Measuring-Network of Wind Energy Institutes

16bt01

Full-scale structural blade testing
Proficiency Test

External Report for IECRE

Proficiency test conductor: Ramon Obdam, Knowledge Centre WMC

Wieringerwerf, September 26th 2019

Acknowledgement

This project has been carried out in the framework of MEASNET, in close collaboration with the SG551 group of IEC-RE. The author wishes to recognize the collaboration of the MEASNET secretariat and the SG551 convener in the development of the proficiency test.

Abstract

This document presents the results of the 16bt01 proficiency test organized by MEASNET in collaboration with IECRE. This proficiency test is organized according to IEC-RE OD *General Process of Performing Proficiency Tests (PTs) for IEC-RE.*

The laboratories participating in this Proficiency test are:

- Beijing CGC Certification Center Co., Ltd
- Fundación CENER CIEMAT
- IWES Fraunhofer
- LM Wind Power A/S
- NREL
- Shangai SERCAL New Energy Technology Co.
- Knowledge Centre WMC
- WTTC

The results have been compared and analyzed by Knowledge Centre WMC acting as the conductor of the proficiency test. Measures have been taken to prevent the conductor from getting the results of the other test labs before having presented its own results to the MEASNET secretariat.

Contents

1. Introduction & Methodology

Within the framework of the MEASNET network internal quality evaluation programme, the collaboration with the IEC-RE organization and the consideration of proficiency testing as a service offered to its customers, a proficiency test for full-scale structural blade testing according to IEC 61400-23: 2014 was organized and performed. The following test labs have participated in this proficiency test:

- Beijing CGC Certification Center Co., Ltd
- Fundación CENER CIEMAT
- IWES Fraunhofer
- LM Wind Power A/S
- NREL
- Shangai SERCAL New Energy Technology Co.
- Knowlegde Centre WMC
- WTTC

A typical full-scale blade testing programme is a combination of different tests like determining the blade weight, a modal analysis, static tests in multiple directions and fatigue tests. Due to practical constraints it was not possible to perform any physical tests on a common blade. Therefore, the scope of this proficiency test was limited to analyzing a data set of measurement results from a modal analysis. The modal analysis was performed on a 29-meter rotor blade. The measurements were performed at Knowledge Centre WMC in Wieringerwerf, the Netherlands.

The full description of the modal analysis and the measurement data shared with the test labs is given in document *WMC-2016-070a-01 IEC-RE proficiency test - description of modal analysis and measurement data*.

The results have been compared and analyzed by Knowledge Centre WMC. The full results comparison report can be found in document *WMC-2017-032-03 IEC-RE proficiency test - Results comparison*.

Note that due to the limited scope of the current proficiency test no pass / fail criteria have been applied.

1.1. Modal analysis method

To perform the modal analysis the blade was mounted on a test stand with the trailing edge up (pitch angle of 4.5 deg) and with an 8 degree tilt angle.

Three accelerometers were used during the measurements (see Figure 1 and Figure 2):

- On the leading edge (LE) measuring in X_{lab} and Y_{lab} direction.
- On the trailing edge (TE) the accelerometer is clamped to the blade surface. So the direction of the measured acceleration depends on the angle of the blade surface. The angle of the acceleration direction with respect to X_{lab} (AC01) is measured with an inclinometer (see Table 1).

The masses of the accelerometer boxes at the leading and trailing edge were 432 and 354 gram, respectively. The mass of the strap was 339 gram. The connection cables were hanging from the blade.

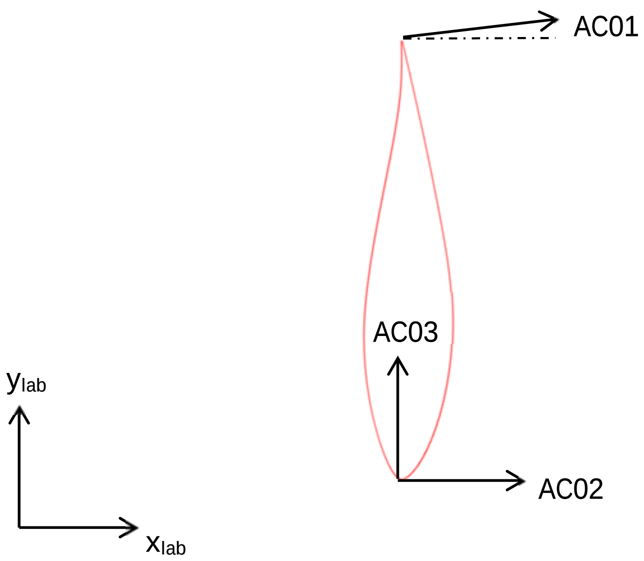

Figure 1 Acceleration measurements (view from tip)

Figure 2 Accelerometers placed on the blade

In subsequent measurements the three acceleration transducers were placed at the spanwise positions Z_{blade} listed in Table 1, measured from the blade root. Blade coordinates of the leading and trailing edge are given too for reference.

Table 1 Locations of the accelerometers and angle of AC01

#	Z_{blade} [m]	X_{LE} [m]	Y_{LE} [m]	X_{TE} [m]	Y_{TE} [m]	Angle AC01 [deg]
1	5.5	-0.157	-0.756	0.348	1.678	2.4
2	9	-0.080	-0.675	0.172	1.454	6.6
3	11	-0.052	-0.597	0.110	1.263	8.3
4	13	-0.035	-0.521	0.073	1.086	9.0
5	15	-0.024	-0.450	0.049	0.939	9.3
6	17	-0.015	-0.392	0.031	0.818	10.6
7	19	-0.005	-0.342	0.016	0.711	10.0
8	21	-0.031	-0.303	-0.031	0.620	7.3
9	23	-0.092	-0.268	-0.108	0.543	6.3
10	25	-0.217	-0.239	-0.238	0.475	9.1
11	27	-0.416	-0.210	-0.436	0.414	9.0

The blade was excited by impact excitation at a spanwise position of 22.5 m. A small wooden block with a mass of 107 gram was glued onto the pressure side spar cap to provide an impact point and to protect the blade, see Figure 3. Impact was done at an angle of approximately 45° to the local blade chord. The impact load was measured by a loadcell. Three measurements were made for each spanwise position of the acceleration transducers.

Figure 3 Impact point for excitation

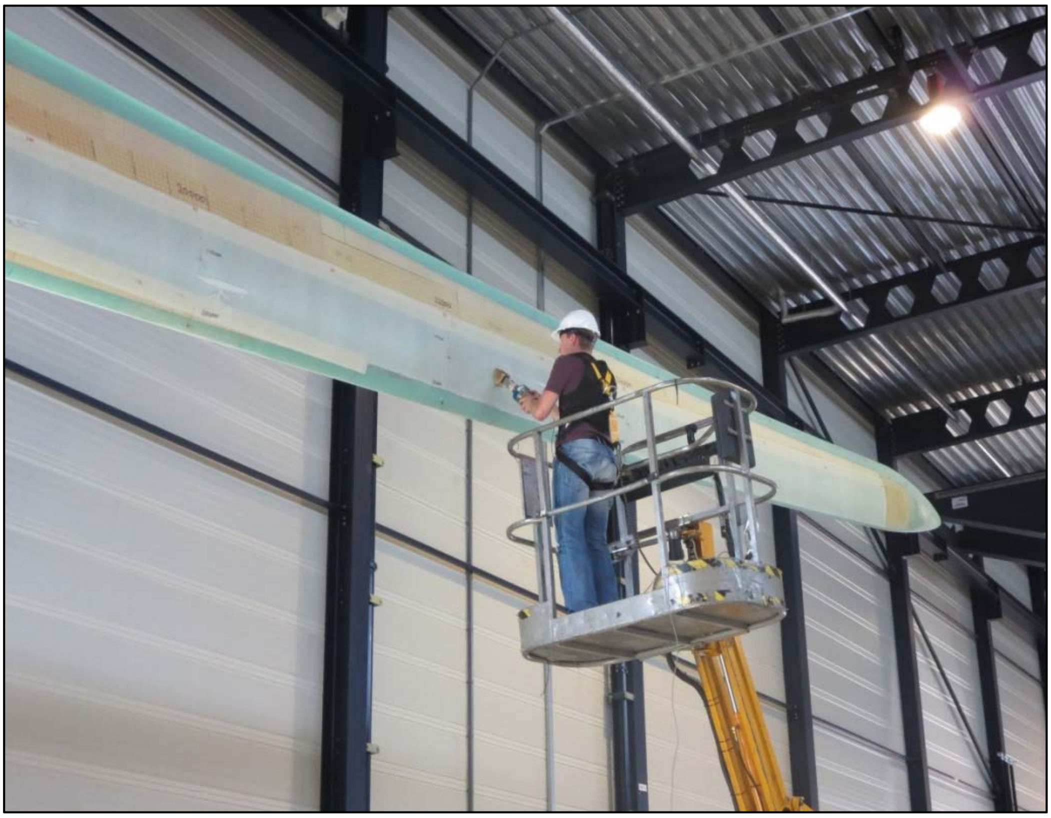

Figure 4 Impact excitation

To measure free vibration of the blade, the accelerometers as described above were placed at a cross-section 27.0 m from the blade root. The blade was excited manually in the corresponding mode. After satisfactory amplitude had been achieved the excitation was stopped, followed by free vibration of the blade. During this period of vibration measurements were recorded until the blade vibration was damped out. The measurements for each mode were repeated three times.

1.2. Measurement data

The measurement files were provided in text format. In Table 2 the impact excitation measurement files are listed and in Table 3 the free vibration measurement files. It is noted that all supplied data is raw so outliers and anomalies may exist.

Table 2 Impact excitation measurements

#	Z_{blade} [m]	Measurement a	Measurement b	Measurement c
1	5.5	ma055a	ma055b	ma055c
2	9	ma090a	ma090b	ma090c
3	11	ma110a	ma110b	ma110c
4	13	ma130a	ma130b	ma130c
5	15	ma150a	ma150b	ma150c
6	17	ma170a	ma170b	ma170c
7	19	ma190a	ma190b	ma190c
8	21	ma210a	ma210b	ma210c
9	23	ma230a	ma230b	ma230c
10	25	ma250a	ma250b	ma250c
11	27	ma270a	ma270b	ma270c

Table 3 Free vibration measurements

Mode	Measurement a	Measurement b	Measurement c
First flap	fl100	fl101	fl102
Second flap	fl200	fl201	fl202
First edge	ed100	ed101	ed102
Second edge	ed200	ed201	ed202

The measurement files contained the following signals with a sample frequency of 800 Hz:

- measurement record
- time in seconds
- F01: impact load in N (impact excitation measurements only)

- AC01: acceleration at the TE in m/s^2
- AC02: acceleration at the LE in m/s^2
- AC03: acceleration at the LE in m/s^2
- T01: lab temperature in °C
- RH01: lab relative humidity in %

A digital low pass Bessel filter at 100 Hz was applied before the measurements were stored. Note that the sample frequency remains 800 Hz.

1.2. Expected deliverables

The following blade properties needed to be determined:

- Blade natural frequencies [Hz]
- Blade mode shapes (both graphical and numerical)
- Damping of the first two flap and edge modes [% of critical damping]

1.3. Calendar

The Proficiency Test was executed according to the following Calendar:

Data Base sent to participants	13.01.2017
Participant's analysis timeframe	16.01.2017 to 13.04.2017
Report & results discussion	31.05.2017 to 14.06.2017

2. Results provided by the test labs

2.1. Natural frequencies

In accordance to the IEC 61400-23, Section 10.4.2 – *Natural frequencies*, as a minimum the first and second flatwise and first edgewise frequencies shall be measured.

The natural frequencies reported by each lab are given in Table 4.The results are given in the number of digits as reported by the test lab. For flatwise and edgewise modes the first three natural frequencies are compared and for torsion only the first frequency. The mean, standard deviation and coefficient of variation (COV) of the results of the different labs are also listed in Table 4.

Table 4 Comparison of natural frequencies

Lab	1st flat	2nd flat	3rd flat	1st edge	2nd edge	3rd edge	1st torsion
	Freq. [Hz]	Freq. [Hz]	Freq. [Hz]	Freq. [Hz]	Freq. [Hz]	Freq. [Hz]	Freq. [Hz]
A	1.12	3.01	6.29	1.86	5.42	11.93	18.78
B	1.121	3.008	n/a	1.854	5.410	n/a	~~11.933~~
C (free vibr.)	1.121012367	3.0090332	n/a	1.852417	5.4077148	n/a	n/a
C (impact ex.)	~~3.0151367~~	~~6.2988281~~	n/a	1.8676758	5.4199219	n/a	n/a
D	1.13	3.02	n/a	1.86	5.42	n/a	n/a
E	1.121	3.008	6.293	1.857	5.410	11.929	18.775
F	1.12	3.01	6.29	1.86	5.42	11.93	18.79
G (free vibr.)	1.1209	3.0082	n/a	1.8528	5.3999	n/a	n/a
G (impact ex.)	1.12	3.01	n/a	1.86	5.42	n/a	~~11.93~~
H	1.13	3.01	n/a	1.86	5.41	n/a	n/a
mean	*1.12*	*3.01*	*6.29*	*1.86*	*5.41*	*11.93*	*18.78*
std dev	*0.00419*	*0.00373*	*0.00173*	*0.00456*	*0.00719*	*0.00058*	*0.00764*
COV	*0.37%*	*0.12%*	*0.028%*	*0.25%*	*0.13%*	*0.0048%*	*0.041%*

The following remarks are made related to the results:

- The torsional frequencies as reported by lab B and G are probably the 3rd edge mode. These results are not used to calculate the mean value, standard deviation and COV of the first torsional frequency.
- Lab C reports separate natural frequencies based on 'free vibration' and 'impact excitation'. The reported 'impact excitation' first and second flatwise frequency are actually the second and third frequency. These results are not used in the calculation of the mean value, standard deviation and COV.

- The maximum coefficient of variation (COV) is 0.37% so the spread in the (valid) results is small.

All labs report at least the number of frequencies required by IEC 61400-23. In general the results match well. However, in some cases the correct interpretation of the particular mode seems to be an issue.

2.2. Damping

The damping coefficients reported by each lab are given in Table 5. Note that only one lab reported the damping coefficient of the third flat, the third edge and the first torsion mode.

Table 5 Comparison of damping coefficients

Lab	1st flat	2nd flat	3rd flat	1st edge	2nd edge	3rd edge	1st torsion
	Damp. [%]	Damp. [%]	Damp. [%]	Damp. [%]	Damp. [%]	Damp. [%]	Damp. [%]
A	0.25	0.16	n/a	0.23	0.26	n/a	n/a
B	0.331	0.193	n/a	0.241	0.262	n/a	~~0.317~~
C	0.3214	n/a	n/a	0.2398	n/a	n/a	n/a
D	0.18	0.14	n/a	0.21	0.27	n/a	n/a
E	0.131	0.154	0.15	0.217	0.259	0.22	0.23
F	0.13	0.13	n/a	0.20	0.25	n/a	n/a
G	0.17	0.13	n/a	0.20	0.35	n/a	~~0.35~~
H	0.31	0.17	n/a	0.23	0.21	n/a	n/a
mean	*0.23*	*0.15*	*n/a*	*0.22*	*0.27*	*n/a*	*n/a*
std dev	*0.086*	*0.023*	*n/a*	*0.017*	*0.042*	*n/a*	*n/a*
COV	*38%*	*15%*	*n/a*	*8%*	*16%*	*n/a*	*n/a*

The following remarks are made related to the results:

- The torsional frequencies as reported by lab B and G are probably the 3rd edge mode. So these reported torsional damping coefficients are assumed to be incorrect.
- The spread in the reported damping coefficients is big as indicated by the large coefficients of variation (COV).
- The coefficients of variation (COV) are larger for the flatwise modes than for the edgewise modes.

After discussion of revision 01 of the comparison report it became clear that the methods to determine the damping coefficient differ significantly between the various test labs. This leads to large variations in reported damping coefficients. To get more insight into the different methods all labs were asked to give detailed information about their method. The resulting information as received from lab A, B, D, F and H can be found in the full comparison report.

3. Recommentations for IEC 61400-23

The IEC 61400-23 currently provides very limited guidance on modal testing of rotor blades. Section 10.4.2 – *Natural frequencies* contains:

As a minimum, the first and second flatwise and first edgewise frequencies shall be measured. The mass of the test instrumentation can influence the results of the natural frequency tests.

Damping and mode shapes are mentioned as optional blade property tests in section 10.4.3:

Testing of other blade properties may be of interest. These may include (but are not limited to):

- *damping;*
- *mode shapes;*
- *creep;*
- *mass distribution;*
- *stiffness distribution.*

In general the IEC 61400-23 standard only specifies what to test. The particular test method and hardware implementation is up to the individual test labs. Therefore there will be differences in the methods selected by the labs. Even when all labs are using the same measurement data, significantly different results may be obtained, as shown in this report for the damping calculation in particular. Note that having to use a given data set can also be a source of deviation in results since the post-processing method of a particular test lab might be tailor made to its own measurement method and might be not fully compatible with the measurement data provided.

It could be considered whether the standard can dictate the suitable method(s) to determine the modal properties, damping in particular. The following items could be added to the standard in any case:

- Guidance on the influence of mass loading on the measured natural frequencies.
- Clarification that the damping coefficient to be measured is the *structural* damping and care should be taken to prove the influence of the aerodynamic damping is negligible.
- Requirement for mode shapes to be clearly visualised to allow proper identification of the modes.
- Requirement to take the influence of the finite mounting stiffness into account or to show that it is negligible.
- Description of the possible uncertainty sources for modal analysis and how to take them into account.