of the data acquisition system shall be at least 0,02 m/s. In the case of an analogue voltage instrument, the signal shall be adequately buffered to prevent its attenuation by low impedance logging equipment.

Mounting arrangements can have dramatic effects on instrument performance, particularly if the ratio of tube diameter to rotor diameter is high. Therefore during calibration the anemometer shall be mounted on top of a tube in order to minimize flow distortion and only one anemometer may be calibrated at a time. This tube shall be of the same diameter as the one on which the anemometer will be mounted in service in the free atmosphere. The vertical distance between the anemometer rotor and the upper and lower boundaries of the wind tunnel test section should not be less than 0,5 m. In case of a directional sensitive anemometer with respect to horizontal flow, a reference orientation shall be defined and documented and referred to during calibration. The anemometer shall be positioned at the test section perpendicular to the flow field of the wind tunnel as accurately as possible. The maximum deviation of the anemometer mounting tube is 0,2°. An example of a typical cup anemometer tilt response is shown in Figure 1.

It is important to ensure that the anemometer is not influenced by the presence of any reference wind speed measurement equipment. Conversely, the presence of the anemometer shall not affect the flow in the region of the reference instrument. If flow distortion effects are encountered, then the pitot tube shall be repositioned. This effect can be assessed by removing and then reinstating the anemometer and afterwards the reference instrument, and ascertaining whether the output of the remaining instrument changes.

The pitot static tubes shall be positioned in the test section aligned with the mean flow direction. The maximum misalignment allowed is 0,5°.

NOTE Misalignment of pitot static tubes can lead to a bias in differential pressure measurement. An alignment to within 0,5° of the mean flow direction assures a bias in differential pressure reading of less than 0,1 % for the NPL type pitot tube (note ISO 3966:2020, Figure A.5).

During calibration, the anemometer output signal shall be examined to ensure that it is not subject to interference or noise.

8.4 Calibration procedure

8.4.1 General procedure for cup and sonic anemometers

This procedure relates to the calibration of the horizontal wind speed measurement from a cup or sonic anemometer. The anemometer shall run in for minimum 5 min at about 10 m/s before the calibration procedure begins. Calibration shall be performed under both rising and falling wind speed in the range of 4 m/s to 16 m/s at a calibration interval of 1 m/s or less. If heating is switched on during calibrations, it shall be noted in the calibration certificate.

NOTE 1 m/s intervals can also be realized with the allowance for 2 m/s jumps, for example 4 m/s, 6 m/s, 8 m/s, 10 m/s, 12 m/s, 14 m/s, 16 m/s, 15 m/s, 13 m/s, 11 m/s, 9 m/s, 7 m/s, 5 m/s.

The sampling frequency shall be at least 1 Hz and the sampling interval at least 30 s. This sampling interval can be increased when low resolution anemometers are calibrated. It is important to ensure that anemometer and reference wind speed readings span the same period of time. Before collecting data at each wind speed, adequate time shall be allowed for stable flow conditions to become established, see 8.2. This can take 1 min, but will vary from facility to facility.

8.4.2 Procedure for the calibration of sonic anemometers

Sonic anemometers are designed to measure 2D or 3D wind components. Where the use case of the wind measurement requires the measurement of horizontal wind speed (e.g. for power performance measurement), sonic anemometers shall be set up for measurement of horizontal wind speed preferably internally or by post processing.

During calibration the complete sonic anemometer shall be placed in the wind tunnel test section. The active part of the sonic anemometer shall be located within the test section volume. The yaw alignment shall be set at the reference calibration yaw direction, see 8.3. It is often advantageous to set a yaw alignment that imposes the least flow disturbance from the supports of the acoustic transceivers.

The setup parameters of the sonic anemometer during its calibration shall be documented in the calibration certificate or alternatively in an annex of the calibration certificate. The calibration holds only for identical settings of the sensor and identical signal output format.

For this test the sonic anemometer shall be calibrated at variable wind speeds in accordance with 8.4.1. Calibrations of additional yaw position (i.e. yaw angle for maximum flow disturbance from the supports) can be performed if desired. Calibrations of additional yaw positions should be performed at 10 m/s as a quality control of compliance with classification results.

Status signal of the sonic anemometer (if available) shall be monitored during the calibrations. The status signal shall be used to exclude erroneous data.

8.4.3 Determination of the wind speed at the anemometer position

Air density ρ shall be calculated on the basis of the mean wind tunnel air temperature T , relative humidity Φ and barometric pressure B , using Equation (20) (standard uncertainty less than 10^{-3} kg/m³):

$$\rho = \frac{1}{T} \left(\frac{B}{R_0} - \Phi P_w \left(\frac{1}{R_0} - \frac{1}{R_w} \right) \right) \quad (20)$$

where

B is the barometric pressure [Pa];

T is the absolute temperature [K];

Φ is the relative humidity (range 0 to 1);

R_0 is the gas constant of dry air [287,05 J/kgK];

R_w is the gas constant of water vapour [461,5 J/kgK];

P_w is the vapour pressure [Pa].

Vapour pressure P_w depends on mean air temperature.

$$P_w = 0,000\,020\,5 \cdot \exp(0,063\,184\,6 \cdot T) \quad (21)$$

The mean flow speed at anemometer position is calculated from mean differential pressure ΔP_{ref} at reference position using Equation (22):

$$\bar{v} = f(k_b, k_i, k_p, \bar{v}_p, \dots) \alpha k_c \frac{1}{n} \sum_{i=1}^n \sqrt{\frac{2\Delta p_{\text{ref},i}}{\rho}} \quad (22)$$

where

α	is the pitot static tube head coefficient;
k_c	is the wind tunnel calibration factor, which gives the relation between the conditions at the reference measurement position and those at the anemometer position;
$f(k_b, k_i, k_p, \bar{v}_p, \dots)$	is a correction function due to interference between the anemometer including its mounting tube and the wind tunnel flow;
k_b	is the interference correction factor due to blockage;
k_i	is the correction factor due to interference between the anemometer (including mounting tube) and test section enclosure, also including flow effects due to mounting tubes extending through the enclosure;
k_p	is the correction factor due to interference caused by the anemometer (including mounting tube) on the velocity measured by the pitot tube;
$\bar{v}$	is the average wind speed at the anemometer position;
$\bar{v}_p$	is the average wind speed at the reference position;
n	is the number of samples within the sampling interval.

The correction function $f(k_b, k_i, k_p, \bar{v}_p, \dots)$ should be equal to one for a test section without an anemometer and its supporting tube. The influence of the correction function on the calibration results shall be assessed and included in the calibration facility setup report and uncertainty calculation.

8.5 Data analysis

A linear regression analysis shall be carried out on the calibration data for the estimation of the following regression parameters: offset, slope, regression coefficient, standard uncertainty. The wind speed values shall be regressed upon the anemometer outputs.

If the correlation coefficient, r , for the data is less than 0,999 95, then it shall be checked if it is due to anemometer non-linearity or to other reasons. In case of anemometer non-linearity, it shall be documented in the certificate.

8.6 Uncertainty analysis

It is important to identify the uncertainty of the horizontal wind speed incident upon the anemometer. An uncertainty analysis shall be carried out in accordance with ISO/IEC Guide 98-3:2008, comprising both category A and category B uncertainty. The magnitude of the net uncertainty shall be assessed statistically and shall take account of:

- flow speed measurement uncertainty (pitot tubes, transducers, air density evaluation, etc.);
- wind tunnel calibration factor;
- wind tunnel correction factors through the correction function $f(k_b, k_i, k_p, \bar{v}_p, \dots)$ defined in Equation (22);
- the influence of wind tunnel cross section size;
- measurement of anemometer output;

- f) the influence of non-vertical anemometer alignment for each anemometer type in the uncertainty assessment;
- g) statistical uncertainty due to short term scatter of the anemometer output (variation of the indicated anemometer signal, i.e. fluctuation of the angular rotor velocity, bias from signal generation, sampling bias, over the averaging time);
- h) uncertainty due to the difference between the result of the wind tunnel performing the calibration and the average result of other wind tunnels as determined through proficiency testing to the extent not covered by other uncertainty components;
- i) uncertainty due to linearization of calibration expression.

8.7 Reporting format

The relevant documentation shall provide information on the procedure followed and the facility used for calibrating the anemometers (report on the calibration facility setup) and on the individual anemometer calibration. The calibration facility setup report shall contain the following information as a minimum:

- a) description of the wind tunnel (including test section, settling chamber, flow straighteners, fan arrangement);
- b) sketch of the wind tunnel showing the positions of anemometer and pitot tube(s) in the test section;
- c) flow quality measurements;
- d) blockage effect assessment;
- e) influence of mounting height of the anemometer;
- f) influence of bottom plate;
- g) influence of mounting position into reference measurement;
- h) influence of the correction function;
- i) turbulence measurements;
- j) instrumentation certificates;
- k) measurement procedure;
- l) data evaluation procedure;
- m) repeatability documentation of the anemometer calibration;
- n) uncertainty analysis;
- o) deviations from these requirements.

The calibration report of an anemometer shall as a minimum contain the following information:

- 1) make, type and serial number of the tested anemometer and cup serial number if transported separately;
- 2) specification of yaw orientation during calibration (yaw sensitive devices);
- 3) tube diameter of the mounting system;
- 4) make, type and serial number of external converters;
- 5) name and address of the customer;
- 6) signatures from the persons who carried out the calibration, checked the results and approved their issue;
- 7) name of the wind tunnel;
- 8) environmental conditions during calibration (air temperature, air pressure and humidity);
- 9) regression parameters (offset, slope, regression coefficient);
- 10) uncertainty due to linearization (scatter of residuals);
- 11) uncertainty due to the correction function $f(k_b, k_i, k_p, \bar{v}_p, \dots)$;

- 12) tabular and graphical presentation (deviations from linear regression line amplified) of all calibration points and regression results;
- 13) uncertainty associated to each measuring point;
- 14) reference to the corresponding calibration facility setup report;
- 15) date of the calibration;
- 16) photo showing the anemometer and the mounting in the wind tunnel.

8.8 Example uncertainty calculation

As it is practically impossible to measure the flow velocity at the place of the anemometer and as the sensor in the wind tunnel experiences a significantly smaller flow field as in the free atmosphere, corrections are necessary. The optimization of the wind tunnel in terms of the corrections as well as the determination of the correction factor is crucial for the calculation of the measurement uncertainty.

Ideally, the uncertainty calculation should be applied independently to each wind speed calibration condition used in a calibration test. For this example, take a notional calibration point of 10 m/s using a wind tunnel rated at 25 m/s.

Table 5 deals with each uncertainty source; first with those of category B.

To avoid repetition, a detailed assessment of barometric pressure measurement has been left out, as it can be dealt with in the same way as temperature measurement.

Table 5 – Example of evaluation of anemometer calibration uncertainty

Error source u_i	Discussion	Value u_i	Sensitivity value c_i	$u_i c_i$ m/s
u_f , wind tunnel correction factor, f	An uncertainty on the correction factor $f(k_b, k_t, k_p, \bar{v}_p, \dots)$ based on investigation of calibration influence factors.			
u_t , wind tunnel calibration factor, k_c	Wind tunnel calibration can be carried out by using two pitot tubes, one at the permanent reference position and one at the location to be occupied by the test anemometer. By swapping the two pitot systems, all category B errors can be eliminated, and standard regression analysis can be applied to yield a correction factor (the intercept being forced through the origin) and a related category A standard uncertainty. Assume the correction has a value of 1,02 and the standard uncertainty is 0,01.	0,01	$C_t = 0,5 \text{ v}/k_c$ $= 0,5 \times 10/1,02$ $= 4,90 \text{ m/s}$	0,049
u_B , blockage correction factor, k_B	If a solid object is positioned in the flow of the wind tunnel, the flow will be affected depending on the relation between object size and wind tunnel area. Conditional on the spatial dimensions of the specimen, a raise in the flow velocity occurs in a closed measurement section because of the continuity. In an open measurement section, the current will be widened, which is equivalent to a speed reduction. Assuming the blockage effect is known, the uncertainty value of 0,1 % is appropriate. The calibration facility setup report shall present the calculations applied and estimated value of the correction factor and the associated uncertainty.	0,001	$C_t = v/k_B$ $= 10 \text{ m/s}/1,001$ $\approx 10 \text{ m/s}$	0,01

Error source u_i	Discussion	Value u_i	Sensitivity value c_i	$u_i c_i$ m/s
u_{k_i} , position correction factor, k_i	An anemometer needs a certain free space (depending on the size of the mounting pipe and the anemometer) below and above it, to experience the same flow conditions as in free atmosphere. Therefore, the centre of the measurement section is not necessarily the best position for the specimen. If the wind tunnel is small and thus the mounting pipe is too short, an error of up to 2 % can occur. Only from a certain length of the mounting pipe, the influence begins to decrease. This free length amounts to approximately 50 cm above the base plate. Assuming the position effect is known, the uncertainty value of 0,1 % can be appropriate.	0,001	$C_p = v/k_p$ $= 10 \text{ m/s}/1,001$ $\approx 10 \text{ m/s}$	0,01
u_p , position correction factor, k_p	The flow around the anemometer exerts some influence on the flow around the reference pitot tube. Assuming the influence effect is known, the uncertainty value of 0,1 % of the effect can be appropriate.	0,001		
u_{FD} , flow correction factor, k_{FD}	Mostly, anemometers are mounted on measurement masts of considerable length – a situation which cannot be reproduced in the wind tunnel. If an anemometer is mounted on a tube stub and if this stub is mounted in a wind tunnel with an open measurement section, the current can escape downward. This means a loss of impetus for the anemometer and thus a systematic error. By installing a base-plate, this loss can be considerably reduced. Assuming a base-plate is installed the standard uncertainty value of 0,1 % is appropriate; otherwise the influence shall be examined.	0,001	$C_{FD} = v/k_{FD}$ $= 10 \text{ m/s}/1,001$ $\approx 10 \text{ m/s}$	0,01
$u_{p,t}$ pressure transducer, $K_{p,t}$	The calibration certificate for the pressure transducer shows a maximum uncertainty of 0,5 Pa in the range from 0 to 500 Pa.	0,5 Pa	$c_{p,t} = 0,5 \text{ v}/K_{p,t}$ $= 0,5 \times 10/5000$ $= 0,001$	0,000 5
$u_{p,s}$ pressure transducer signal conditioning gain, $K_{p,s}$ and $u_{p,d}$ pressure transducer data sampling conversion $K_{p,d}$	The calibration of the equipment used to measure the pressure transducer output shows a maximum uncertainty of 0,000 15 V in the range from 0 to 10 V.	0,000 15 V	$c_{p,s} = 0,5 \text{ v}/K_{p,s}$ $= 0,5 \times 10/0,01$ $= 500$	0,010
$u_{T,t}$ ambient temperature transducer, $K_{T,t}$, $u_{T,s}$ temperature signal conditioning gain, $K_{T,s}$ and $u_{T,d}$ temperature signal digital conversion, $K_{T,d}$	The calibration of the equipment used to measure the temperature shows a maximum uncertainty of 0,1 °C in the range from 10 °C to 30 °C.	0,1 °C	$c_{T,t} = 0,5 \text{ v}/K_{T,t}$ n/a n/a	0,001

Error source u_i	Discussion	Value u_i	Sensitivity value c_i	$u_i c_i$ m/s
u_h pitot tube head coefficient, C_h	The head coefficient of a pitot tube depends upon the angle of attack of the wind. Two error sources are possible, one related to the accuracy with which the pitot tube is set up in alignment with the mean flow direction, and the other due to turbulent variations in instantaneous flow direction. Assume the nominal head coefficient, C_h , is 0,997, and assume also that it is possible to deduce that the standard deviation on angle of attack is 2°. Relevant ISO standards suggest this will give rise to a 0,1 % change in head coefficient.	0,000 997	$C_h = -0,5 v/C_h$ $= -0,5 \times 10/0,997$ $= -5,015$	0,005
u_{pcal} pitot tube calibration	From the calibration certificate of the pitot tube, an uncertainty of 0,25 % in the range of 4 m/s to 16 m/s can be used.	0,002 5	$C_{ph} = -0,5 v/C_h$ $= -0,5 \times 10/0,997$ $= -5,015$	
$u_{B,t}$ sensitivity of barometer, $K_{B,t}$, $u_{B,s}$ signal conditioning gain on barometer, $K_{B,s}$ and $u_{B,d}$ digital conversion of barometer signal, $K_{B,d}$	The calibration of the barometer shows a maximum uncertainty of 0,5 hPa in the range from 900 hPa to 1 100 hPa.	0,5 hPa	$c_{B,t} = -0,5 v/k_{B,t}$	
s_A statistical uncertainty in the mean of the wind speed time series	Assume the turbulence intensity is 2 %, and that 2 Hz sampling over 30 s is used, giving 60 samples. The standard uncertainty in the mean value of 10 m/s is then given by $\sqrt{1/60 \times 0,02 \times 10}$	0,026	1	0,026
u_ρ , humidity correction to density, k_ρ or u_ϕ , relative humidity, ϕ	The calibration of the relative humidity measurement equipment shows an uncertainty of less than 2 % in the range 10 to 95 %. A value of 2 % is selected for the calculation. $c_\phi = \frac{\partial \bar{v}}{\partial k_\rho} \cdot \frac{\partial k_\rho}{\partial \phi} = \frac{1}{2} \frac{\bar{v}}{k_\rho} 0,378 \frac{P_w}{B}$ At 15 °C, $P_w = 1\,700$ Pa and assuming $B = 1\,013$ mbar = 101 300 Pa, k_ρ is evaluated as 0,997 and c_ϕ (at 10 m/s) is 0,032.	$u_\phi =$ 0,02 % RH	$c_\rho = 0,032$	0,001

The combined standard uncertainty can be obtained by taking the root mean square of the contributory uncertainties in the right-hand column. For the values which have been dealt with, this amounts to 0,06 m/s.

The example shows that category B uncertainty is liable to dominate. Extending the calibration period can help reduce the category A uncertainty, but will have no effect on category B. Furthermore, category B uncertainty sources, although not correlated with one another for a particular wind speed, are fully self-correlated across wind speeds, meaning that good apparent calibrations (good straight lines) can be obtained, whilst still retaining significant uncertainty.

9 In-situ comparison of anemometers

9.1 General

Where it is required to prove that an anemometer does not change its calibration during a measurement period, there are two methods available. The anemometer can be calibrated in a wind tunnel after the measurement period to show the differences to the calibration before the measurement period. Alternatively (or additionally) an in-situ comparison, made by comparing the primary anemometer to a control anemometer installed in close proximity during the measurement period, can be carried out. This method does not identify a gradual degradation of the calibration of the anemometer if the control anemometer degrades at a similar rate. The in-situ comparison should be repeated on a regular basis to identify problems at an early stage.

9.2 Prerequisite

During the measurement period the two anemometers are installed on the meteorological mast in accordance with Clause 10. The primary anemometer is the instrument being used for the measurement of interest. The other anemometer is the control anemometer, and is used for the in-situ comparison. The anemometers can be installed in three variants:

- a) variant 1: top mounted in accordance with 10.2;
- b) variant 2: alternative top mounted in accordance with 10.3;
- c) variant 3: both anemometers side-mounted in accordance with 10.4.

9.3 Analysis method

Two databases will be compared using the 10 min average values recorded during the measurement period. The first database includes data that start directly after the installation of the anemometers. The second database includes data for the last part of the measurement period. Each database shall meet the following requirements.

- a) A range from 4 m/s to 12 m/s shall be covered.
- b) Wind directions shall be in the valid measurement sector.
- c) Each wind speed bin shall have a minimum of three points of data. There are two possible choices of binning the data as follows:
 - 1) Binning option 1: Wind speed bins of 1 m/s width, centred on 1,0 m/s values, based on the control anemometer wind speed from one wind direction bin not larger than $\pm 15^\circ$.
 - 2) Binning option 2: Wind speed bins of 4 m/s width centred on 2 m/s, 6 m/s, 10 m/s and 14 m/s based on the control anemometer wind speed and wind direction bins of 10° .

This wind speed range of 0 to 16 m/s is for this interim analysis step only and the final analysis shall be based on the 4 m/s to 12 m/s range.
- d) Include a wind direction sector with the meteorological mast free of wakes of any wind turbines and with the anemometers free of wakes of the meteorological mast as follows:
 - 1) In the case of side-by-side anemometer mounting (variant 2) and using only wind speed binning for one wind direction sector (binning option 1), the wind direction sector shall include the wind direction that is 90° to the boom direction and in acceptable wind directions.
 - 2) In the case of a top-mounted anemometer (variant 1), the wind direction bin(s) shall be out of the wake of the meteorological mast. Therefore the horizontal connection lines (see Figure 8 and Figure 9) between the centre of the control anemometer and any part of the meteorological mast shall have a minimum angular distance of 45° to the border of the bin(s).
- e) Maximum duration shall be eight weeks.

The wind direction bin(s) used for the analysis shall be clearly stated in the report.

If 1 m/s wind speed bins and one wind direction bin of 30° (binning option 1) are applied, a linear regression is performed with the primary anemometer as the dependent variable and the control anemometer as the independent variable. This regression will be used to calculate the estimated primary anemometer wind speed, termed $V_{\text{primary_est}}$.

$$V_{\text{primary_est}} = m \cdot V_{\text{control}} + b \quad (23)$$

where

m is the slope of the regression relating V_{control} to $V_{\text{primary_est}}$;

b is the offset of the regression relating V_{control} to $V_{\text{primary_est}}$;

V_{control} is the wind speed of the control anemometer.

The intention is to show a change over time in the behaviour of an anemometer, not an absolute calibration.

If 4 m/s width wind speed bins and 10° wind direction bins (binning option 2) are applied, a piecewise linear interpolation between wind speed bins in each wind direction bin from the first database can be used to estimate the primary anemometer wind speed based on Equation (24):

$$V_{\text{primary_est}} = \frac{V_{\text{primary},i} - V_{\text{primary},i-1}}{V_{\text{control},i} - V_{\text{control},i-1}} (V_{\text{control}} - V_{\text{control},i-1}) + V_{\text{primary},i-1} \quad (24)$$

In this case, only data of the control anemometer within the wind speed bins covered by the first database in each wind direction bin shall be used for the evaluation of the in-situ comparison in the second database. Equation (24) may be used for extrapolation up to the borders of the covered wind speed bins. If there is only one wind speed bin covered in a wind direction bin, the ratio of the bin averages of the wind speeds measured by the primary anemometer and the control anemometer shall be used as correction factor for the measurement of the control anemometer.

9.4 Evaluation criteria

Apply the regression or the piecewise linear interpolations from the first database to the control anemometer measurements of the second database resulting in an estimated primary anemometer wind speed for each 10 min period.

Calculate the average of differences (systematic deviation) in the measured and estimated primary anemometer wind speed for 1 m/s wide wind speed bins centred around 1 m/s values. The systematic deviation is:

$$\gamma = \frac{\sum (V_{\text{primary_est}} - V_{\text{primary}})}{n} \quad (25)$$

Calculate the standard uncertainty of wind speed differences (statistical deviation) of the estimated primary anemometer and the measured primary anemometer wind speeds for each wind speed bin. The standard uncertainty of the wind speed differences is the standard deviation of wind speed differences divided by the square root of the number of measured data points. The standard uncertainty is:

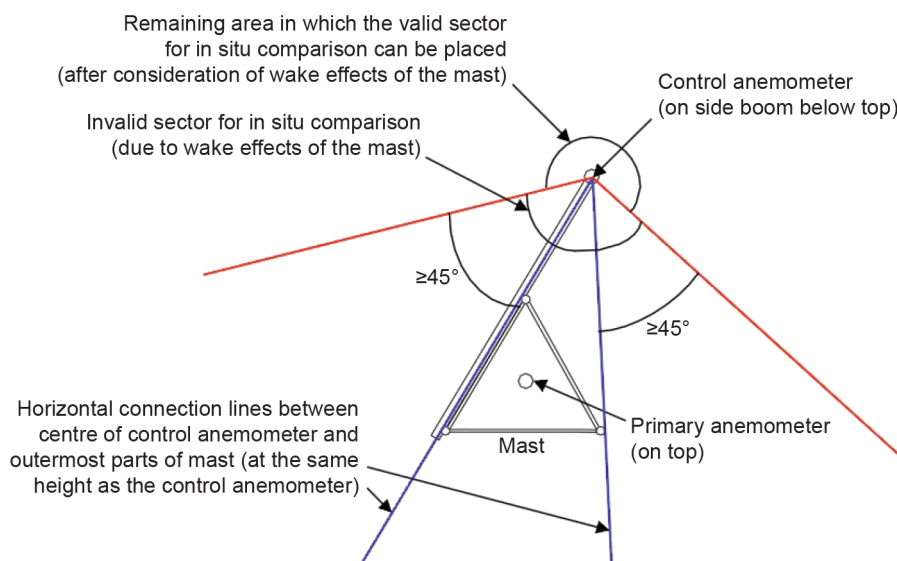
$$\sigma = \frac{\text{stdev}(y)}{\sqrt{n}} = \frac{\sqrt{\frac{\sum (V_{\text{primary_est}} - V_{\text{primary}})^2}{n}}}{\sqrt{n}} \quad (26)$$

If the root-sum-square of the average of differences (systemic deviation) and the standard uncertainty of wind speed differences (statistical deviation) does not exceed 0,1 m/s in any bin between 4 m/s and 12 m/s, the in-situ test has passed.

$$\delta = \sqrt{\gamma^2 + \sigma^2} < 0,1 \text{ m/s} \quad (27)$$

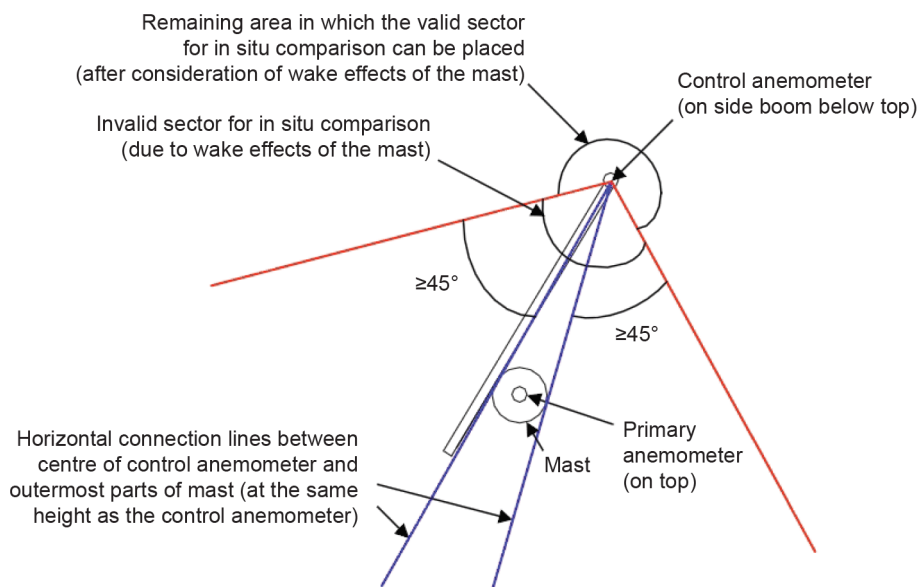
If the value δ is above 0,1 m/s in at least one bin and does not exceed 0,2 m/s in all bins between 4 m/s and 12 m/s, the uncertainty of the anemometer calibration $u_{V1,i}$ shall be increased at least to the maximum value of δ in the wind speed range 4 m/s to 12 m/s. If the value δ is larger than 0,2 m/s in any bin between 4 m/s and 12 m/s, the in-situ test should be shifted to an earlier period until δ no longer exceeds 0,2 m/s. The measurement campaign data after this period shall be rejected, and the uncertainty of the anemometer calibration $u_{V1,i}$ of the remaining measurement campaign data shall be treated as in the case of no data rejection.

NOTE The in-situ test can be repeated often during the measurement campaign to aid in the identification of intermittent anemometer degradation.



IEC

Figure 8 – Example valid control anemometer direction sector for a single top-mounted anemometer on a triangular lattice meteorological mast



IEC

Figure 9 – Example valid control anemometer direction sector for a single top-mounted anemometer on a tubular meteorological mast

10 Mounting of instruments on the meteorological mast

10.1 General

Appropriate arrangement of instruments on the meteorological mast is important for accurate wind measurements (where instruments are to be mounted on a wind turbine nacelle rather than on a meteorological mast, refer to Annex C for guidance). The arrangement of anemometers on a meteorological mast shall include at least a primary top-mounted anemometer and a control anemometer. The purpose of the control anemometer is to provide a means of in-situ consistency checking of the primary anemometer as described in Clause 9. Before using an anemometer classified in accordance with the requirements of the intended purpose (e.g. in a power performance measurement), it is recommended that the geometry of the anemometer is checked with the geometry description that corresponds to the anemometer type on which the classification was made. In particular, the anemometer shall be located to minimize flow distortions, especially from mast and boom influences. When minimal flow distortion across a wide wind direction range is required, then this is obtained with a single top-mounted anemometer. However, a side-by-side arrangement of two top-mounted anemometers provides redundancy and a robust method of anemometer consistency checking with only marginally increased flow distortion if both adequate horizontal separation and a stable mounting structure for the anemometers are achieved. When anemometers are mounted on side booms at elevations below the meteorological mast top, flow distortion from both the meteorological mast and the boom is significant and shall be taken into account. Irrespective of the type of mounting arrangement, the boom structure shall be sufficiently stable to avoid significant vibrations. Those other instruments on the meteorological mast which are required to be mounted close to the primary anemometer mounting height (control anemometer, wind vanes, temperature and pressure sensors) should be mounted in a way that avoids interference with the primary anemometer.

10.2 Single top-mounted anemometer

To achieve negligible flow distortion of the wind speed measurements over a wide wind direction range, a single top-mounted anemometer is the ideal configuration. Where this configuration is adopted all provisions of 10.2 shall be met. However, careful consideration should be given to whether sufficiently robust anemometer consistency checks against a lower elevation anemometer can be achieved with this configuration. This is particularly the case where the meteorological mast is of large cross-sectional area and as a consequence the lower anemometer is subject to more significant meteorological mast interference effects than the top-mounted anemometer or in cases where large variations in wind shear are experienced.

The anemometer shall be supported such that the anemometer cups are at least 1,5 m above the meteorological mast and any other sources of flow disturbance and such that no parts of the support structure or meteorological mast extend outside of an 11:1 half-cone whose vertex is coincident with the anemometer cups.

NOTE 1 Where the anemometer is an allowable type of anemometer other than a cup anemometer (e.g. an ultrasonic anemometer), then "cups" has the meaning "sensor measuring elements" throughout Clause 10.

NOTE 2 The cone is defined such that the base of the cone is of diameter equal to the characteristic width (maximum width of the mast or protrusions for a distance of 4 m below the cups) of the mast and the height of the cone equals 11 times the radius of the cone base.

The anemometer shall be mounted on a round vertical tube of the same ($\pm 1,5$ mm) outer diameter as used during calibration (and classification), but of no larger diameter than the body of the anemometer. The combined length of the tube and anemometer (measured to the anemometer cups) shall be at least 0,75 m. Furthermore, the anemometer shall be held steady, which can necessitate the mounting of the small-diameter vertical tube concentric with another tube of larger diameter to provide a stable structure. This additional tube shall not be of greater diameter than the anemometer body for a height of 1,5 m below the cups. The bracket connecting the anemometer to the vertical tube shall be compact, smooth, and symmetrical. Where the anemometer is designed for internal cable routing in the support tube, the cable shall be routed inside the vertical tube. For other configurations (e.g. pig tail), the cable should be spirally wound around the vertical tube (approximately three turns per metre or similar to that used during calibration and classification). The anemometer should be calibrated with the same cable attachment and routing configuration as is to be used in the field. The anemometer (and mounting tube) inclination from vertical shall be less than 2° . It is recommended that this is verified by measurement. No other instruments shall be positioned closer than 1,5 m to the anemometer cups nor outside of the 11:1 half-cone to a distance of at least 4 m below the anemometer cups. In this case, the control anemometer for the top-mounted anemometer shall be a side-mounted anemometer located at least 4 m and no more than 6 m below the top-mounted anemometer and otherwise satisfying the requirements for side-mounted anemometers in 10.4. Figure 10 shows an example of a top-mounting configuration.

Dimensions in metres

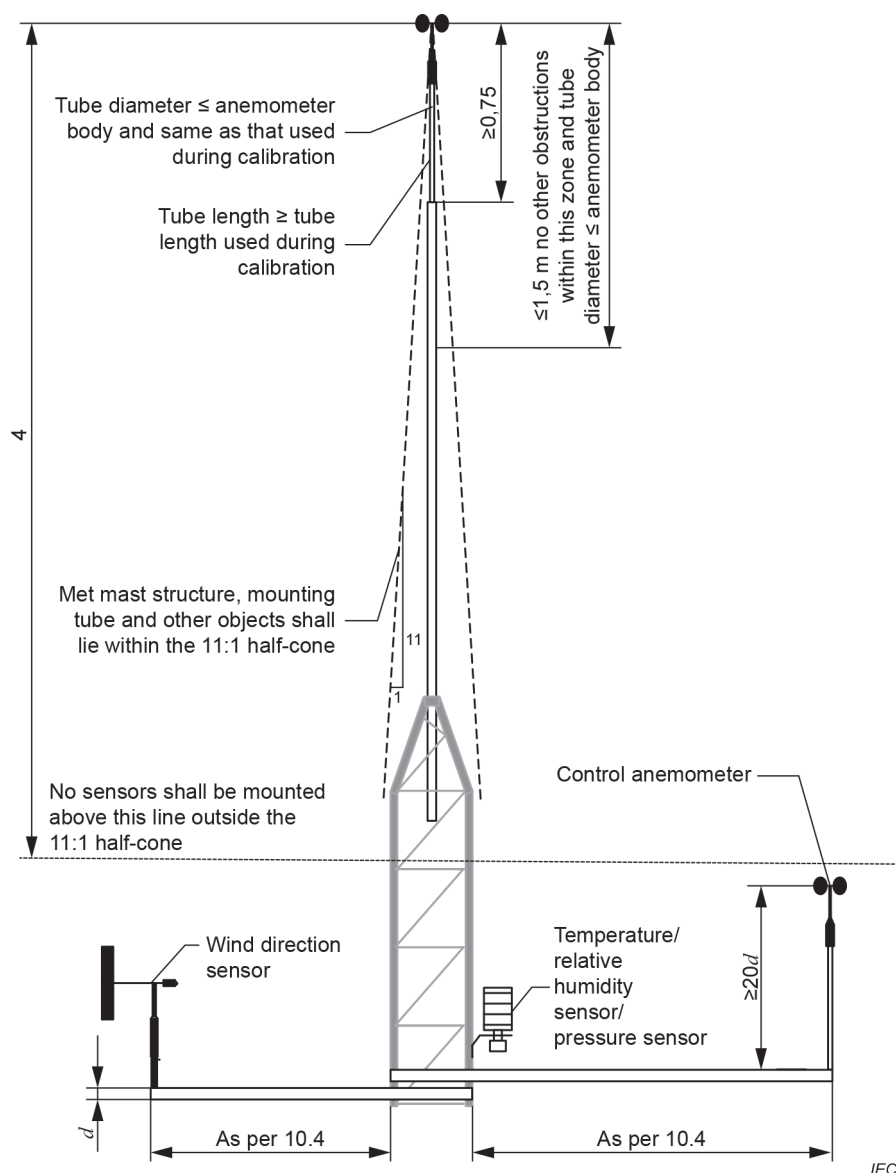


Figure 10 – Example of a top-mounted anemometer and requirements for mounting

10.3 Side-by-side top-mounted anemometers

In the side-by-side arrangement, all mounting conditions in 10.2 shall be met in addition to those specified here. The anemometer cups shall be mounted above the boom by a minimum of 20 times the boom diameter, but 25 times the boom diameter is recommended. The boom, consisting of both the horizontal portion and vertical stems, shall be of round cross-section. The anemometers shall be separated by at least 2,5 m and no more than 4,0 m. No parts of the meteorological mast shall extend beyond a 11:1 half-cone whose vertex is coincident with the midpoint between the cups of the two top-mounted anemometers (the top boom itself is excluded from this requirement provided that it meets the foregoing dimensional criteria). No other instruments shall be positioned closer than 1,5 m to the anemometer cups nor outside the 11:1 half-cone to a distance of at least 4 m below the anemometer cups. Figure 11 shows an example of a side-by-side configuration. It is recommended that the boom is mounted concentric with the meteorological mast axis or centrally on the upwind side of the meteorological mast.

NOTE "Upwind" is dependent on the use case. For example, in the case of a power performance measurement where a relatively narrow direction sector of interest is used, then "upwind" is the direction which places the instruments on the upwind side of the mast relative to the turbine. However, in the case of a resource assessment measurement, "upwind" can mean the side of the meteorological mast which faces the expected predominant wind direction sectors.

The influence of one anemometer on the other shall be assessed and the measurement sector restricted such that the overall uncertainty of the wind speed measurement remains within the desired limits. The uncertainty due to flow distortion from other instruments, the meteorological mast and booms shall be determined.

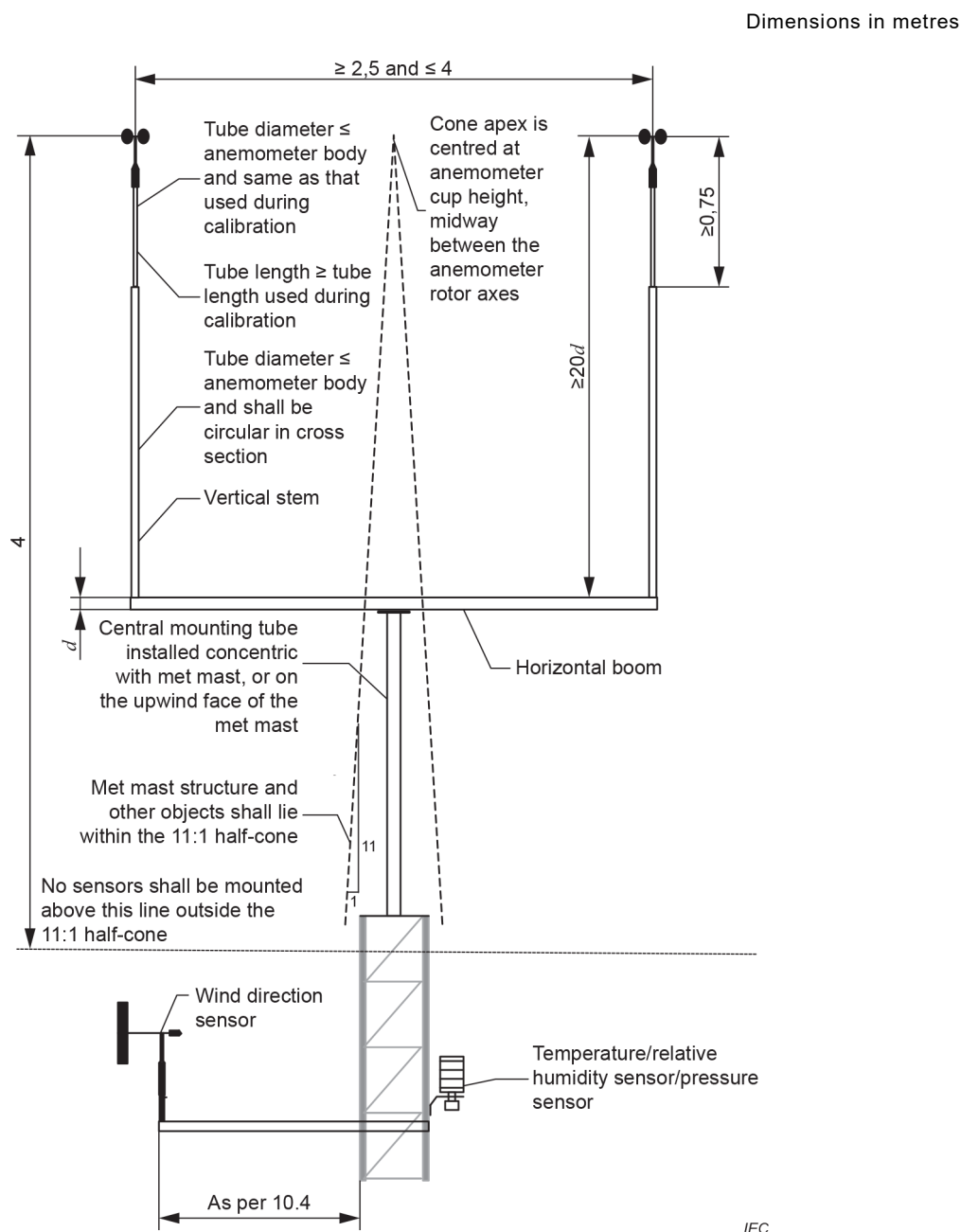


Figure 11 – Example of alternative top-mounted primary and control anemometers positioned side-by-side and wind vane and other instruments on the boom