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DTU Wind Energy E-0036

October 2013

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Title: Bondlines – Online blade measurements (October 2012 and January 2013)
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Summary (max 2000 characters):

Some local deformations in an operating Wind Turbine blade (V80) have been measured during October 2012. Displacement and load values generated between the trailing edge panels at blade radius R9.2m, R10,2m, and R11,2m were obtained. A fluctuating loading of between 100 - 200N existed when the two panels were connected, and with a displacement of between 6.5 - 10mm when the panels were free to flex as they do in normal operating conditions. Shear distortion within the main loading spar of the blade (at approximately R10m) showed a fluctuating cross beam shear distortion of about 9mm.

The trailing edge displacement was re-measured (during January 2013) following a reinforcement of the blade to prevent trailing edge distortion. This trial showed that the new displacement values were below 1mm during similar operating conditions.

This report describes the planning for and procurement of hardware for the on-site measurements. The data output is then summarised. The full data files will be used to improve models and sub-component testing of these structures, as well as the continuing development of the reinforcement approaches designed to prolong structural life.

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Summary

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1. Introduction

The BONDLINES project (EUDP File Number 64012-0128) is subtitled “Regain the operational life time of installed WTG blades with structural defects”. The Objective is to develop, prepare for market and demonstrate an applicable method for regaining operational life of installed wind turbine blades with structural defects based on patented technologies (Bladena) for limiting deformations in panels. In the project this method will be demonstrated on a turbine in operation. The solution will remove the root cause for bond line defects, which are the dominant defect on blades.

Work Package 2 of the Bondlines project deals with relevant damage assessment and measurement techniques (led by DTU Wind), and Work Package 3 covers the Full-scale field testing (led by Bladena). Together these work packages co-ordinate to assemble a combination of measurement and data acquisition hardware that is capable of providing adequate detail regarding the structural response of the blade during operating; in particular details of the displacement and load values between the trailing edge panels and the load-bearing internal beam.

This report describes the agreement on and implementation of an instrumentation plan suitable for the structural sections of interest in the operating wind turbines. All the relevant measurement hardware and attachment consumables assembled and utilised within this task, including an appropriate data acquisition system, are described. The collaboration with Total Wind Blades for the installation of the system on the VGT11901 (Vattenfall number 314) turbine and the presentation and initial analysis of the results are included.

The data generated in this activity will provide information necessary to successfully develop the reinforcement approach envisioned by the project, as well as updating current models for structural behaviour used to describe blade response. The sub-component test series planned in Work Package 4 of the Bondlines project will calibrate the mechanical testing around the values measured here, and a further report in WP2 will assess the measurement system as developed here and propose improvements to assist future on-site monitoring work.

2. Timeline

2.1 Work Package 2 (measurement system) and 3 (Field tests)

23. Jul	Initial discussions between Bladena and DTU Wind regarding the on-site testing (WP3) and the hardware requirement (WP2). Drilling through the trailing edge and connecting the panels with either a surface mounted string potentiometer (deformation) or load washer.
02. Aug	Meeting at DTU Wind (Risø) between Find Mølholt / Raphael Sajous (both Bladena) and Gabriele Chiesura / Malcolm McGugan (both DTU Wind) to discuss measurement approach and hardware. Agreement reached that DTU Wind will source the (3) string potentiometers, (3) load washers, an inclinometer, and the appropriate Data Acquisition (CATMAN software?) and system control hardware. These will be assembled by DTU Wind as an on-site measurement and data logging system with the required power supply, cabling, fittings, and so on (as described in WP2 definition). DTU Wind will manufacture fittings for the instrumentation to Bladena specifications. The on-site instrumentation and measurement will be led by Bladena who are responsible for the organisation/management of the task, as well as supplying auxiliary hardware and consumables as appropriate (WP3 definition).
06. Aug	Initial possible problem identified with the DTU Wind license for CATMAN software as it is only for academic use on campus. If so a possible solution of “direct measurement” is discussed.
16. Aug	Bondlines Project kickoff at DTU (Lyngby) with the entire consortium represented. WP2 (measurement hardware) and WP3 (On-site measurement) are presented and approved by the consortium. An additional task for WP2 and 3 is the measurement of any shear distortion taking place inside the box beam during turbine operation.
20.-31. Aug	Sourcing and pricing for appropriate measurement hardware by DTU Wind
04. Sep	Meeting at Total Wind (Brande) with Bladena. After input from DTU Wind agreement is reached on using a robust (solid state hard drive) laptop running DASYLab software (instead of digitising the sensor outputs and using CATMAN software). The WS10SG “posiwire” string potentiometers, LCMWD-20kN load washers, and ZCT1180KS-SNS-29 1-axis inclinometer are the agreed sensors. Initial inspection of the test system (operating at the DTU Wind, Risø laboratory) is proposed for the week Sep 17-21, with measurements on-site possible from Sep 24-28.
10.-14. Sep	Manufacture “cone” fittings for WP3 at DTU Workshop (Risø); order sensors.

18. Sep	Meeting at Total Wind (Brande) with Johnny Plauborg (TWB), Raphael Sajous (Bladena), Anders Kyndesen, Gabriele Chiesura, and Malcolm McGugan (all DTU Wind). All available test instrumentation and installation hardware was inspected and discussed. An example of a V80 turbine blade (39m) stored at TWB was measured to establish the location for the instrumentation measurements. It was further agreed that final preparations would continue until week Oct 01-05 when there would be a “fittings” trial at Brande using the available turbine blade as a test structure. From the week starting Oct 08 and onwards until the end of October all involved in WP2 and 3 (DTU Wind, Bladena, and TWB) should be ready to attend the instrumentation turbine at short notice depending on a favourable weather forecast.
21. Sep	The design of the reinforcement string attachment is changed from the initial “cone” insert placed in scarf joint cut, to a flat “button” plate mounted on the surface over a flat edge drill hole.
24.-28. Sep	New “button” fittings manufactured by DTU Workshop (Risø); source power supply.
03. Oct	Meeting at Total Wind (Brande) between Johnny Plauborg (TWB), Rikke Juul Balle (Vattenfall), Anders Kyndesen, Gabriele Chiesura, and Malcolm McGugan (all DTU Wind). The attachment procedure for the posiwire and force transducers was attempted on the available blade. Aligning the holes and passing a rod from one side to the other in order to “thread” the reinforcement string was not a straightforward task. The “button” fixing plates were drilled in place and the string pulled taut. The measurement sensors were always attached on the flatter and less turbulent “suction” side of the blade. Also discussed was the measurement hardware to be installed in the hub and the best way to configure and secure this. From a practical point of view it was preferred if all proposed measurements (trailing edge force, trailing edge displacement, and box beam shear) could be completed within as short a time period as possible. It was agreed that at least three days on-site with good weather conditions would be required to achieve this.
05. Oct	A solution to the reinforcement string misalignment problem is suggested.
05.-19. Oct	DTU Workshop (Risø) manufacture the posiwire angle fittings to be used in the box beam shear measurements
08. Oct	Agreement on the week starting Oct 22 for the on-site measurements.
12. Oct	Problem highlighted regarding the available power source in the hub. Only 24V with limited capacity and not standard 230V as assumed.

15. Oct	The measurement hardware is configured to the new power situation and it is suggested that an additional “power trial” is conducted at the V80 Tjærborg site (Esbjerg) on Friday Oct 19. The full measurement trial is scheduled to start Tuesday Oct 23.
19. Oct	Visit to V80 Tjærborg, Esbjerg to check power supply and good system operation with Anders Kyndesen (DTU Wind) and Johnny Plauborg (TWB).
23.-25. Oct	On-site trailing edge measurements at V80 Tjærborg (Esbjerg); detailed timeline and measurement overview available
23. Oct	Full “rope” access to the Blade A V80 Tjærborg turbine. Instrumentation of the blade trailing edge (drill holes, sensor attachment, and cabling) by rope crew and installation of the measurement system in the hub. This was followed by initial force transducer measurements that evening.
24. Oct	More load washer measurements in the morning, trailing edge displacement measurements in the afternoon, and instrumentation of Blade C with the internal box beam shear displacement fittings in the evening.
25. Oct	Beam shear measurements in the morning, system dismantle in the afternoon prior to severe weather warning.

2013

08. Jan	Mark drill positions on Blade and stat drilling (protect holes overnight with blue tape).
09. Jan	Finish drilling, thread strings, bond fittings, attach and tension D-strings (protect holes overnight with blue tape).
10. Jan	Set up data acquisition system and displacement measurement posiwires. Run turbine and measure residual deformation in reinforced trailing edge panels. Demount all installation.

2.2 Detailed timeline for 23.-25. October 2012

23. Oct	0800	Hardware packed and head off from DTU Wind, Risø.
	1100	Arrive at Tjærborg V80
	1200	Mount data acquisition hardware in hub, Instrument Blade A trailing edge with load transducers (see schematic)
	1550	Bondlines test 1 data file
	1635	Bondlines test 2 data file
	1800	Day 1 completed
24. Oct	0715	Bondlines test 3 data file
	0905	Bondlines sensor position data file
	0930	Bondlines test 4 data file
	1100	Instrument Blade A trailing edge with displacement transducers (see schematic)
	1340	Bondlines wire position data file
	1425	Bondlines posiwire test 1 data file
	1600	Instrument Blade C box beam with internal displacement transducers (see schematic)
	1800	Day 2 completed
25. Oct	0925	Bondlines posiwire beam test data file
	0930	Bondlines posiwire beam test 1 data file
	1000	Bondlines posiwire beam test 2 data file
	1200	High winds forecast for afternoon and evening
	1300	All test Hardware removed from turbine
	1500	Day 3 completed

2.3 Measurement data overview

Vattenfall V80, Østerbyvej, Tjærborg (Esbjerg) - October 2012

Machine number: VGT11901 (Vattenfall number 314)	Date	Wind condition	Time (start)	Time (end)	Data file name	Raw data file (kB)
Blade A (24317) instrumented for load and displacement from the outside of the shell	23-oct	6-8 m/s from S/SE	15:49	16:29	Bondlines test 1 start	1.574
		6-8 m/s from S/SE	16:34	17:27	Bondlines test 2	2.171
	24-oct	3-5 m/s from W	07:16	09:02	Bondlines test 3	4.154
		3-5 m/s from W	09:05	09:28	Bondlines sensor position	858
		3-5 m/s from W	09:30	10:25	Bondlines test 4	2.175
		4-7 m/s from W	13:41	13:42	Bondlines wire position	28
		4-7 m/s from W	14:24	15:46	Bondlines posiwire test 1	3.090
Blade C (24577) instrumented for cross wire on the inside of the spar	25-oct	8-12 m/s from W	09:26	09:27	Bondlines posiwire beam test	36
		8-12 m/s from W	09:28	10:00	Bondlines posiwire beam test 1	1.265
		10-12 m/s from W	10:02	11:37	Bondlines posiwire beam test 2	3.760

January 2013

Machine number: VGT11901 (Vattenfall number 314)	Date	Wind condition	Time (start)	Time (end)	Data file name	Raw data file (kB)
Blade A(24317) reinforced and instrumented for displacement from the outside of the shell	10-jan	9 m/s from NE	13:39	15:02	130110 Test 01	2.629
		9 m/s from NE	15:09	16:49	130110 Test 02	3.705

Table 1: Measurement data overview

3. Variables to be measured

As described in the technical overview of the project the aim of the work is to regain the reliability of a wind turbine blade, by designing a retrofit solution on the trailing edge of the blade, since one of the root causes of failure is related to the debonding on this jointed area between the two shells at the trailing edge location and on the box girder as can be seen in fig. 1.

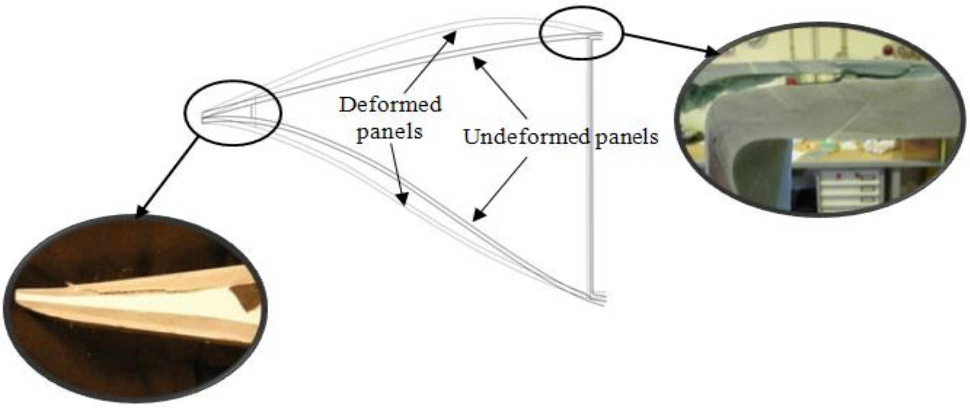

Fig. 1 - Sketch of the trailing edge shells with out-of-plane deformations (the deformations are scaled for clarity). The close-ups show failure at the trailing edge as well as debonding of the outer aerodynamic shell on the box girder.

Looking at the pronounced deformations of the shells, one can have an idea of the “pumping phenomena” which occurs on the blade during operation. Based on this model it is therefore supposed that the cause of debonding is the opening loads near the trailing edge (TE). A strong assumption made on this model is that only MODE I (peeling mode) occurs at the TE debonding, and this can be justified considering that bond-lines have a lower strength when exposed to peeling stresses (MODE I), compared to shear stresses (MODE II). Therefore the interest is to measure only the loads and the displacements normal to the shells surface.

Again looking at Fig. 1, one can assume the maximum displacement between the two shells to occur at half the distance between the TE bond-line and the box grinder bond-line.

In Work Package 2, the aim of task 2.2 is to define an instrumental setup, which can give us an idea of the maximum loads (tension) and maximum displacements (relative deformation between the shells) at the TE location in different wind conditions and at different pitch configurations.

Moreover local loads and displacements have to be referred to a specific blade position (rotational angle) and to the wind speed and direction, thus giving an idea of which are the effects on the TE of the maximum edgewise bending (own weight of the blade occurring at 90° respect to vertical alignment) and flapwise bending (aerodynamic loads at 0° pitch angle).

Besides this essential information it may also be helpful to have a reference of the global displacements of the blade, the actual rotational speed (19 rpm in operational condition) and the power production.

4. Measurement locations

As previously discussed, the aim is to measure the maximum loads and displacements on the TE which is expected to occur at the maximum chord section profile. Since this cannot be provided with certainty, an area near the maximum chord was defined and several measurements were carried out in order to define the optimal position where to place the load cells and the displacement sensors.

The tested blade is a V80 from Vestas, which has a “relatively old design” using an oversized spar cap (as can be seen below) and non-structural outer shells. The overall profile from the top view referred to the suction profile can be seen in figure 2.

The instruments were intentionally placed on the suction face, which has a flatter profile compared to the higher pressure surface and therefore more suitable to house the devices.

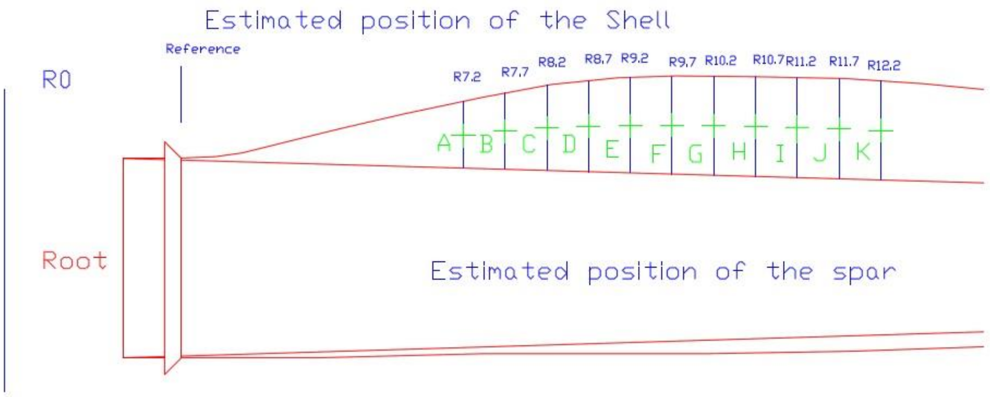

Fig. 2 - Top view of the V80 Vestas WT blade which was tested. 11 sections where defined and the measurement position for each of these can be seen marked with a green cross.

For completeness a table (table 2) with the coordinates of the location for each possible instrumented point is given. The distances were measured in the x direction with respect to the cover sheath and in the y direction with respect to the TE. It has to be noticed that the y coordinate reference changes for each section, due to the curvature of the TE.

SECTION	A	B	C	D	E	F	G	H	I	J	K
Radius [m]	R 7,2	R 7,7	R 8,2	R 8,7	R 9,2	R 9,7	R 10,2	R 10,7	R 11,2	R 11,7	R 12,2
Ref. distance [m]	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5
TE to BG distance [cm]	91	98	100	100	103	102	101	98	97	94	91
Measurement point distance [cm]	45,5	49	50	50	51,5	51	50,5	49	48,5	47	45,5

Table 2 – Location coordinates for each proposed measured point. The distances in the x direction were measured with a laser meter, while the distances in the y direction were taken with a common meter.

5. Instrumentation overview

In this section a detailed description of the chosen instruments is given along with an overview of the calibration procedure and the wiring connection scheme.

5.1 String potentiometer POSIWIRE WS10SG

In figure 3 the adopted displacement transducer with the wiring and fixing solution can be seen. Basically the string potentiometer is a transducer which gives a linear response of the displacement using a cable on a spring-loaded spool.

Fig. 3 – POSIWIRE WS10SG string pot from ASM, which was used in the test to measure the relative displacement between the shells in the defined points. In the picture can be noticed the connection plate then screwed to the laminate.

The specific features of the POSIWIRE **WS10SG-1250-10V-L10-SB0-M12** are listed below:

Model WS10SG
Measurement range 1250 mm
Output 10V 0 … 10V signal conditioner
Linearity L10 ±10%
Cable fixing SB0 cable clip
Connection M12 8pin socket M12 (ADCANOP 5pin)

The most important features considered for the selection were surely a wide measurement range – which in this specific task was not required – an analog output from 0 to 10V and an adequate length of the cable in order to have access at the defined TE locations. The cables, 15 meters long, were purchased with the sensors, assuring the best compatibility for the signal transmission.

5.2 Load washer LCMWD-20KN

In figure 4 one can see the load cells adopted to measure the compressive load on the bolted connection at the TE. This specific design of load cell is called load washer, due to the fact that it is mounted as a washer in a rigid bolted connection.

Fig. 4 – LOAD WASHER LCMWD-20KN from OMEGA adopted to measure the compressive load on the bolt connecting the two shells of the TE. The load cell is mounted by means of a proper designed plate through the drilled holes in the sandwich panel. The load washer is connected to a 2,5 mm diameter string fixed through a plate to the lower panel. Any adjustment in the alignment is allowed thanks to the spherical washer set – "IGUS washer", which provide a proper load distribution on the load cell. The initial tension on the string (compression on the load cell) is adjusted by screwing the fitting button on top (not showed in figure), in order to have a stiff configuration.

The load washer measure the applied compressive strain through a full Wheatstone bridge and gives a linear output as a voltage signal, which can be ascribed to the applied load. The transfer function of the adopted load washer can be described by this equation:

$$\Delta V_o = K \times V_{ex}$$

where the ΔV_o is the full scale output voltage in mV, K is sensitivity of the strain gauge (or gauge factor) in mV/V and V_{ex} is the excitation voltage in V. Those are the requirements for the used strain gauge:

Model LCMWD-20kN
Measurement range 20 kN
Output 2mV/V ±20% (K factor)
Accuracy (<50kN) ±0,5% BFSL
Zero balance ±4% FSO (full scale output)
Operative temp. range -40 to 127 °C
Compensated temp. range 16 to 71 °C
Save (max) overload 120% (200%) of capacity
Bridge resistance 350 Ω min
Full scale deflection 0.025 mm typical
Connection M12 8pin socket M12 (ADCANOP 5pin)
Cabling 15 meter shielded cable

The adopted load washer has a full bridge configuration, than means the related strain is defined, under the hypothesis of pure axial stress, as:

$$\varepsilon = \frac{4}{K} \times \frac{V_o}{V_{ex}}$$

where ε is the strain in $\mu\varepsilon$ ($10^{-6}\ \varepsilon$) and is given as the sum of the "measured" strain for each resistance of the full bridge:

$$\varepsilon = \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4$$

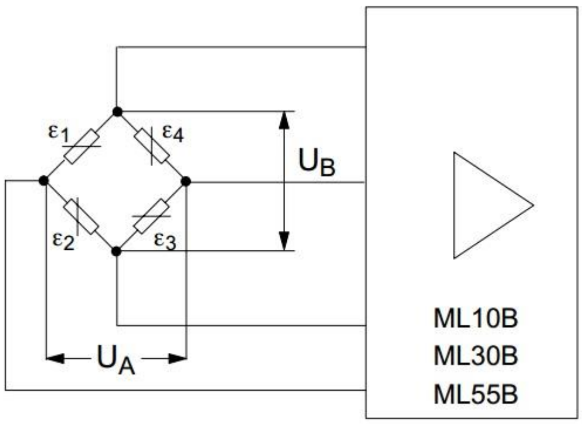

Fig. 5 – Full bridge strain gauge configuration: U_A correspond to the output voltage, while U_B is the excitation voltage

Since generally the strain gauges need an external amplifier to be powered, as well as to read out the voltage variation, the 3 adopted load washers where connected to an amplifier MGCplus, and then the conditioned signals were sent to the DAQ card. The excitation voltage for the load cells was set to 2,5Vdc, while the maximum available that could be chosen on the

MGCplus amplifier was of 5Vdc. The suggested excitation voltage from the datasheet of the Omega load washers was 10V, however with our setting we noticed we reduced partially the noise on the output signal. The output signal was varying from 0 to 10V according on the output scale set on the amplifier.

Each of the 3 compressive load cells were calibrated by applying a compression sin wave cycle through a tensile testing machine, thus confirm us that the parameters set on the amplifier were correct and that the resulting sensitivity corresponds to the one stated on the certification paper. However the noise on the out coming signal, especially for low load level, was not negligible; this due probably to the amplifier and to the large measuring load range (20KN) chosen for the load cells.

5.3 Inclionometer ZCT1180KS-SNS-29 (1-axis)

In order to couple the measured load and displacement to the rotational angle of the blade, an inclinometer was used. This could give us a better understanding of the worse load situation depending on the influencing parameters and, moreover, it could help us to interpret the dependency of the loads and displacements at the TE with the rotational speed. In figure 6 the selected inclinometer is showed.

Fig. 6 – 1-axis Inclinometer sensor ZCT1180KS-SNS-29 by ZC Tech. The measuring range goes from -45° (-90°) to 135° (90°) and the analog voltage output vary from 0,5V to 4,5V.

The technical specifications for the inclinometer are described below:

Model ZCT1180KS-SNS-29
Measurement range 180° (-90° to 90°)
Output 0.5 to 4.5 V
Accuracy 2V/g
Sensitive error -1.5 … 0.5 %
Zero drift tolerance ±2° at 2.5 V
Operative temp. range -40 to 85 °C
Power supply 12V DC typical (min 8V max 36V)

The characteristic curve for the inclinometer is shown in figure 7: as can be noticed the transfer function is not linear along the full range of the instrument. This has revealed to be an issue, since the acquisition rate was time based (fixed acquisition frequency), and the resulting acquired points were differently spaced in the region close to -90° and 90°.

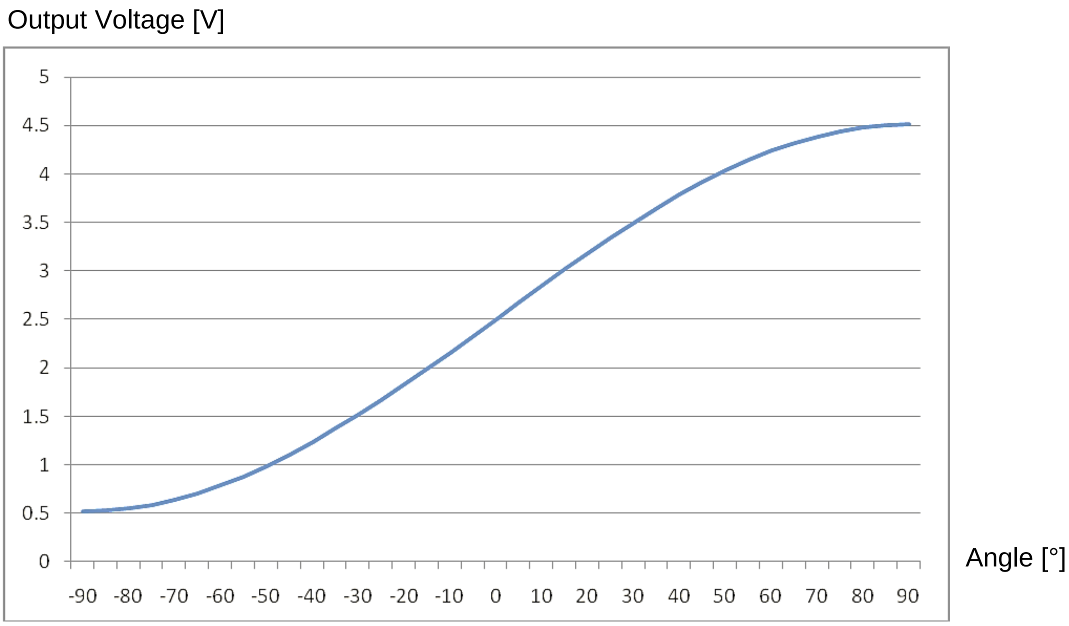

Fig. 7 – Characteristic transfer curve for the inclinometer: the output voltage from the inclinometer is not a linear function of the angle. This means that, as the angular speed is constant (19 rpm) and the acquisition frequency rate too, the acquired points will be differently spaced (time based acquisition rate) in the non-linear region.

The transfer function can be described as follows:

$$Angle = \sin^{-1}\left[\frac{V_{Out} - offset}{Sensitivity}\right]$$

$$V_{Out}\ analog\ voltage\ output$$

$$offset = 2.5\ V\ output\ voltage\ at\ zero\ position$$

$$Sensitivity = 2\ V/g$$

It was possible to overcome to this problem by setting an adequate acquisition frequency resulting in a sufficient number of data points in the nonlinear region. However the linear region had an excessive number of acquired points without any significant variations of load and displacement. Another issue encountered was related to the measurement range which is of 180°. This does not mean that the remaining 180° range could not be acquired, but that the resulting output voltage was varying from 4.5 to 0.5 V pretending to indicate a change in the rotational direction. It was possible to overcome to this in post processing.

In figure 8 a screenshot of the acquired data from the inclinometer is proposed with the evidence that the position is always known even in a range of 180°.

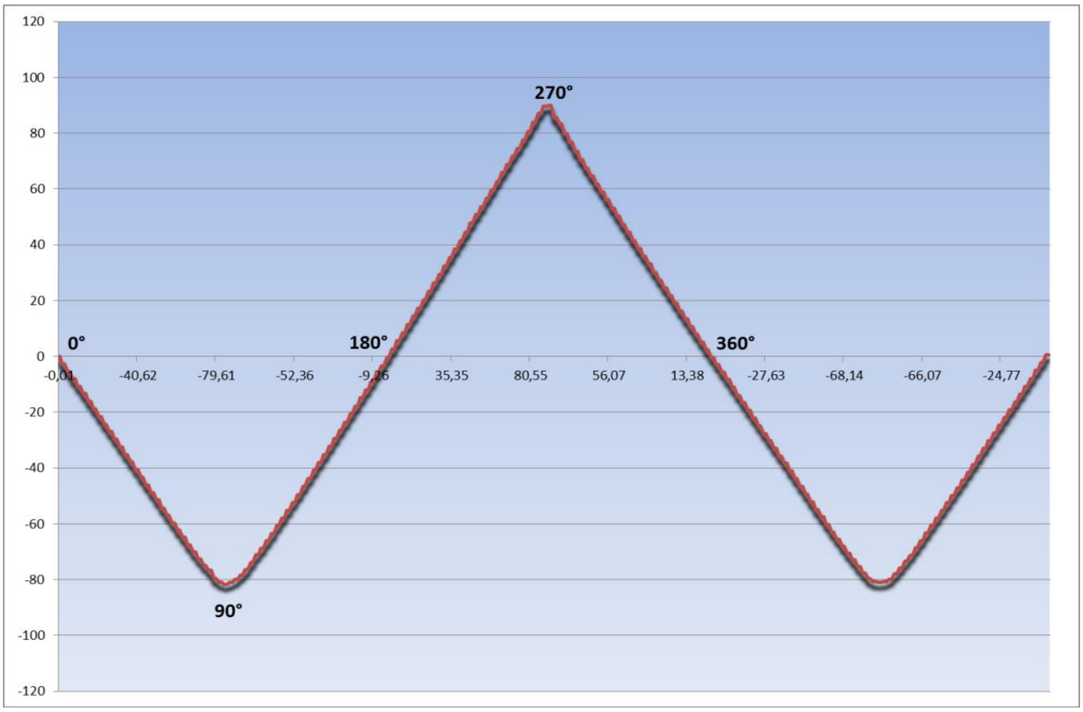

Fig. 8 – Zoom resulting from an acquired set of data through the inclinometer sensor. The raw data were acquired in Volt and further post processed, applying the transfer function of the instrument, to obtain the indicated curve in degrees versus time. It can be noticed that each position (min, max and intersections with the time axis) correspond to an absolute position of the blade.

The adopted reference positions for the instrumented blade can be recognized from figure 9.

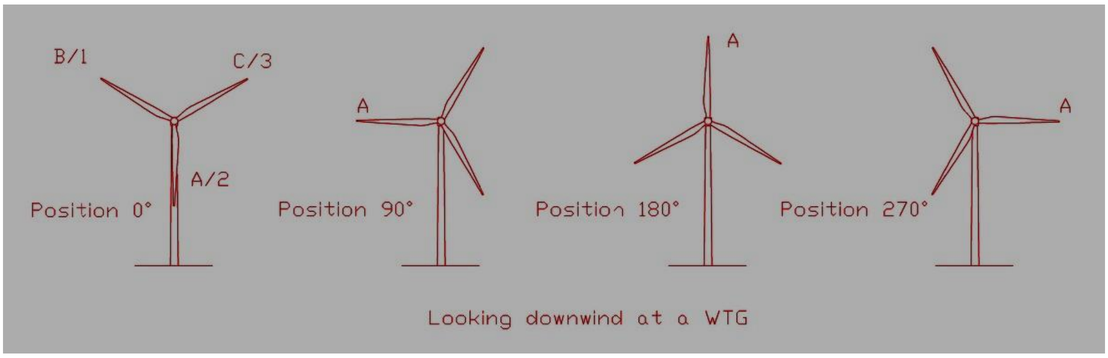

Fig. 9 – Reference position for the instrumented blade A/2 with respect to the angle measured from the inclinometer.

5.4 MGCplus HBM amplifier

As previously stated the load washers needed to be powered from an external source and we had to connect them through a proper strain gauge amplifier, which in the case was the MGCplus from HBM, shown in Fig. 10. Basically the strain gauge amplifier could excite the 3 load washers and measure the variation in mV at the ends of the Wheatstone bridge, thus giving an analog output varying from 0 to 10V, which is proportional to the mV variation. The 3 output channels from the amplifier were then connected to the data acquisition card – DAQ – which collected all the data and sent them for storage in the laptop. MGCplus amplifier specifications:-

Model MGCplus AB22A from HBM
Dimensions 255x171x367 mm
Weight (TG001C Desktop housing) approx. 6Kg
Strain gauge config. Full bridge
Calibration mode 2 points calibration (without inputting K factor)
Value displayed directly in KN (and not μStrain)
Measurement range 0 to 5KN
Channel Output 0 to 10 V (Ch. 1 – Ch. 2 – Ch. 3)
Accuracy ±20N (at high load)
Excitation Voltage 2.5 V
Operative temp. range -20 to 60 °C
Power supply 230V AC

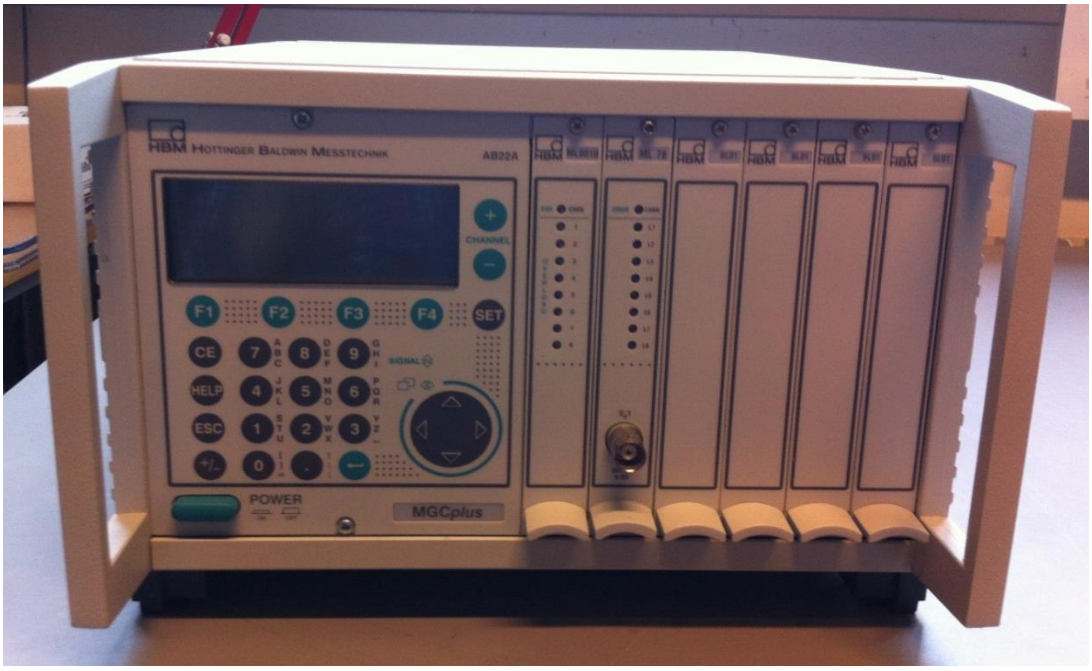

Fig. 10 – MGCplus Amplifier from HBM interconnected between the load washers and the data acquisition card in order to allow the read out the signal measured from the compressive load cells.

A problem encountered during the load washer calibration phase was the high noise level, which could not be reduced even by changing any parameters on the strain gauge amplifier or by changing the load cell's connectors. The noise level at "no load" was up to ±50N, while increasing the load this noise reduced to ±20N. We tried to reduce it by setting low pass filter (Bessel 5Hz) both on the input and on the output without any significant improvements. Anyway the guaranteed accuracy from the OMEGA load washer was confirming our values, and since the measuring range was of 20KN we could not achieve better accuracy with this hardware. On the other hand, since we could not have a precise idea of the expected TE loads, we adopted this 20KN load range in order not to fall out of range.

5.5 Data Acquisition card – DAQ

As already mentioned all the measured signals where sent to the Data Acquisition Card USB-1608FS from Measurement Computing, which was allocated in the grey plastic case, showed in figure 11.

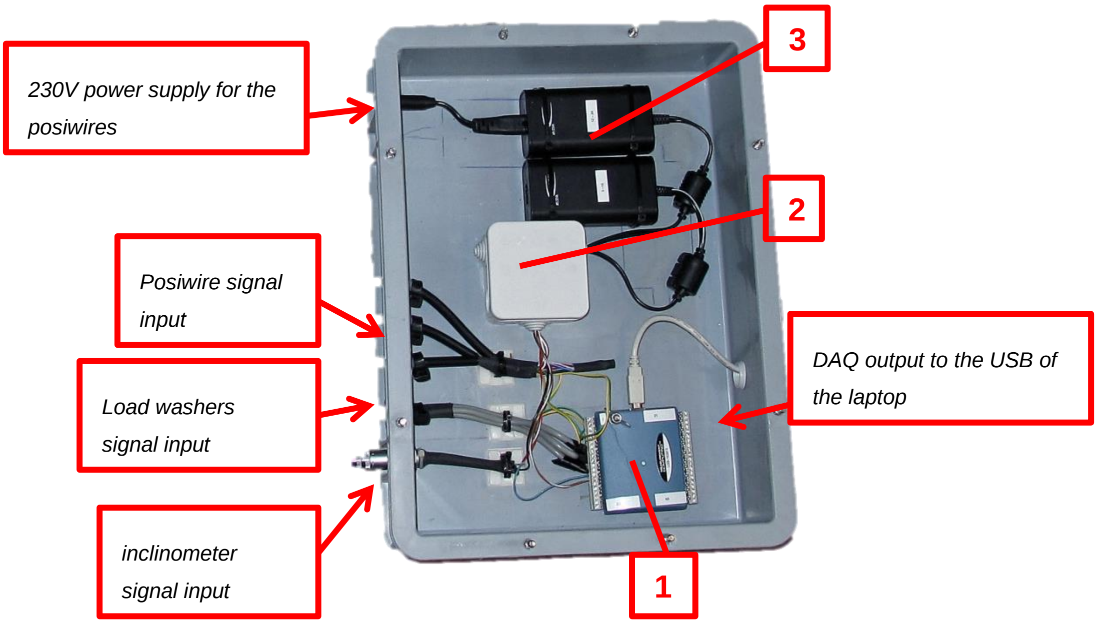

Fig. 11 - Connections case 50x30x10 cm where the DAQ card was allocated (1) with the cabling box (2) and the posiwires power supply (3). On the bottom left side one can see the cables from the posiwires, the load washers and the inclinometer, while on the right side the output to the Laptop running the DasyLab acquisition program. On the upper left the power plug for the posiwire transformer supply.

An additional electricity source was necessary to power the posiwires, while the inclinometer was self-powered and the load washers power comes from the strain gauge amplifier. The Data Acquisition Card USB-1608FS was communicating through a CAN-Bus to the laptop running DasyLab, which was set to store all the desired data in a text file accessible from Excel.

5.6 Laptop running DASYlab

In order to acquire all the data, a block diagram was designed in DasyLab which allow us to store in the local solid disk of the laptop a text file with a header related to the test conditions. For brevity in this subparagraph the DasyLab block diagram main window in shown, while the start-up procedure will be explained in the following sections.

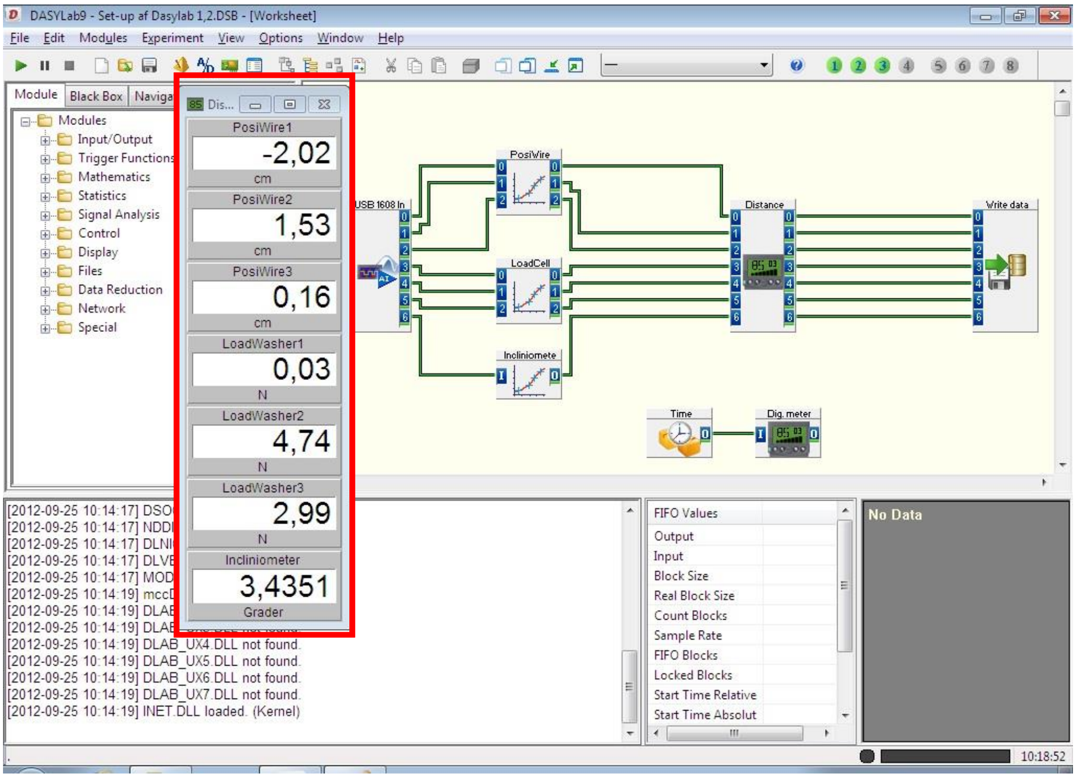

Fig. 12 – Block diagram main window of DasyLab: the highlighted in red window shows all the instant values acquired. As can be easily understood the signal coming from the DAQ – USB 1608 In block – are defined ***RESPECTIVELY*** *– PosiWire, LoadCell and Incliniometer block diagram – and then stored through the write data block. The time block synchronize the laptop internal clock with the starting of the acquisition.*

6. Test system set-up

This chapter contains the information related to the connecting procedure of all the equipment, the calibration of the instruments in order to run a test, and a general explanation of the issues encountered in achieving a successful fixing solution for the load cells and the displacement sensors.

6.1 Connecting the instruments

The instrumental equipment consists of the following items, which can be recognised in Fig. 13:

1. Laptop running DASYLab;
2. N.3 20KN load washers LCMWD Series from Omega;
3. HBM MGCplus Amplifier for the load washers;
4. N.3 String pots POSIWIRE WS10SG from ASM;
5. Connections case 50x30x10 cm;
6. Data Acquisition Card USB-1608FS from Measurement Computing;
7. 1-axis inclinometer sensor ZCT1180KS-SNS-29 from ZC Tech;
8. 24V DC to 230V AC inverter (100W power required) – not shown here; see fig 15

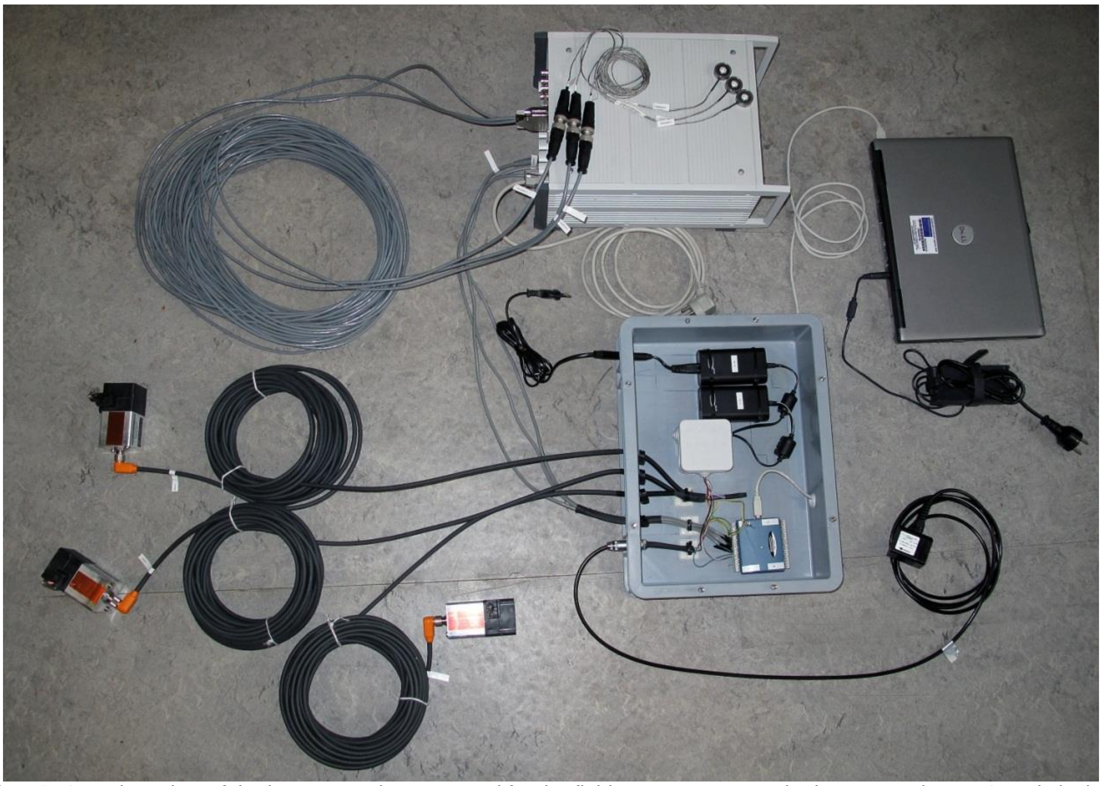

Fig. 13- Complete view of the instrumental set-up used for the field measurements. The laptop running DASYLab (point 1), 3 load washers with the relative amplifier (indicated with 2 and 3), 3 "posiwire" string pots (indicated with 4), the connections box with the data acquisition card (point 5 and 6), the inclinometer (point 7).

The connections between the instruments can be summarised as following:

a. The N.3 “posiwires” (4) are connected through the orange plug connectors to the 15 meters black cables, which are therefore already connected to the grey connection box (5)

b. The N.3 “load washers” (2) are connected through the black pins connectors to the 15 meters grey cables

c. These grey cables are then connected to the MGCplus Amplifier (3) through the single 25-pins connector, which is defined as input in figure 14.

d. The N.3 grey coaxial cables from the connection case (5) are connected to the output channels of the MGCplus Amplifier (3), as can be seen from figure 14. Channel 1 is attached to load washer 1, Channel 2 to load washer 2 and Channel 3 to load washer 3

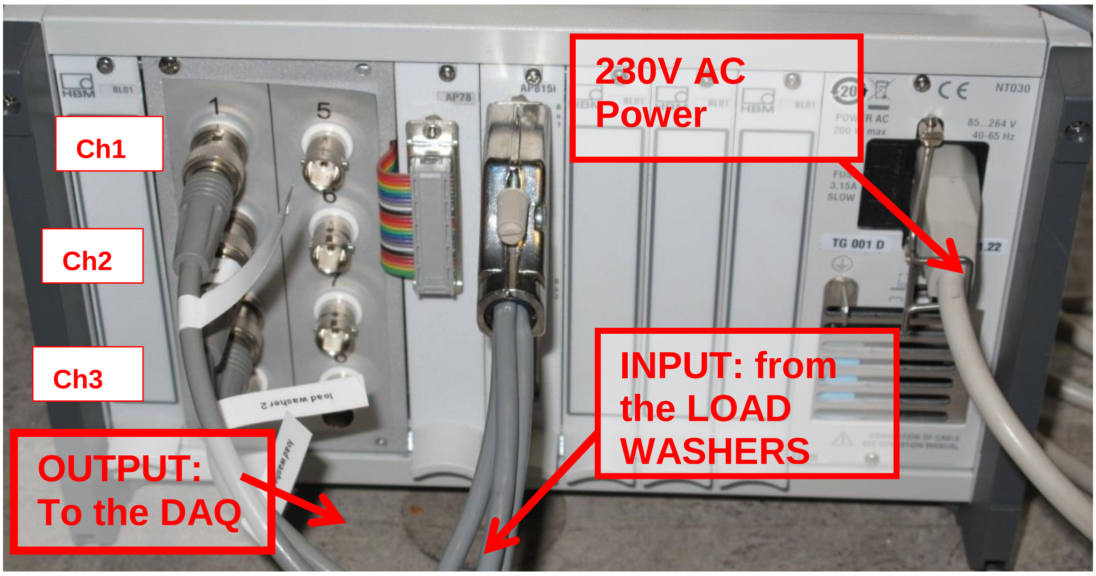

Fig. 14 - Detailed view of the back HBM amplifier connection: as one can see the 3 coaxial cable are the numbered output and are connected to the DAQ through the connections box, while the input coming from all the 3 load washers are connected through a 25-pins connector. On the right the power source of the amplifier can be noticed.

e. The inclinometer is attached to the connection case (5) through the coaxial plug

f. The Data Acquisition Card (6) is plugged to the Laptop through the USB cable

g. N.3 230V power sources are needed:

- 1 for the source of the MGCplus amplifier
- 1 for the Laptop
- 1 for the source of the 3 “posiwires”

As already discussed, the 3 load washers and the 3 string pots where placed on the maximum chord TE zone and one can recognize the 15 meters cable bundle on left of figure 13. The remaining instruments (DAQ system + inclinometer) were mounted on the interface between the outer rotor hub shell and the load bearing section, as can be seen from figure 15.

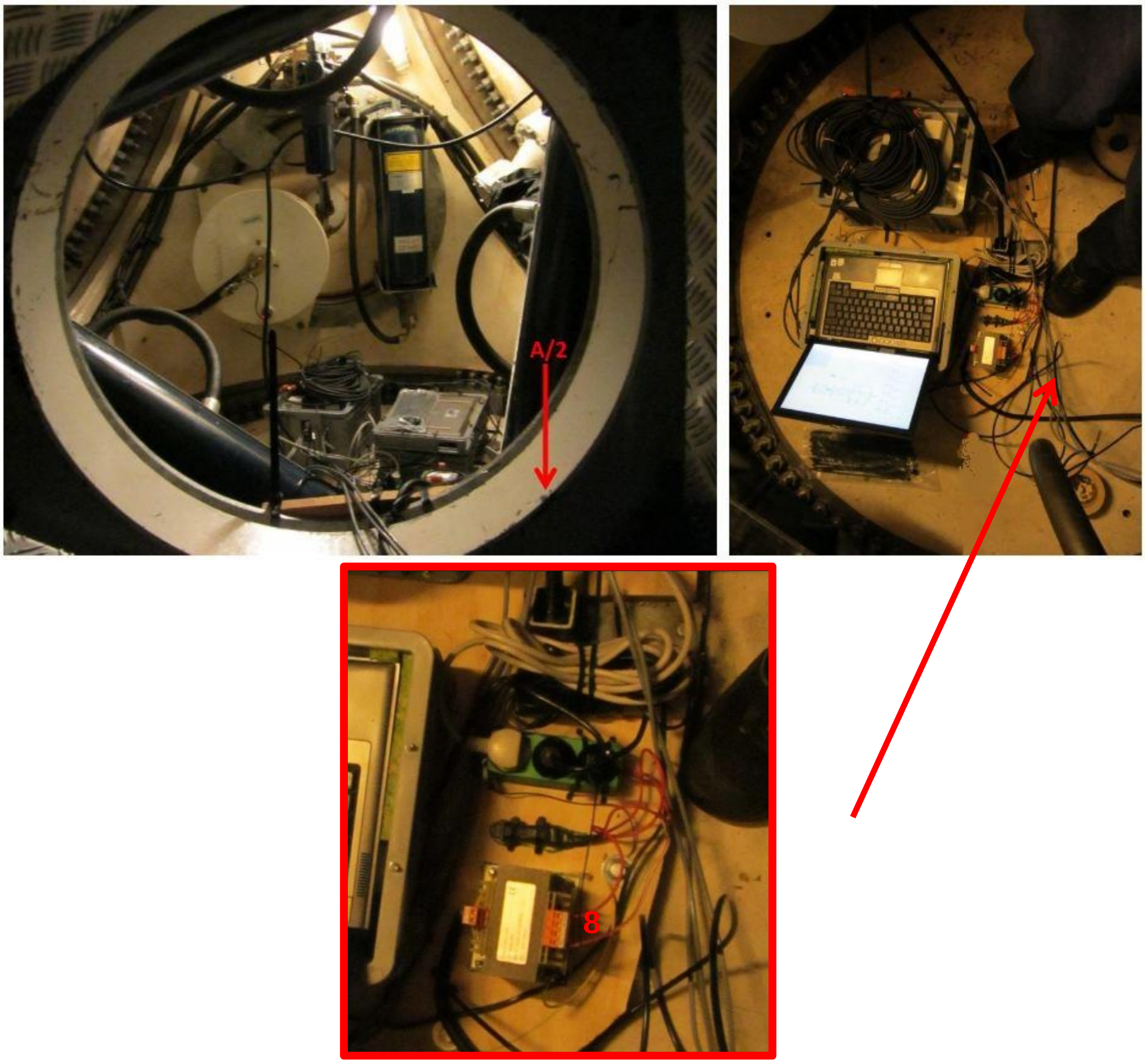

Fig. 15 – Rotor hub hollow space view where the DAQ system was mounted. Both the Laptop and the Amplifier were enclosed in a grey box properly modified with cooling hollows and Plexiglas cover; these were stacked one to each other close to the rotational axis of the WTG. In the bottom figure indicated with a red arrow, zoomed view of the inverter (point 8 on the list) which was needed to convert the power supply took from the auxiliary to a proper 230V AC required from the instruments.

The connection case, as well as the other 2 boxes for the amplifier and the laptop (visible in Fig. 15), were made waterproof using a Plexiglas layer as a cover, and placed on a fixed plate. The inclinometer was also fixed on this plate, though a wooden stick and adjusted in order to align it with the instrumented blade along the vertical position. The power was provided thought an inverter from an auxiliary supply used for maintenance operations, the overall power consumption was expected to be approximately 100W.

6.2 Fixing solutions adopted

At the end of the previous subsection the fixing solution adopted for the DAQ system was already briefly explained, in this subsection more focus is given to the instrumentation of the TE.

The string pots were mounted aligned to the edgewise direction – as can be seen in figure 16 – by means of an aluminium plate, screwed directly on the composite panel. It can be noticed that it was chosen to place them between the instrumented point and the max chord point, since we should expect to have an aerodynamic flow from the leading edge to the trailing edge which could otherwise affect our measurement. By doing this in fact we could partially shield the string location, in order to minimize the fluctuation of the string. It was also considered to cover with a Plexiglas tube the outer string, but the displacements measured revealed not to be influenced from the wind flow.

The upper “button” plate was designed with that particular shape (triskelion) in order to help minimise the distance between the posiwire and the hole through the panel. Moreover a certain thickness was necessary to align the string to the axis of the posiwire, thus avoid any potential friction effects.

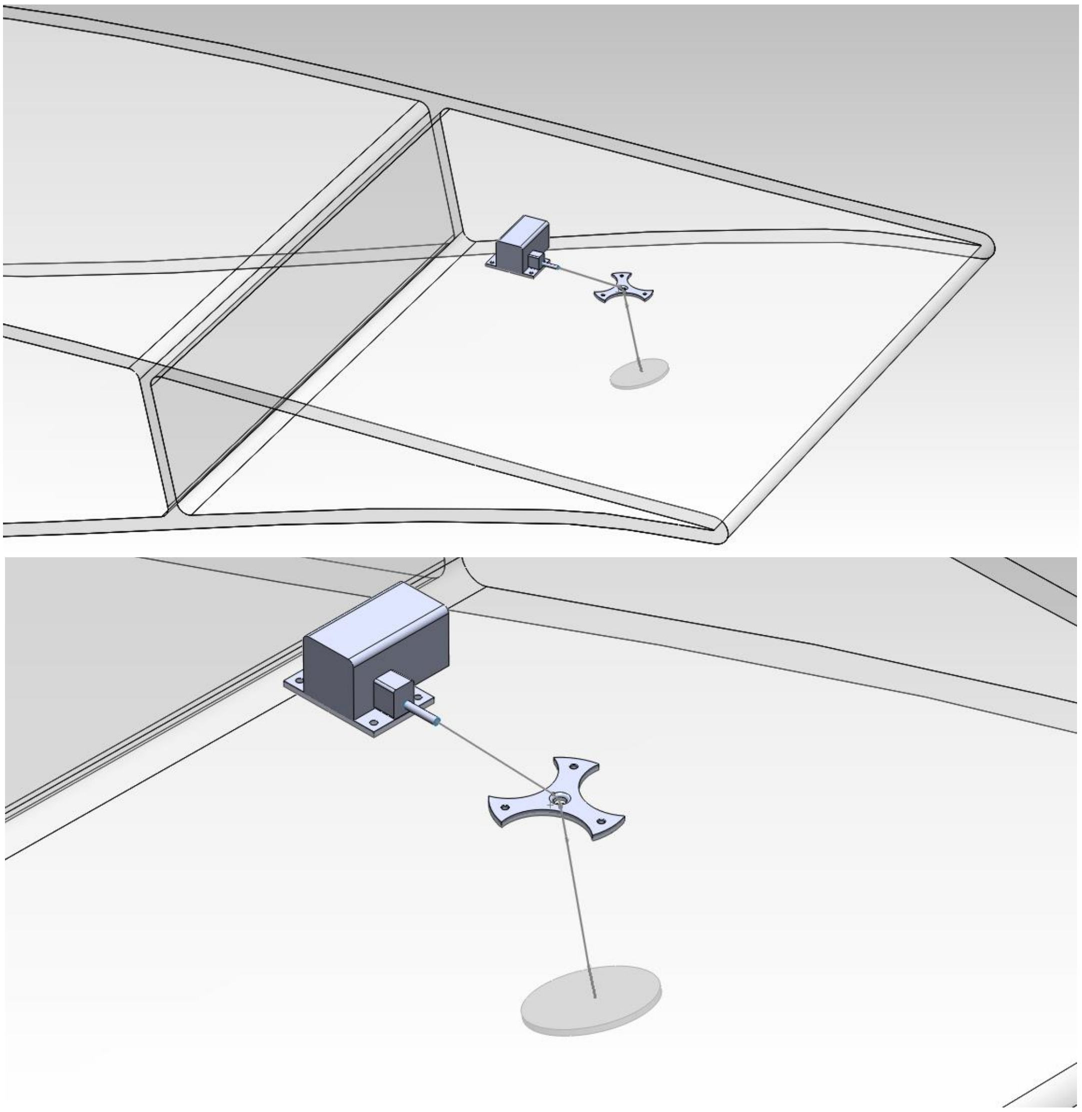

Fig. 16 – Schematic 3D model of the adopted fixing solution for the posiwires on the suction profile of the WTB V80 from Vestas. The posiwire is screwed through an aluminium plate directly to the sandwich panel, the (triskelion) shaped plate on the upper surface allows the string to be aligned with the axis of the posiwire and ensure a smooth curvature of the string. A hole on the shell allows the string to connect upper and lower shells and measure the relative displacements, the lower end of the string is attached to the lower panel by means of an aluminium plate screwed directly on it.

The load washers were also connected through a string to the lower shell using the same plates, as can be seen in figure 17. The bolt-string structure need to be pre-tensioned in order to set an adequate zero value on the measured compression load and this could be achieved by manually adjusting the tension on the string.

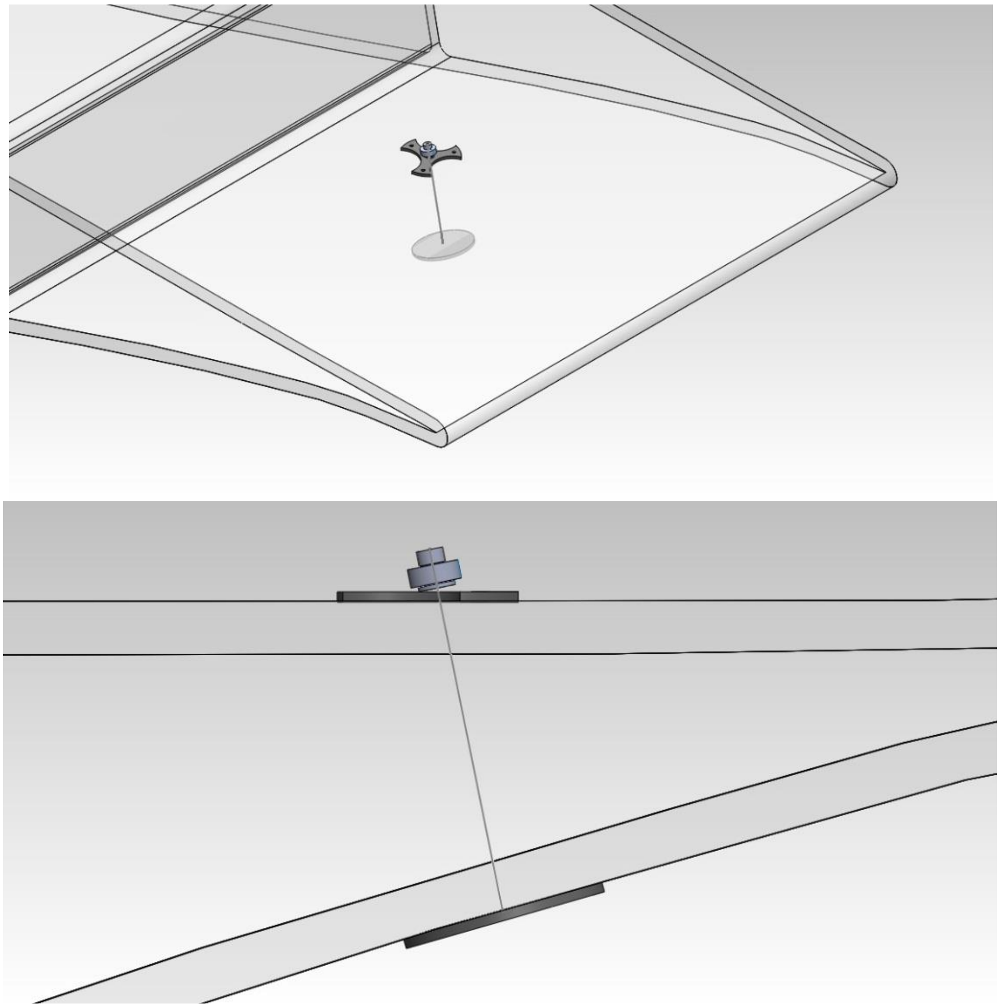

Fig. 17 - Schematic 3D model of the adopted fixing solution for the load washer on the suction profile of the WTB V80 from Vestas. A hole on the shell allows the bolt to be connected through a string to the lower shell.

The alignment of the all system (load cell + bolt + string) has to be verified, in order to avoid bending effects, which may affect the measure. Indeed – as can be seen in figure 18 – we had to adjust the inclination of the load cell, by means of an “IGUS washer”.

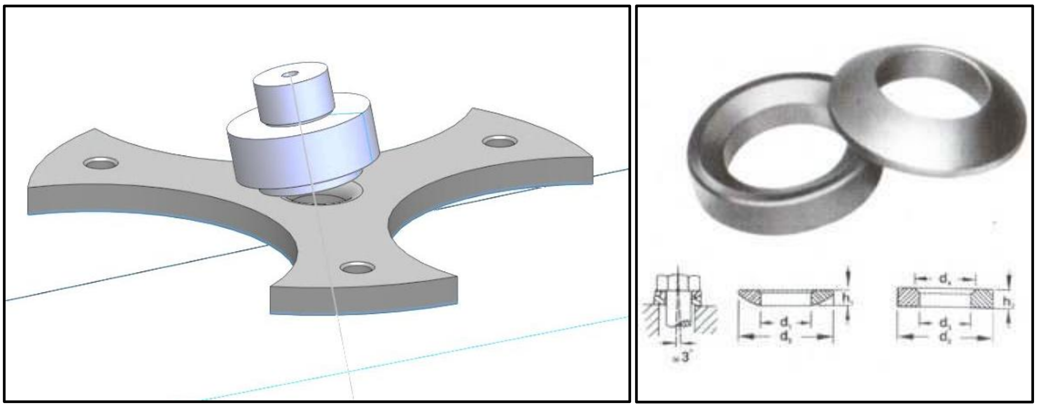

Fig. 18 – Detailed view of the load washer mounting solution adopted: on the left it can be noticed that it was necessary to tilt of an adequate angle the load washer/string connection to have a pure compression stress. We achieved to this adopting proper spherical washers – IGUS washers – showed here on the right.

The fact that the string had to be placed in the position – reference figure 17 bottom – instead of being aligned through the vertical, comes from the need to measure the maximum displacement occurring between the shells. Moreover it was impracticable to align the two holes in the vertical direction; it was already pretty complicated to perform such a procedure clinging to a rope at 80 meters high.

However, the "rope guys" in charge of the mounting stage performed well and could manage to adjust the tension on the load washer through the designed fitting button.

The internal shear measurements between the spar cap upper and lower surfaces were also taken using two of the string pot transducers mounted diagonally across the internal space of the beam.

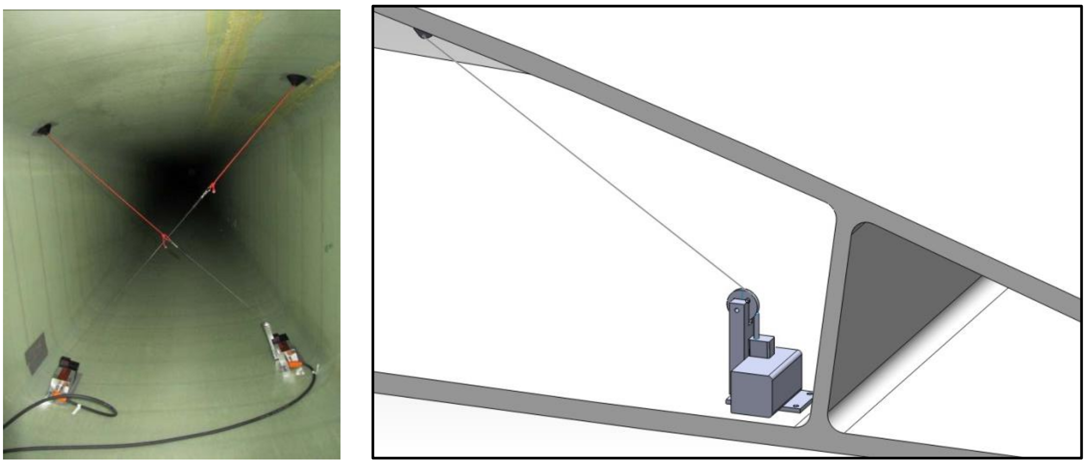

Fig. 19– Realized (left) and 3D schematic (right) fixing solution for the internal "shear displacements" measured with the posiwires at a 10 meters length inside the spar cap. A string was attached with some double side flash tape to the GFRP surface, by means of a plastic cone. The posiwire was mounted in a vertical position on the opposite surface, using this double side flash tape. A pulley was manufactured in order to direct the string in a correct was, avoiding any friction.

The location of the measurement was chosen at 10 meters radius inside the spar cap, it was inconvenient to go deeper due to limited access as the beam tapers. The blade was positioned in a horizontal position and the "rope guys" managed to place the instruments and the cables.

6.3 Calibration & Acquisition Procedure

In this section more information on how to perform an initial calibration of the measurement equipment is given as well as an overview on the use of DasyLab.

Once the hardware connections are made and the main instruments positioned and fixed there is still the need to adjust reference positions for the inclinometer, the string pots (posiwires) and the load cells (load washers).

A. Reference position for the inclinometer
The adopted inclinometer has a range of 180° between -90° and +90°. The 0° position corresponds to the vertical position of the instrumented blade A/2 as shown in figure 20.

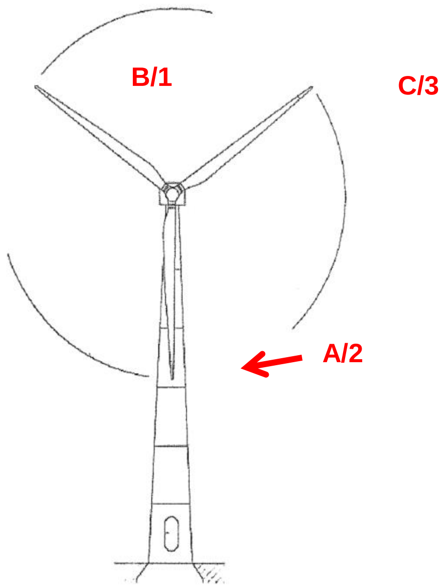

Fig. 20- Schematic illustration of a wind turbine fixed in the "maintenance configuration". The instrumented blade is the vertical one, and is commonly denominated the A/2.

Thus the inclinometer needs to be aligned with the instrumented blade when positioned in the hub, and the 0° reference position set as the vertical one.

By starting up the laptop and launching an acquisition session in DASYLab, one can control the alignment to the reference position as can be seen in figure 22 and the inclinometer can be manually adjusted and screwed on the wooden plate.

To set DASYLab in the acquisition mode, after launching it, go to *file → Open → Desktop → Bondline Project → Bondline Setup → 2012-10-01 Bondline Setup.*

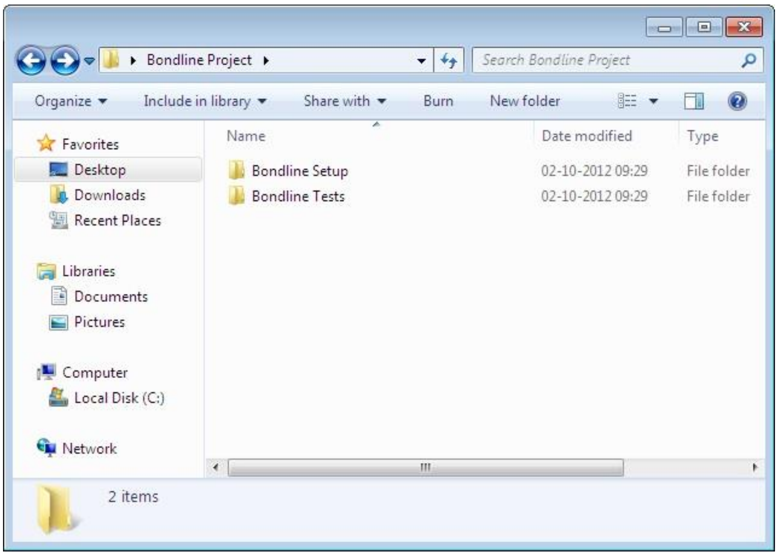

Fig. 21 – Screenshot of the folder where the setup file is located.

Once the setup file is loaded one has to press the “play button” highlighted in figure 22 and the system start to acquire and write the data in a text file located in the same folder of the setup file.

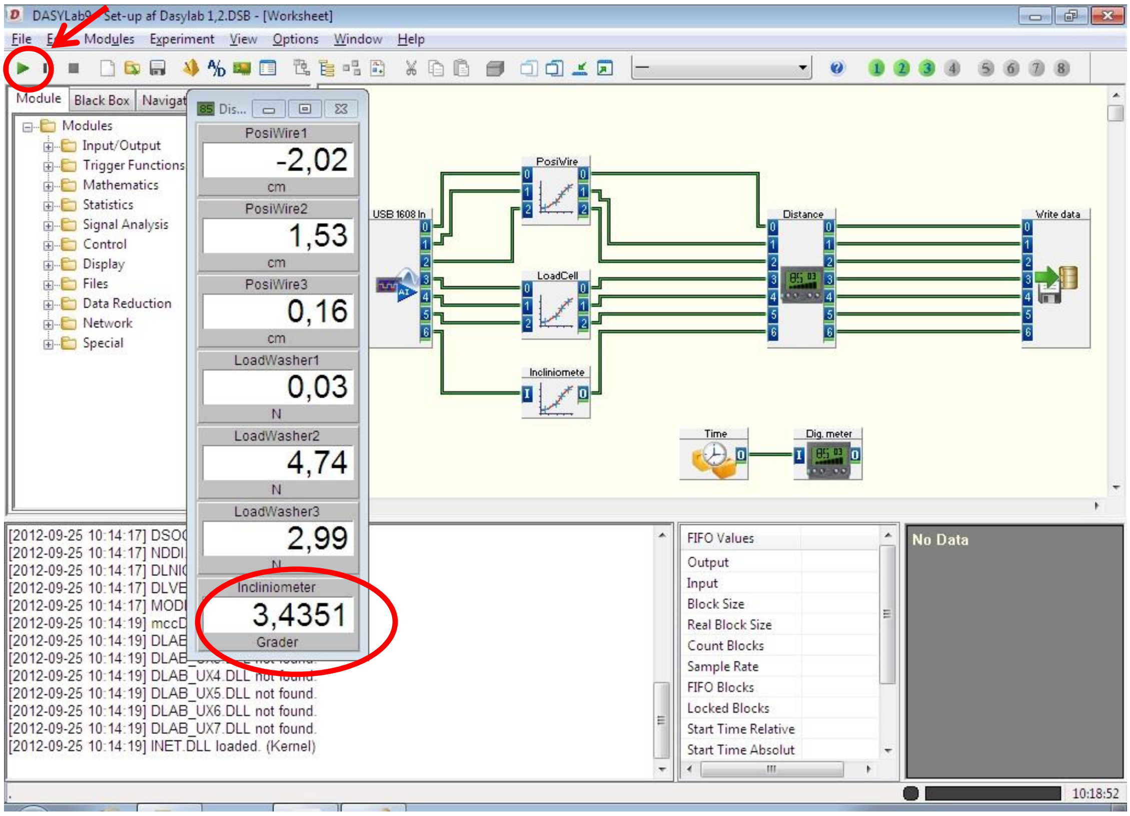

Fig. 22 - Main screenshot of the DASYLab setup file. The vertical window displays the instant acquired values from the connected instruments. The angle for the inclinometer is identified by the red colour circle and in the calibrating procedure it has to be as close as possible to 0° degree reference.

B. Acquisition procedure

After the calibration procedure is completed the test is ready to start, thus the real data acquisition can be performed. An important setting to add before starting is to define the header of the text file, which will be stored during acquisition. The basic file header contains the starting time and date of the experiment, the acquisition rate and the number of acquired channels. Since several test in different conditions will be performed it is therefore useful to define for each test wind conditions (wind speed [m/s], wind direction), rotational speed of the rotor [rpm], pitch angle [°] – if fixed pitch angle test – and eventually other parameters. This is advantageous in order to have a correspondence between each test and external variables influencing which might influence the data.

From the main block diagram window, double click on the *Write data block* and the window showed in figure 24 will appear, then by clicking on the *Comment selection* one can have the possibility to write any comments to append to the header of the stored file. All the steps to follow are shown in the following page.

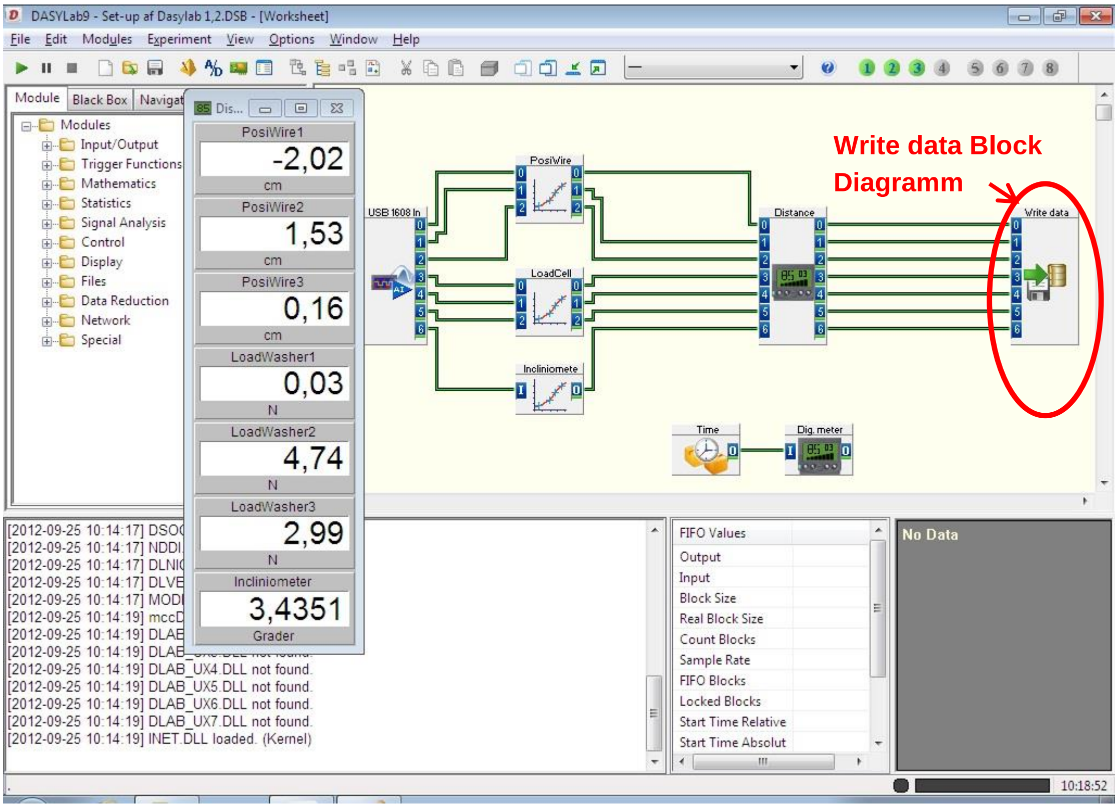

Fig. 23 - Main screenshot of the block diagram: the write data module is highlighted in red colour on the upper right.

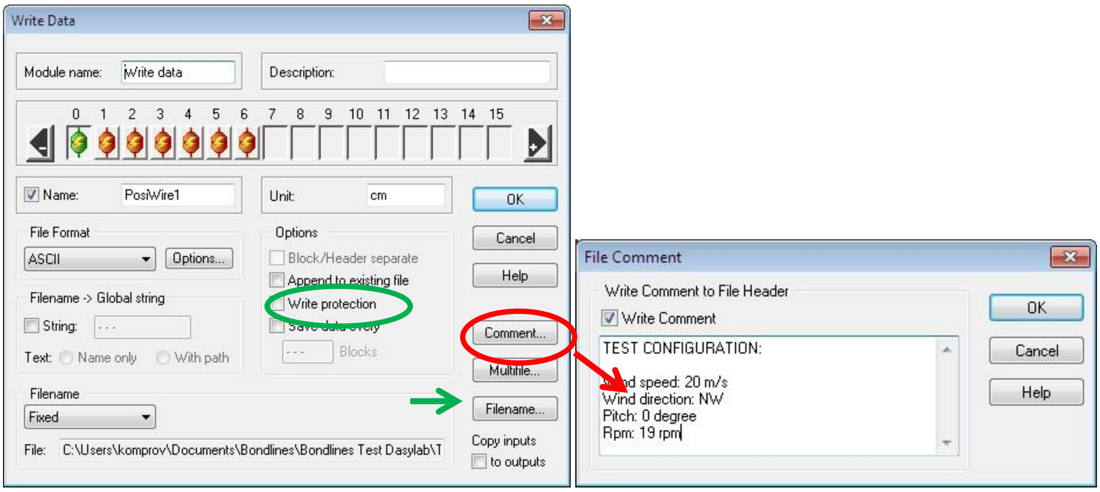

Fig. 24 – Window screenshot of the Write data module at the left and File Comment window on the right. In addition also the Write protection selection has to be flag (circled in green colour) and the Filename (indicated with a green arrow) has to be defined each time a new acquisition is started.

Moreover, in order to be sure not to overwrite the test file once another acquisition is launched the *Write protection* selection in flagged, as highlighted in figure 24, and when pressing the “play button” a message error will occur saying to rename the filename for the new acquired dataset. This can be done, with reference to figure 24, by clicking on *Filename* and renaming the test file as: *YYYY-MM-DD Test N.XX.*

Briefly, the steps to follow in order to perform an acquisition, can be resumed as follows:

1. Launch DASYLab from the shortcut on the Desktop
2. Open the setup file *2012-10-01 Bondline Setup* that can be founded on *file → Open → Desktop → Bondline Project → Bondline Setup*
3. Double click on *Write data module* that can be founded on the right side of the blocks diagram
4. Go to comment and click to open the *file comment window*, where the specific information regarding the relevant parameters influencing the test can be added

   e.g. *Test_XX*
   wind speed: 15 m/s
   wind direction: NW
   rotational speed: 19 rpm
   pitch angle: 0°

5. Change Test File name by clicking on *Filename* which can be found in the same *Write data window*; the test file name has to be named as follows: *YYYY-MM-DD Test_XX*
6. Run the acquisition by pressing the *play button* and make sure that the displayed signals are almost stable and close to a reasonable value.
7. After the test has been performed stop the acquisition by pressing the *stop button*, which is the red square button.

Go to the folder *Desktop → Bondline Project → Bondline Tests → YYYY-MM-DD Test_XX* and send the acquired file to the pen drive. To be sure you are sending the correct file, you may open it and check the header of the file.

6.4 Measurement Plan

Recalling for clarity table 2, the ideal measurement plan is further discussed.

SECTION	A	B	C	D	E	F	G	H	I	J	K
Radius [m]	R 7,2	R 7,7	R 8,2	R 8,7	R 9,2	R 9,7	R 10,2	R 10,7	R 11,2	R 11,7	R 12,2
Ref. distance [m]	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5
TE to BG distance [cm]	91	98	100	100	103	102	101	98	97	94	91
Measurement point distance [cm]	45,5	49	50	50	51,5	51	50,5	49	48,5	47	45,5

Table. 2 – Coordinates of the location for each measured point. The distances in the x direction were measured with a laser meter, while the distances in the y direction were taken with a common meter.

The procedure is summarised as follows:-

a. Define a set of 6 section, i.e. A, C, E, G, I, K

b. Instrument the first 3 section i.e. A, C, E with the “posiwires” and run a first test (10-15 min) at 0° pitch angle, to acquire the displacements and define the maximum of the set;

c. Dismount the “posiwires”, install the “load washers” in the same sections i.e. A, C, E; run a test in similar conditions to acquire the respective loads;

d. Repeat points (b) and (c) for the second set of sections i.e. G, I, K and compare maximum displacements and loads occurred;

e. Point (b) and (c) may be repeated on the remaining intermediate sections i.e. B, D, F, H, J. Based on the value obtained from the previous measurement, it may be sufficient define only 2 more sections;

f. At this stage the maximum displacement (load) point has to be defined, and a new set of measurement for the 3 sections close to this point has to be carried out i.e. E, F, G;

g. Measure the displacement for the last set of sections defined i.e. E, F, G, in different pitch configuration i.e. 0°, 45°, 90° (each test may take no more than 15/30 minutes, depending on the time/weather conditions);

h. Measure the loads for the last set of sections defined i.e. E, F, G, in different pitch configuration i.e. 0°, 45°, 90° (each test may take no more than 15/30 minutes, depending on the time/weather conditions);

i. Extended test on the same sections i.e. E, F, G without fixed picth angle (time can vary depending on the plan and left time, but 2-3h may be sufficient). Since the “loads washers” are already mounted, perform first the load measurements;

j. Dismount the “load washers” and mount the “posiwires” in order to perform the extended the same extended test and acquire the displacements.

More comments are added in the next page in order to give an overview of the important parameters, which has to be controlled during the second stage tests **i.e. point g, h, i, j**.

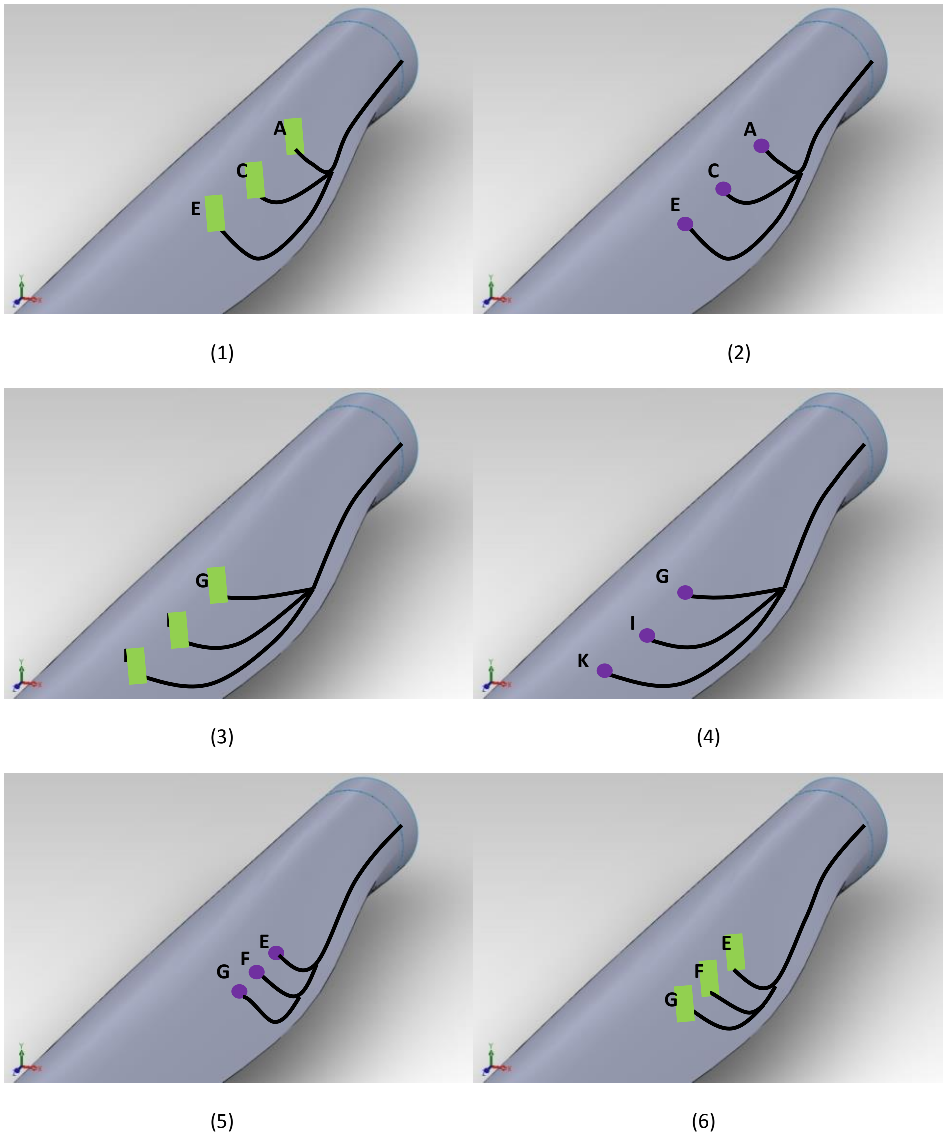

Fig. 25 - Main view of the instrumented blade with highlighted the cables arrangement along the TE. In green colour the 3 string pots, while in purple colour the 3 load washers. (1) 1^{st} set of displacement measurements on section A, C, E in order to find the point where the maximum displacement occur. (2) 1^{st} set of load measurements to acquire the corresponding loads at the same sections A, C, E. (3) 2^{nd} set of displacement measurements on section K, I, J in order to find the point where the maximum displacement occur. (4) 2^{nd} set of load measurements to acquire the corresponding loads at the same sections K, I, J. (5) 3^{rd} set of measurement to acquire the corresponding loads around the maximum displacement point – i.e. F – at different pitch angles. (5) 3^{rd} set of measurement to acquire the corresponding displacements on the same sections – i.e. F – at different pitch angles.

Instruments are always mounted with the blade in position 0° (vertical), and we assume that this is the neutral position (load = 0, displacement = 0).

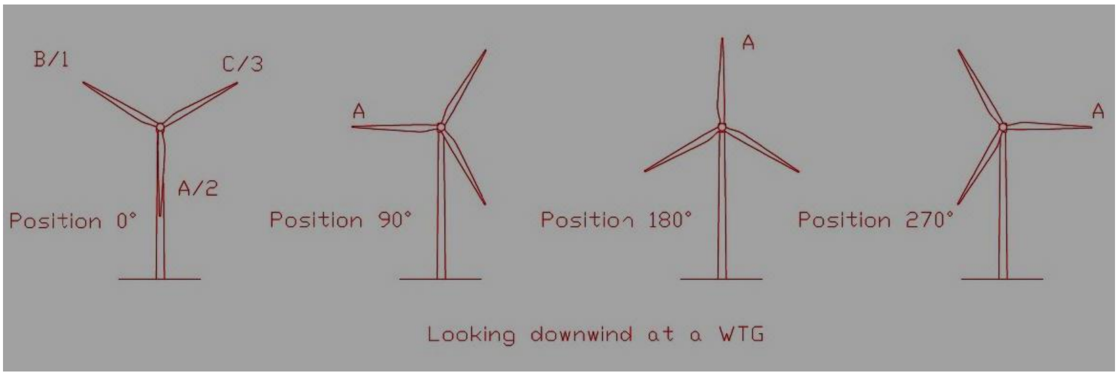

Fig.26 – Schematic representation of different blade positions of interest for the tests. Blade signed A/2, set a 0° reference position, is the chosen one to be instrumented.

A - With blade pitch at 0°, (or as close as possible to 0°)
Measure load and displacement at position 90° (trailing edge in compression)
Measure load and displacement at position 180° (blade self-weight, should be close to neutral)
Measure load and displacement at position 270° (leading edge in compression)

B - With blade pitch at 45° (or as close as possible to 45°)
Measure load and displacement at position 90° (mixed mode on trailing edge)
Measure load and displacement at position 180° (blade self-weight, should be close to neutral)
Measure load and displacement at position 270° (mixed mode on leading edge)

C - With blade pitch at 90° (or as close as possible to 90°)
Measure load and displacement at position 90° (pressure side in compression)
Measure load and displacement at position 180° (blade self-weight, should be close to neutral)
Measure load and displacement at position 270° (suction side in compression)

D - With blade pitch at current (recorded) wind conditions, measurement of load and displacement during rotation, and linked to inclinometer.

This complete procedure however was showed not to be practicable, due to the long testing time required and to the elevated number of holes which were required to measure the all 11 sections. Indeed drilling all these holes on a blade which already required to be maintained was not the best solution for the remaining lifetime, so it was decided to instrument 3 relevant sections with the tests performed by varying the rotational speed of the WTG via control of the pitch angle. A description of the actual test conditions is given in the next section for each test.

7. Experimental results and interpretation

7.1 Load measurements between the shell elements of the trailing edge (Blade A)

See table 2 – red highlighted positions
Load washer 1 – Position E (R9,2m)
Load washer 2 – Position G (10,2m)
Load washer 3 – Position I (11,2m)

Four measurement files were taken for this configuration; the first two on the afternoon of the 23rd October and the second two on the morning of the 24th.

Test 1 - Wind 6-8 m/s from South-SouthEast

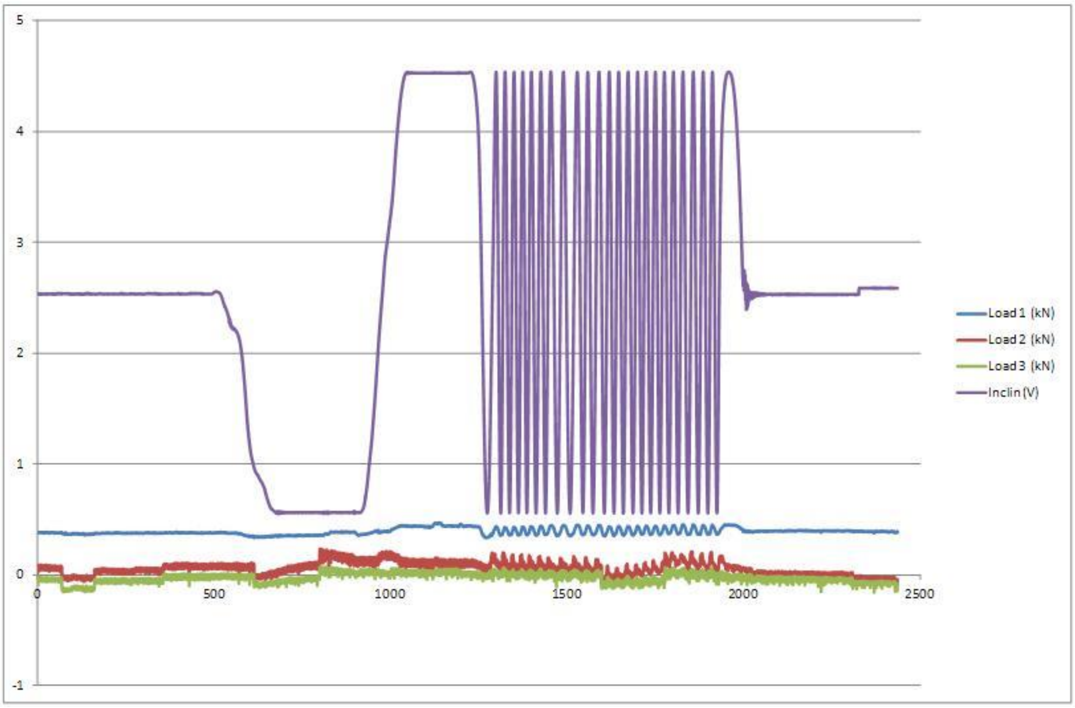

Fig. 27 - Full trace for test 1 (23/oct)

The overview trace for this measurement shows that data acquisition begins with blade A pointing down (position 0°). After about 500s the blade is rotated into the 90° position and held, the pitch is then changed from 90 deg to 0 deg and then back again. After about 900s it is rotated again so it is at position 270°, then the blade pitch is again cycled from 90 deg to 0 deg and back again. The blade is then run at close to 0 deg pitch between 1250 and 1950s. Finally the blade is decelerated and brought to a stop after around 2000s when once more in the 0° position.

Note that the output from load washers 2 and 3 is “noisy”.

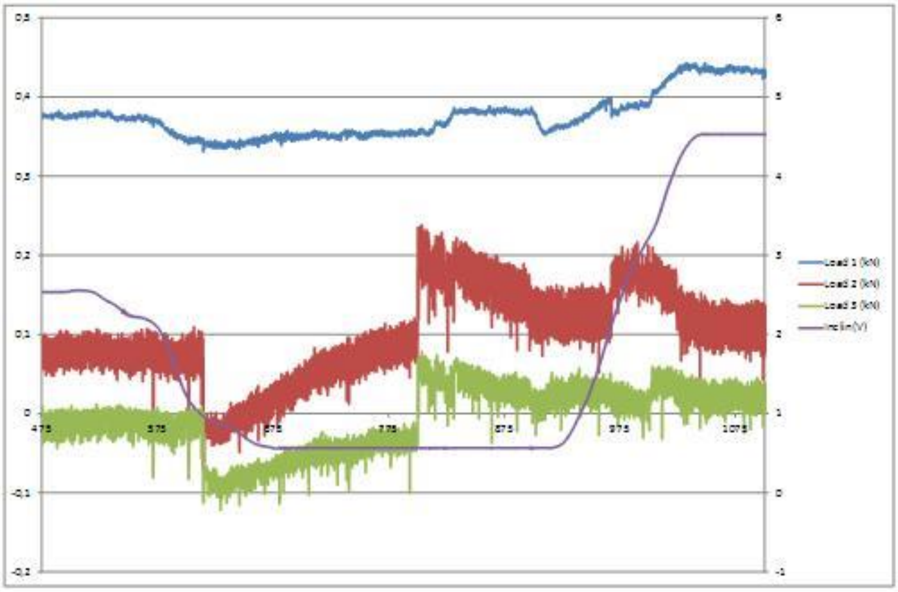

Fig. 28 - Detail from Test 1 showing the blade rotating to the 90° position where the pitch is cycled from 90 deg to 0 deg and then back again

Note that the output from load washers 2 and 3 is not stable during this time. At around 800s it is possible to see the effect on the load washers from the cycle from 90 deg pitch to 0 deg pitch. And at around 900s it is possible to see the effect of the cycle back from 0 deg to 90 deg pitch. This is most evident on the more stable Load washer 1 output.

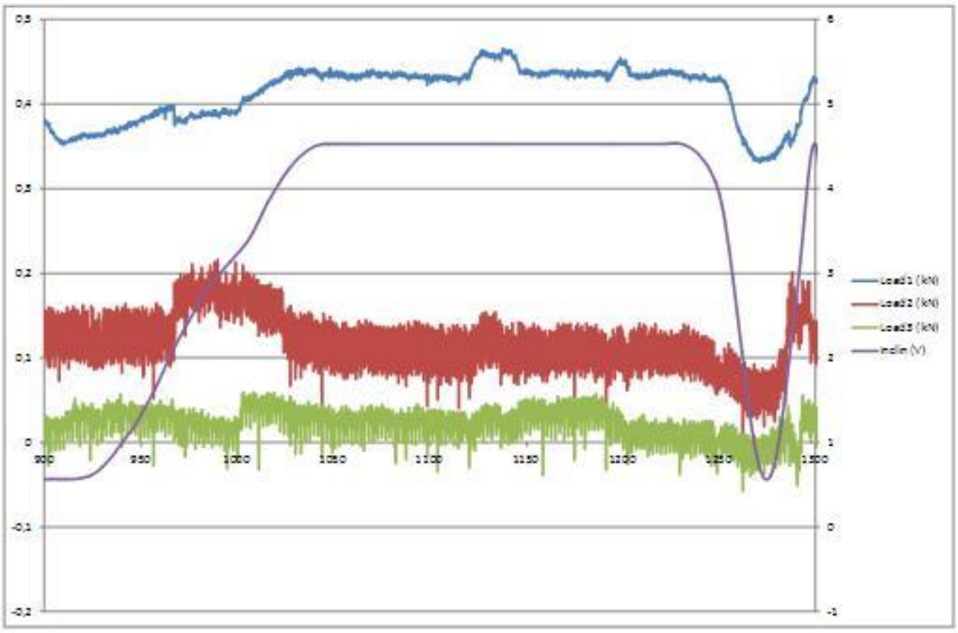

Fig. 29 - Detail from Test 1 showing the blade rotating to the 270° position where the pitch is cycled from 90 deg to 0 deg and then back again

At around 1120s it is possible to see the effect on the load washers from the cycle from 90 deg pitch to 0 deg pitch. And at around 1200s it is possible to see the effect of the cycle back from 0 deg to 90 deg pitch. This is most evident on the more stable Load washer 1 output.

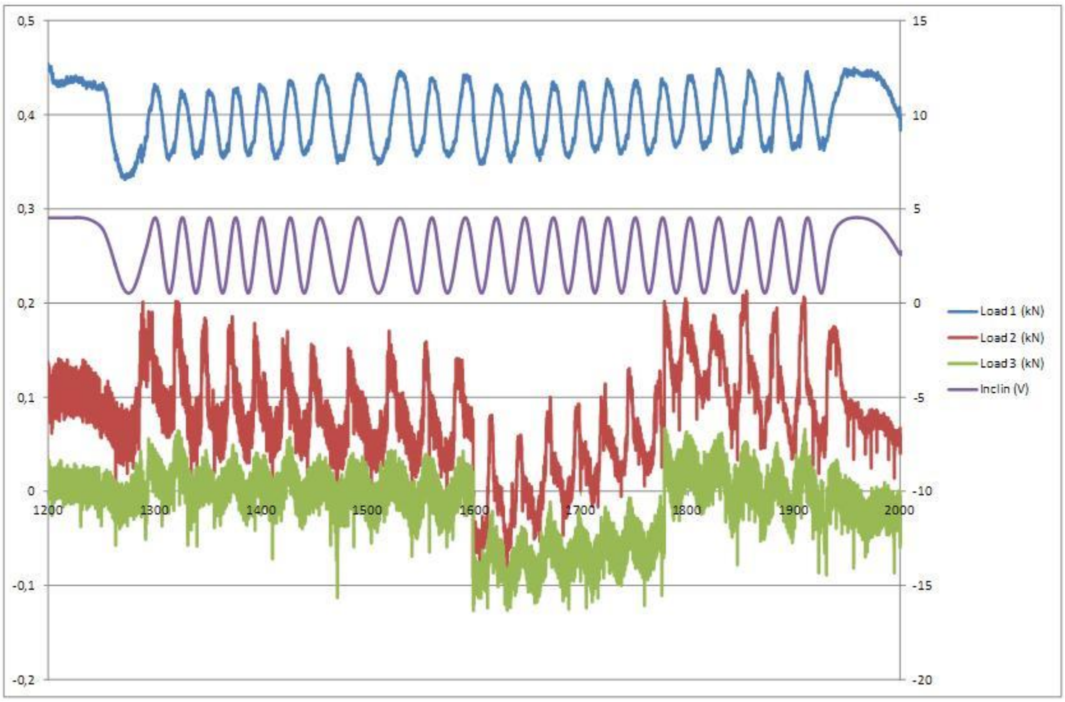

Fig. 30 - Detail from test 1 showing the autorun startup and operation (at close to 0 deg pitch)

Again the Load 1 output is stable whereas the Load 2 and 3 output is “noisy” and has an unexplained drop in load at 1600s followed by a response ramping gradually upwards to 1780s, and then downwards for the remainder of the measurement.

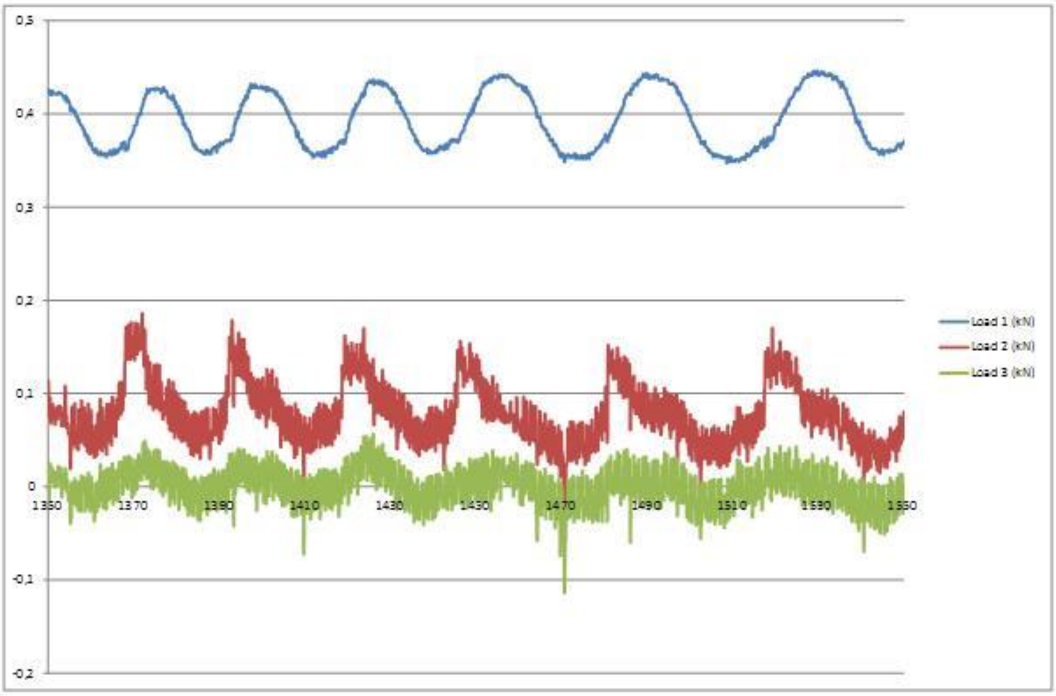

Fig. 31 - Detail of the output from Test 1 showing the most stable part of the autorun condition

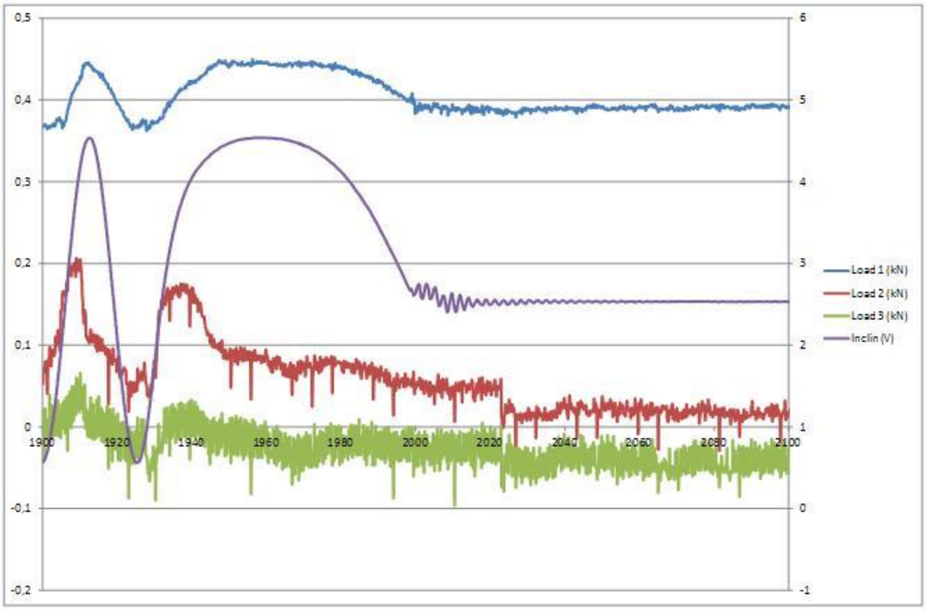

Fig. 32 - Detail of the output from Test 1 showing the turbine deceleration and stop at blade position 0°

Test 2 - Wind 6-8 m/s from South-SouthEast

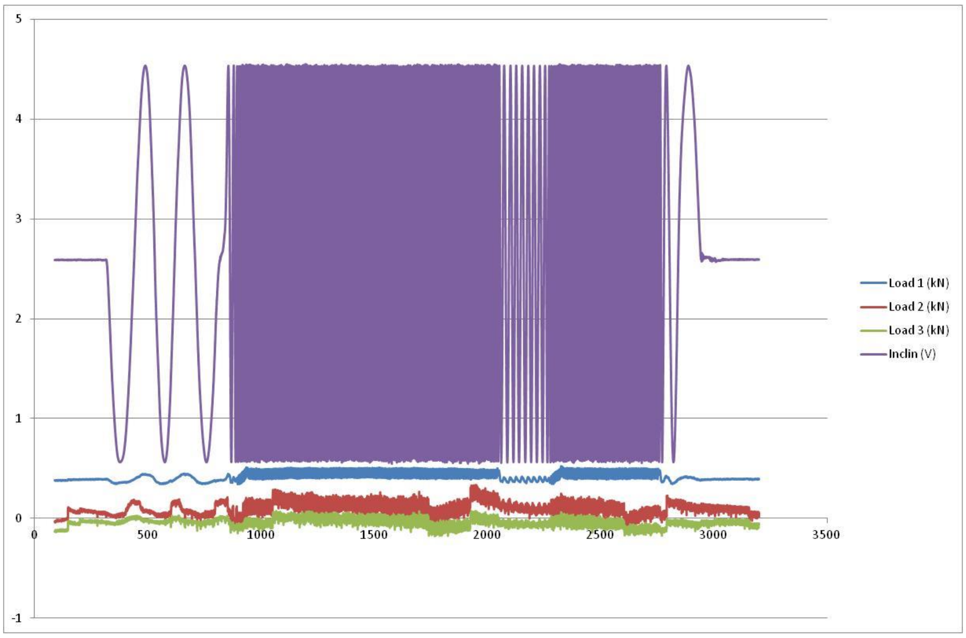

Fig. 33 Full trace for Test 2 (23/oct)

The overview trace for Test 2 shows the data acquisition starts with Blade A pointing down (position 0°). At around 300s the blade begins to rotate in idle condition (around 82-84 deg pitch). Around 850s the blade enters autorun operation (close to 0 deg pitch). Around 2050s the turbine automatically changes to blade pitch 30 deg due to very low wind speeds. At 2275s the turbine changes the blade pitch back to being close to 0 deg again and normal operation resumes. At 2760s the turbine goes to idle again (around 82-84 deg pitch). At 2940s the turbine is halted with Blade A in position 0°.

Again it can be noted that the output from Load Washers 2 and 3 is "noisy".

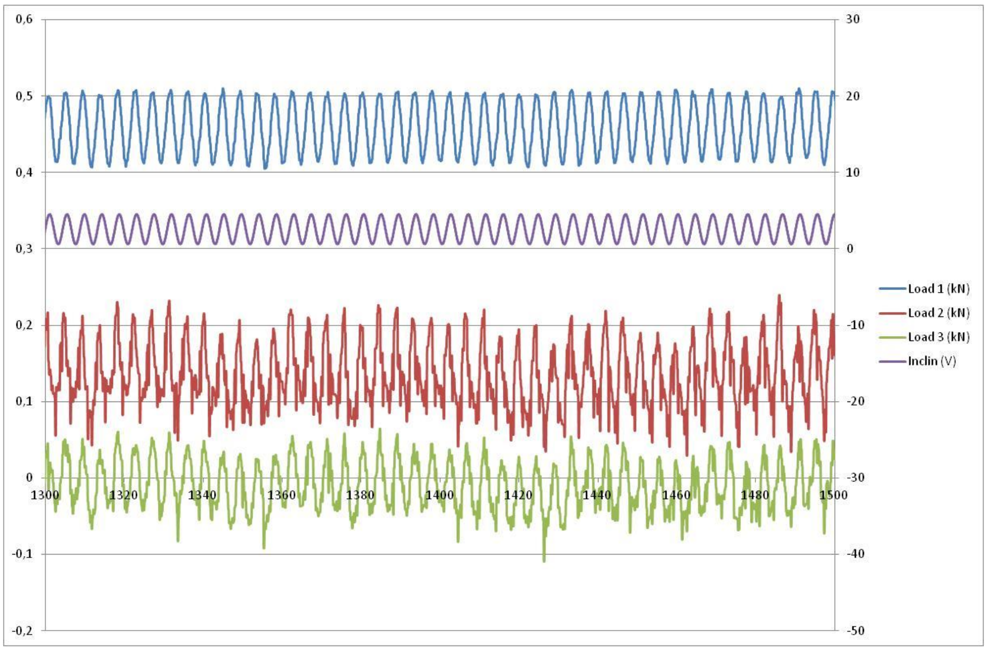

Fig. 34 - Detail from Test 2 showing the first autorun period

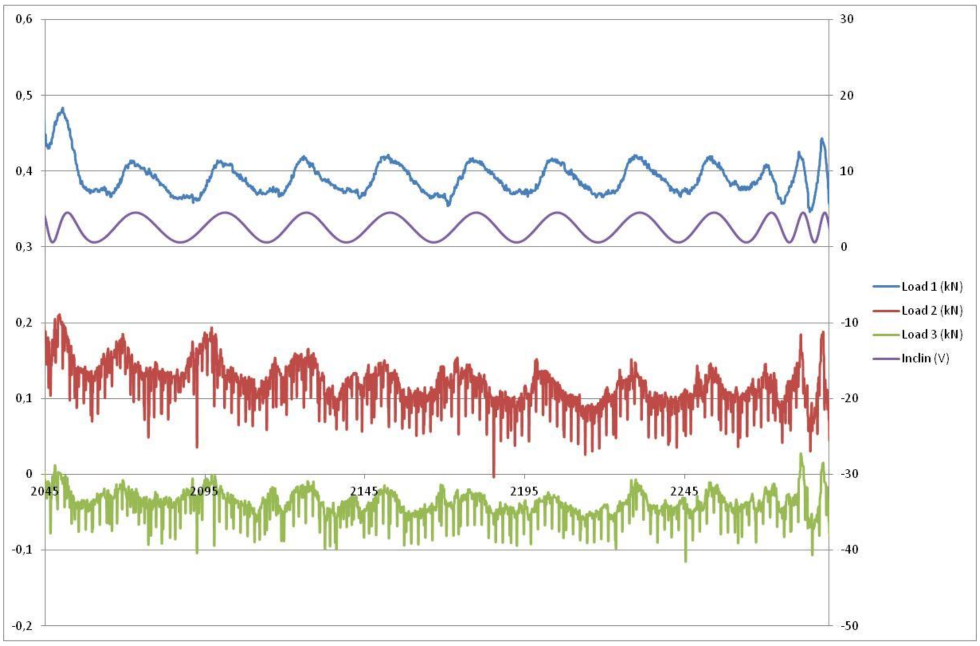

Fig. 35 - Detail from Test 2 showing the automatic change to 30° pitch during low wind conditions

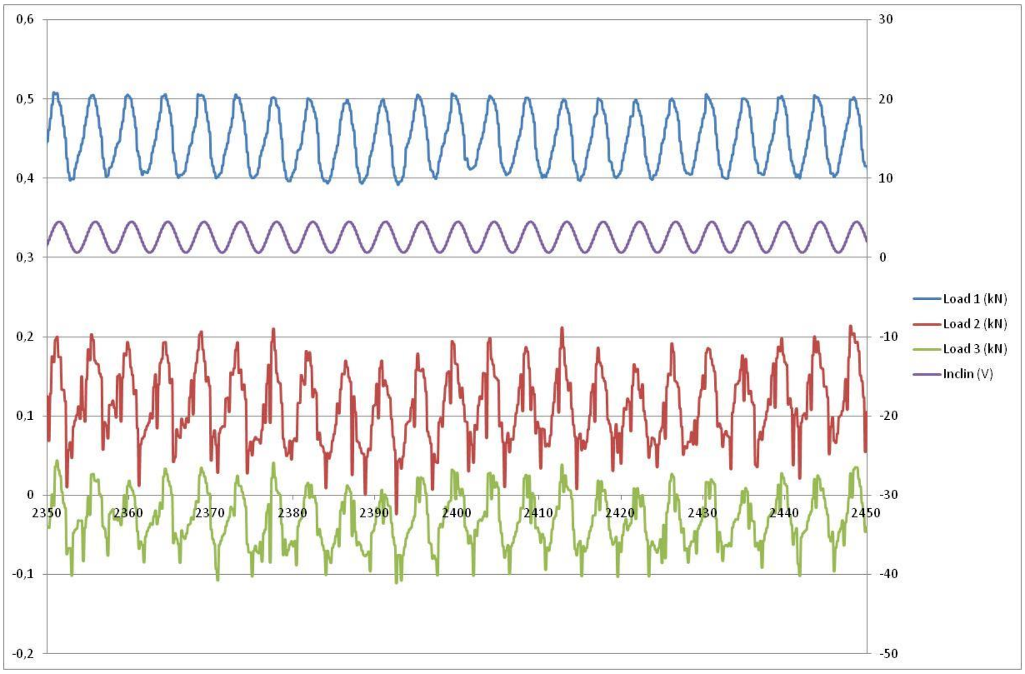

Fig. 36 - Detail from Test 2 showing the first autorun period

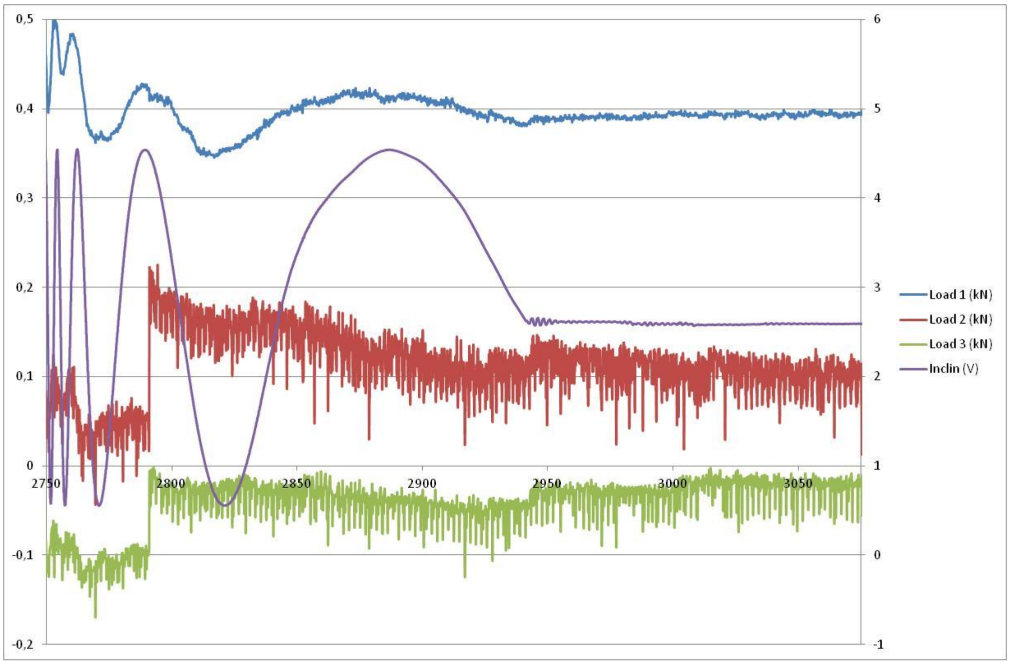

Fig. 37 - Detail of the output from Test2 showing the turbine deceleration and stop at blade position 0°

Test 3 - Wind 3-5 m/s from West

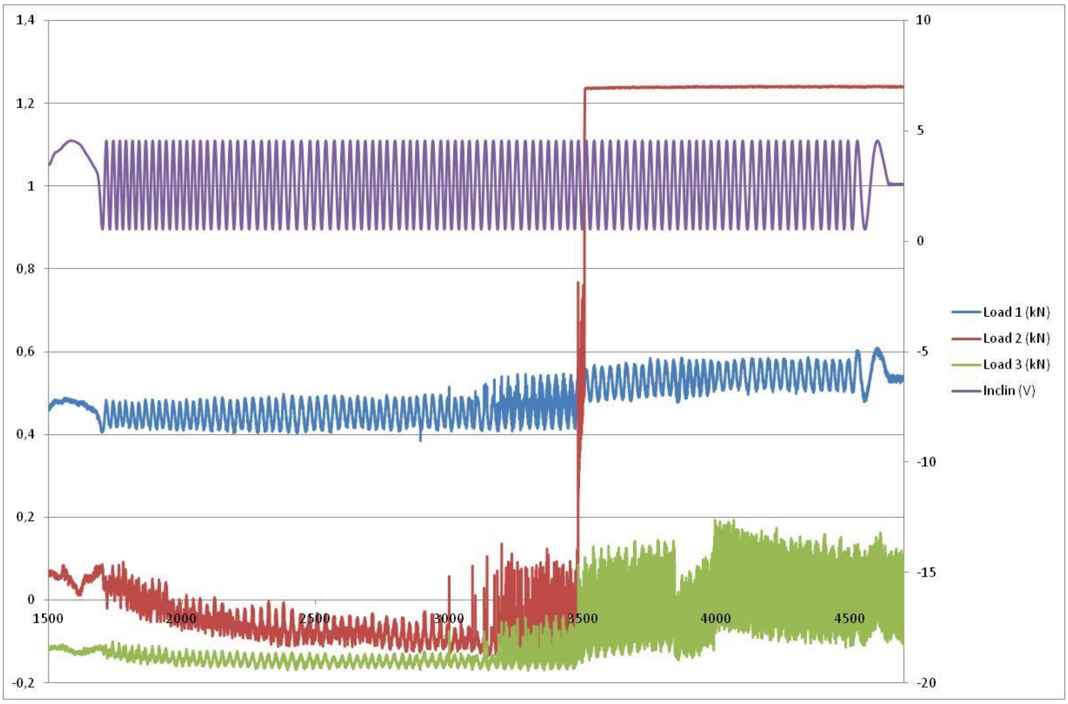

Fig. 38 Detail of the full operation period during Test 3 (24/oct)

At around 1650s following the start of data acquisition, the turbine enters autorun operation (with the blade close to 0 deg pitch). At around 3000s some event appears to occur that changes the response on all the load transducers. At about 3450s a sudden change is noted in the response of load washer 2, although load washers 1 and 3 are also affected. A noise is also heard by the Bondlines personnel. At 4500s the turbine is placed in idle condition (blade pitch around 82-84 deg).

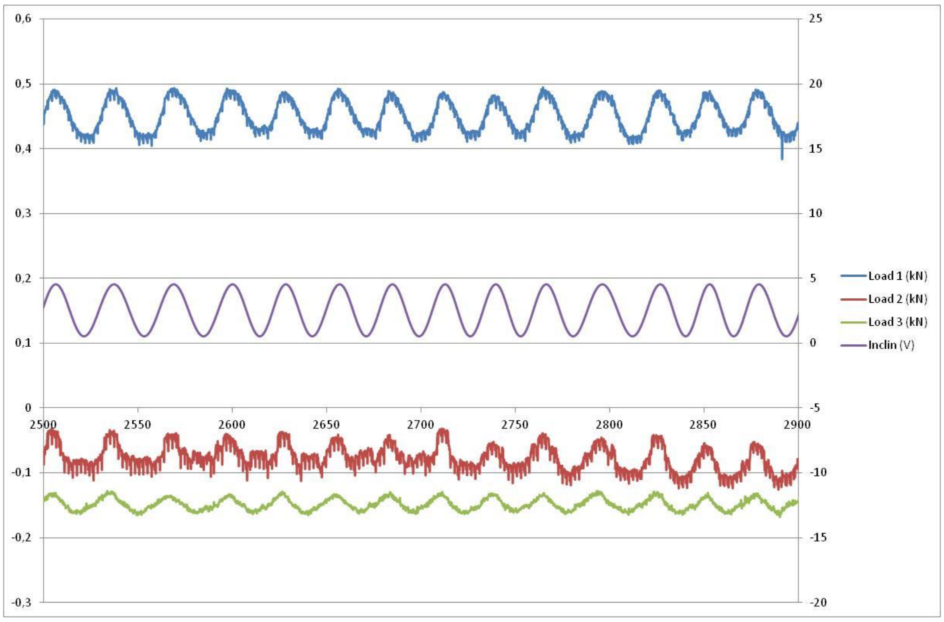

Fig. 39 - Detail from Test 3 showing output during the early stage of autorun condition

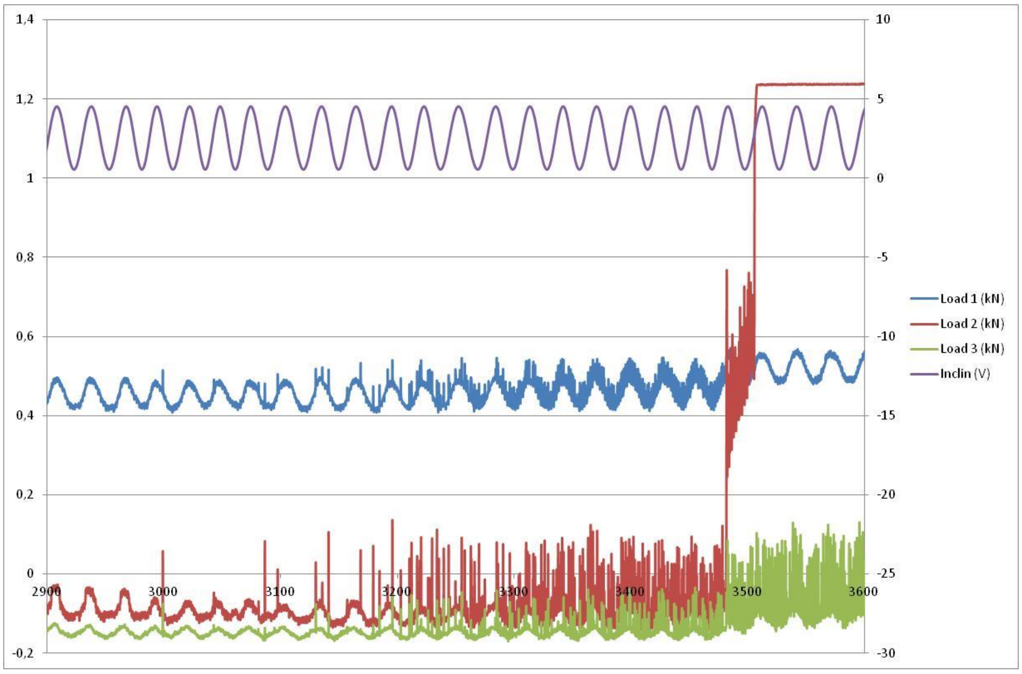

Fig. 40 - Detail from Test 3 showing the event on Load washer 2

This trace also makes clear that some problem existed with the load output on all three sensors from around 3000s.

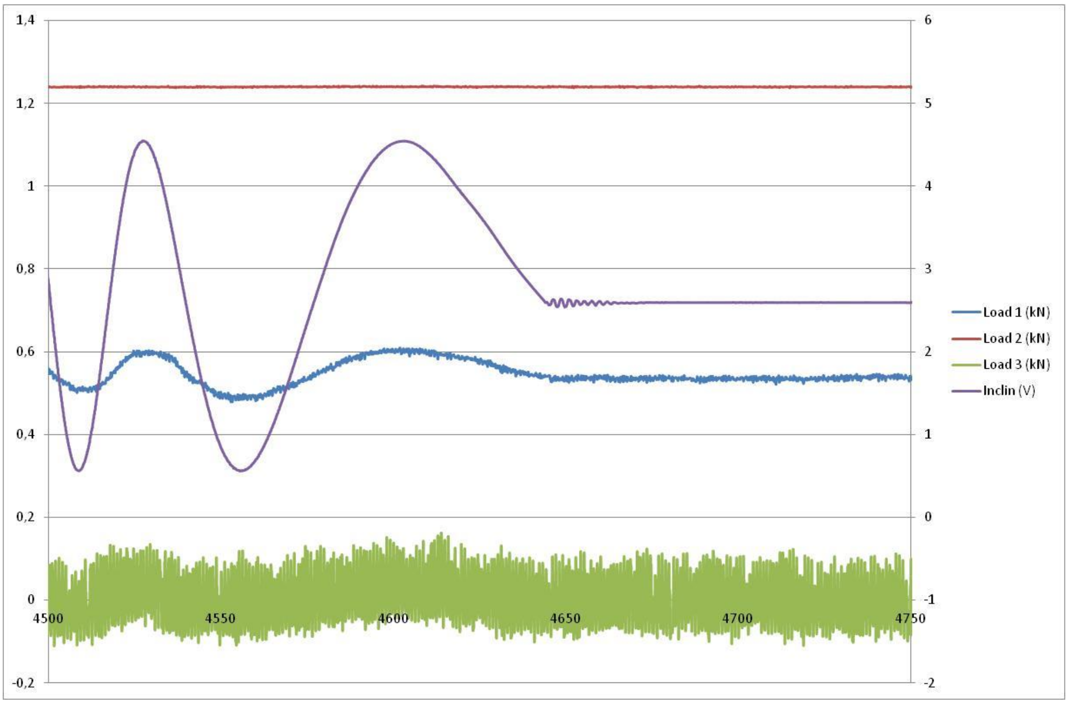

Fig. 41 - Detail from Test3 showing the turbine deceleration and stop at blade position 0°

Test 4 - Wind 3-5 m/s from West

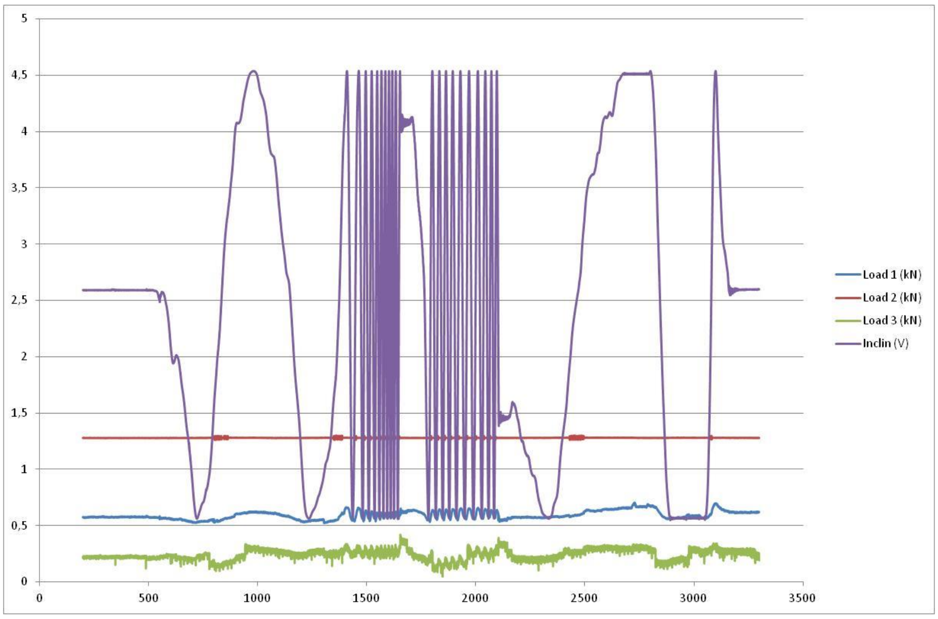

Fig. 42 - Full trace for Test 4 (24/Oct)

The overview trace for this measurement shows that data acquisition starts with Blade A pointing down (position 0°). At around 525s the blade begins to rotate in idle condition (around 82-84 deg pitch). Around 1400s the blade is placed at 30 deg pitch until 1650s when there is an emergency stop on the turbine. Around 1750s the blade is placed at 22 deg pitch until 2100s when there is another emergency stop on the turbine. At around 2175s the blade begins to rotate in idle condition (around 82-84 deg pitch) again. At 2650s the blade is halted in the 270° position and the pitch is cycled from 90 deg to 0 deg and then back again. At 2800s the blade is rotated round to the 90° position and the pitch is cycled from 90 deg to 0 deg and then back again. At 3050s the blade is rotated round to the 0° position and data acquisition is halted at 3300s.

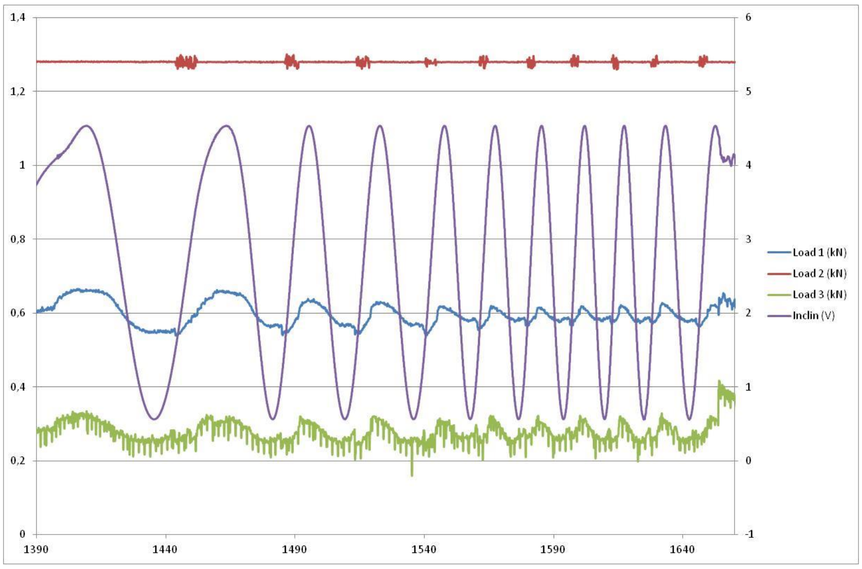

Fig. 43 - Detail from test 4 showing the blade going into operation at 30 deg pitch

Note that while load 1 seems to show good data, load 2 shows only a small pulsed response once per rotation, and the output from load 3 is quite “noisy”.

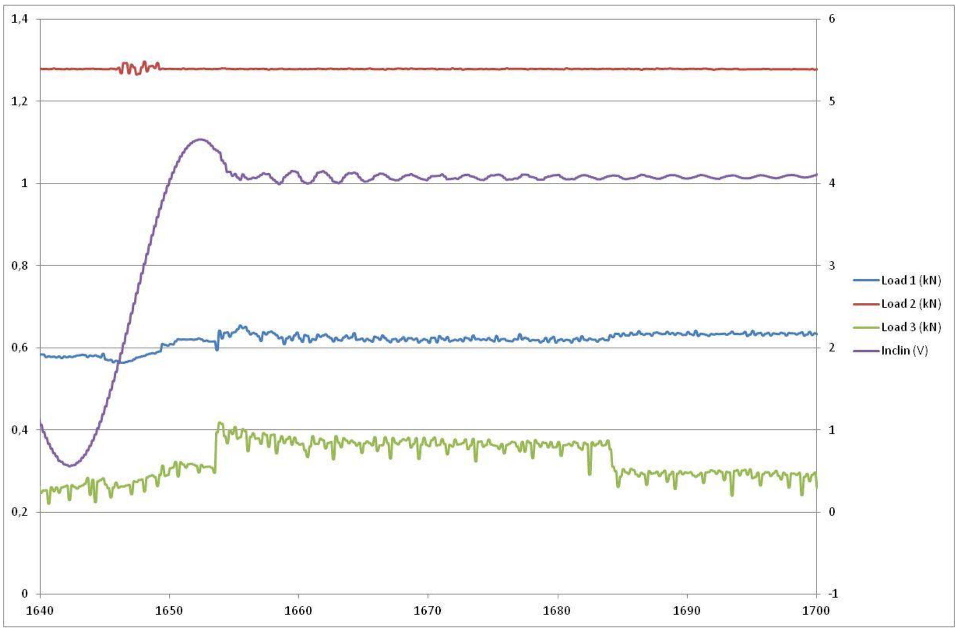

Fig. 44 - Detail from test 4 showing the blade doing an emergency stop whilst rotating at 30 deg pitch

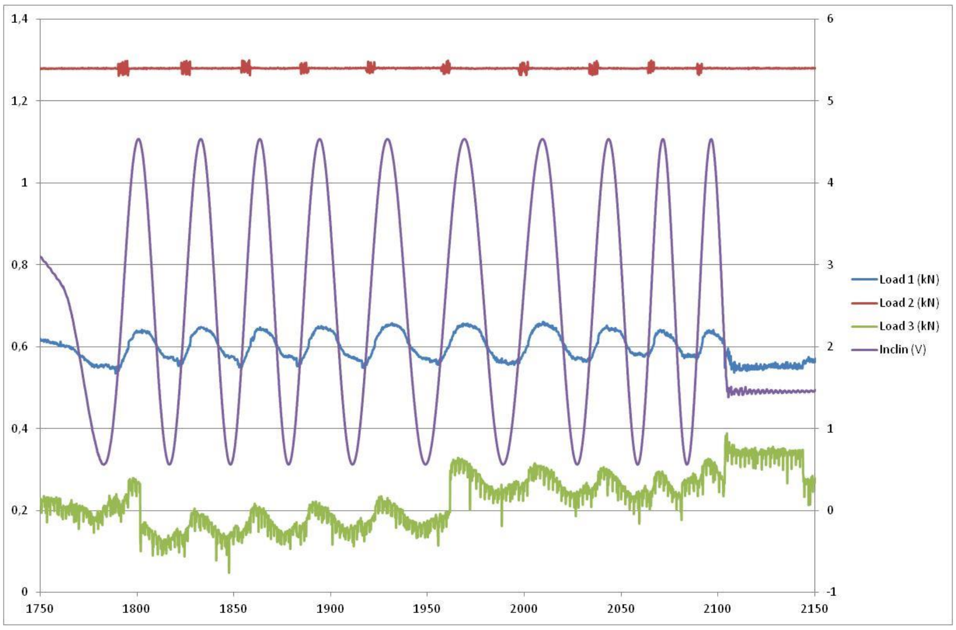

Fig. 45 - Detail from test 4 showing the blade going into operation at 22 deg pitch

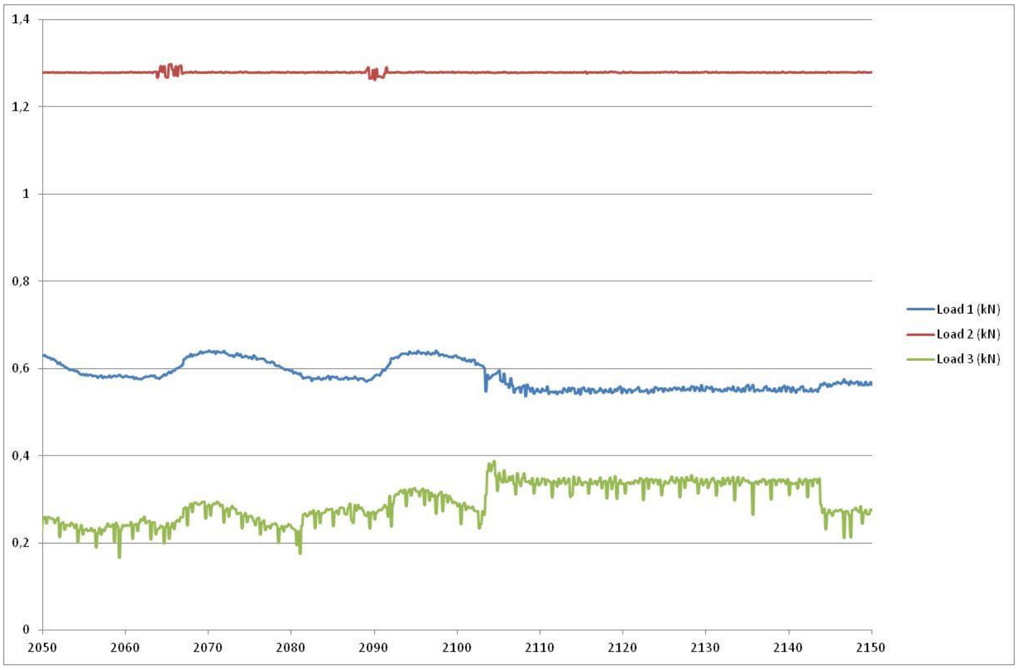

Fig. 46 - Detail from test 4 showing the blade doing an emergency stop whilst rotating at 22 deg pitch

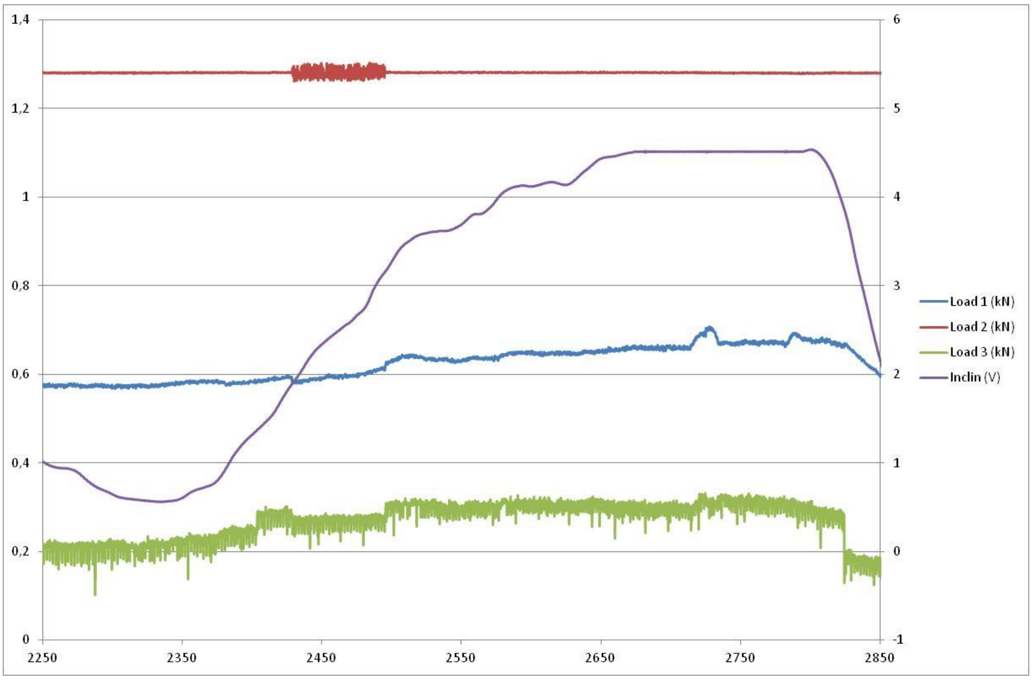

Fig. 47 - Detail from test 4 showing the blade at position 270° and changing blade pitch from 90 deg to 0 deg and then back again

The blade pitch is changed from 90 deg to 0 deg at around 2715s and back from 0 deg to 90 deg again at 2785s. This is apparent on load 1 trace, but difficult to see on load 2 trace. Load 3 shows no effect.

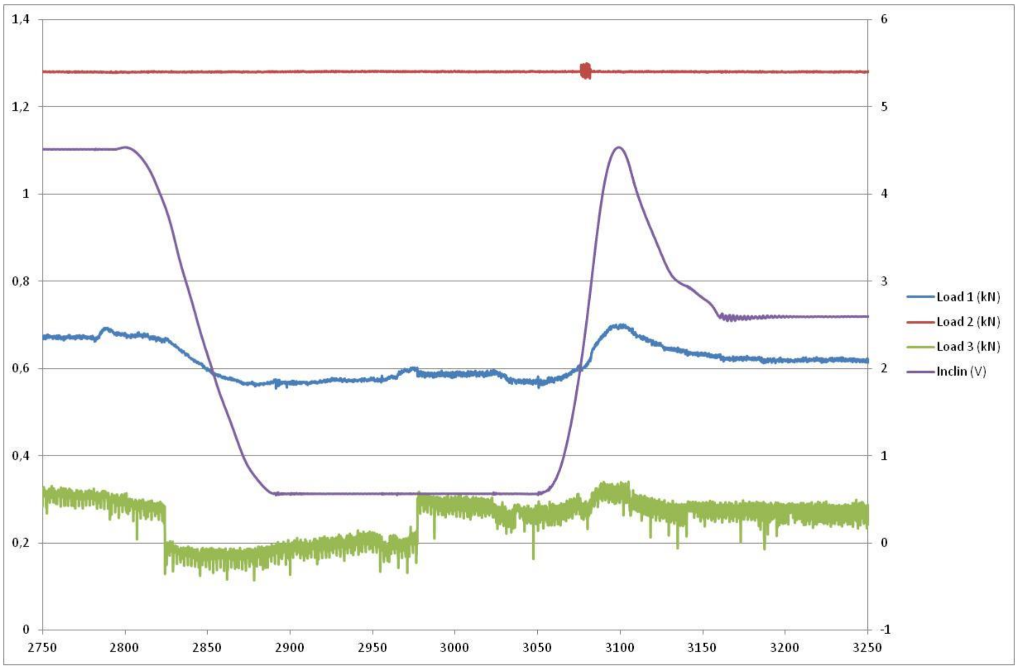

Fig. 48 - Detail from test 4 showing the blade at position 90° and changing blade pitch from 90 deg to 0 deg and then back again

The blade pitch is changed from 90 deg to 0 deg at around 2950s and back from 0 deg to 90 deg again at 3020s. This is only slightly apparent on load 1 trace, the load 2 trace shows a major effect at 2975s (just after the pitch changed is completed), but very little effect on the pitch back again. Load 3 shows no effect during pitch changes.

Table 3 - Bondlines test 1, 2, 3 and 4 table of measurement output

Test event			Load washer 1 (N)			Load washer 2 (N) *			Load washer 3 (N) *		
			start	Δ	end	start	Δ	end	start	Δ	end
Test 1	Position from 0° to 90°		377	***-37***	340	78	***-99***	-21	-13	***-78***	-91
	Pitch change (90 to 0 deg)		354	***+29***	383	90	***+125***	205	-29	***+88***	59
	Pitch change (0 to 90 deg)		382	***-29***	353	143	***-16***	127	23	***-12***	11
	Position from 90° to 270°		356	***+83***	439	128	***+50***	178	14	***+10***	24
	Pitch change (90 to 0 deg)		430	***+34***	464	103	***+19***	122	18	***+13***	31
	Pitch change (0 to 90 deg)		436	***-14***	450	100	***-10***	110	25	***-17***	8
			Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.
	Autorun (0 deg) - data from 1350 to 1550s		348 ***(-46)***	***394***	447 ***(+53)***	-50 ***(-128)***	***78***	186 ***(+108)***	-113 ***(-115)***	***2***	57 ***(+55)***
Test 2	Idle rotation (82-84 deg) - data from 290 to 790s		345 ***(-43)***	***388***	451 ***(+63)***	-52 ***(-123)***	***71***	188 ***(+117)***	-120 ***(-96)***	***-24***	32 ***(+56)***
	Autorun 1 (0 deg) - data from 1300 to 1500s		405 ***(-54)***	***459***	510 ***(+51)***	30 ***(-106)***	***136***	240 ***(+104)***	-109 ***(-100)***	***-9***	64 ***(+73)***
	Low wind (30 deg) - data from 2150 to 2250s		354 ***(-35)***	***389***	421 ***(+32)***	-4 ***(-108)***	***104***	154 ***(+50)***	-115 ***(-70)***	***-45***	-7 ***(+38)***
	Autorun 2 (0 deg) - data from 2350 to 2450s		392 ***(-57)***	***449***	508 ***(+59)***	-23 ***(-137)***	***114***	214 ***(+100)***	-110 ***(-79)***	***-31***	44 ***(+75)***
Test 3	Autorun (0 deg) - data from 2500 to 2900s		384 ***(-67)***	***451***	495 ***(+44)***	-126 ***(-50)***	***-76***	-31 ***(+45)***	-168 ***(-20)***	***-148***	-128 ***(+20)***
			start	Δ	end	start	Δ	end	start	Δ	end
	Event		463	***+52***	515	-88	***+1325***	1237	-144	***+75***	-69
Test 4			Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.
	Idle rotation (82-84 deg) - data from 600 to 1200s		527 ***(-49)***	***576***	628 ***(+52)***	1260 ***(-19)***	***1279***	1299 ***(+20)***	96 ***(-138)***	***234***	333 ***(+99)***
	Rotation (30 deg) - data from 1500 to 1600s		540 ***(-47)***	***587***	630 ***(+43)***	1261 ***(-18)***	***1279***	1298 ***(+19)***	159 ***(-110)***	***269***	322 ***(+53)***
			Peak displacement			Peak displacement			Peak displacement		
	Emergency stop at 30 deg		+59			-			+121		
			Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.
	Rotation (22 deg) - data from 1850 to 1950s		549 ***(-55)***	***604***	657 ***(+53)***	1262 ***(-18)***	***1280***	1299 ***(+19)***	105 ***(-68)***	***173***	234 ***(+61)***
			Peak displacement			Peak displacement			Peak displacement		
	Emergency stop at 22 deg		+47			-			+144		
			start	Δ	end	start	Δ	end	start	Δ	end
	Postn 270°	90 → 0	658	***+48***	706	1281	-	1281	294	***+37***	331
		0 → 90	667	***+25***	692	1281	-	1281	301	***+4***	305
	Postn 90°	90 → 0	576	***+26***	602	1281	-	1281	203	***+94***	297
		0 → 90	594	***-19***	575	1281	-	1281	263	***+17***	280

* - "noisy" data

Autorun load fluctuation	Load 1	108N
	Load 2	194N
	Load 3	134N

7.2 Displacement measurements between the shell elements of the trailing edge (Blade A)

See table 2 – red highlighted positions
Posiwire 1 – Position E (R9,2m)
Posiwire 2 – Position G (10,2m)
Posiwire 3 – Position I (11,2m)

One long measurement file was taken for this configuration on the afternoon of the 24th October.

Bondlines Posiwire - Wind 4-7 m/s from West

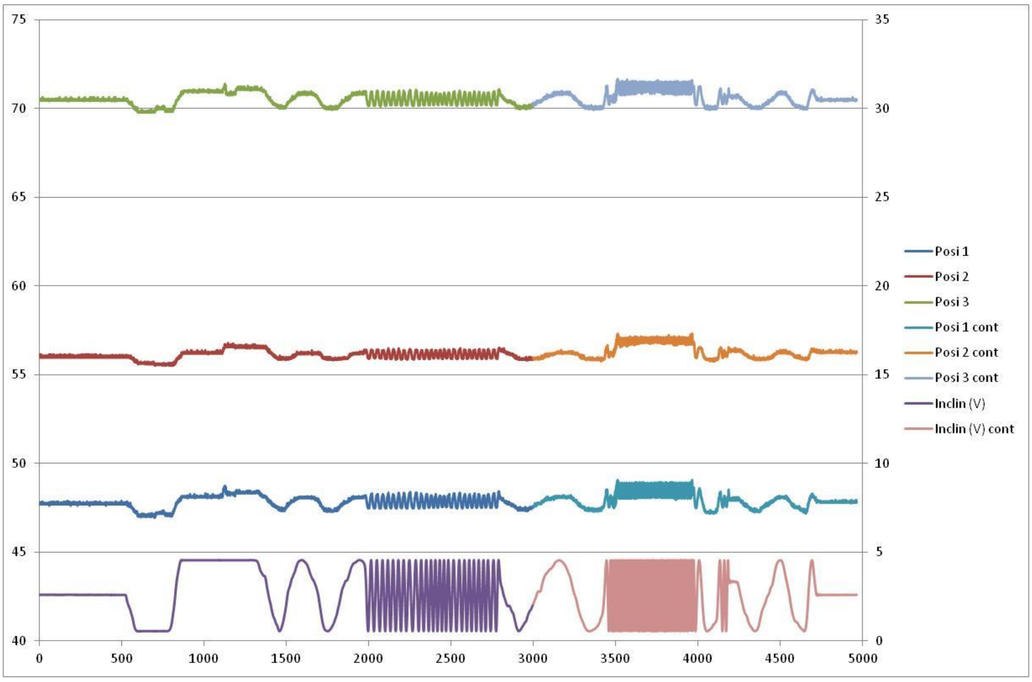

Fig. 49 - Full trace for posiwire measurement (24/oct)

The overview trace for this measurement shows that data acquisition starts with blade A pointing down (position 0°). After about 500s the turbine is rotated so that Blade A is at position 90°, the blade pitch is then cycled 90 deg to 0 deg and back again. After about 800s Blade A is rotated further to position 270°, the blade pitch is then again cycled from 90 deg to 0 deg and back. At about 1300s the turbine begins a slow rotation (with the blade pitch around 85 deg). Around 1950s the pitch is changed to 45 deg and there is a more rapid rotation of the turbine. At 2780s the turbine is changed to “autorun” and begins with an “idle” condition while the slip ring heats up. At 3440s the turbine automatically switches to full run condition (with the blade pitch close to 0 deg). At 4000s the turbine is placed into manual control again and the pitch changed to 90 deg, the turbine slows. At 4130s the pitch is changed to 30 deg and the turbine speeds up again. Finally, at 4180s there is a manual “emergency” stop. The turbine is then allowed to idle until 4720s when the blades are locked with blade A at position 0°. Data acquisition is stopped after about 5000s.

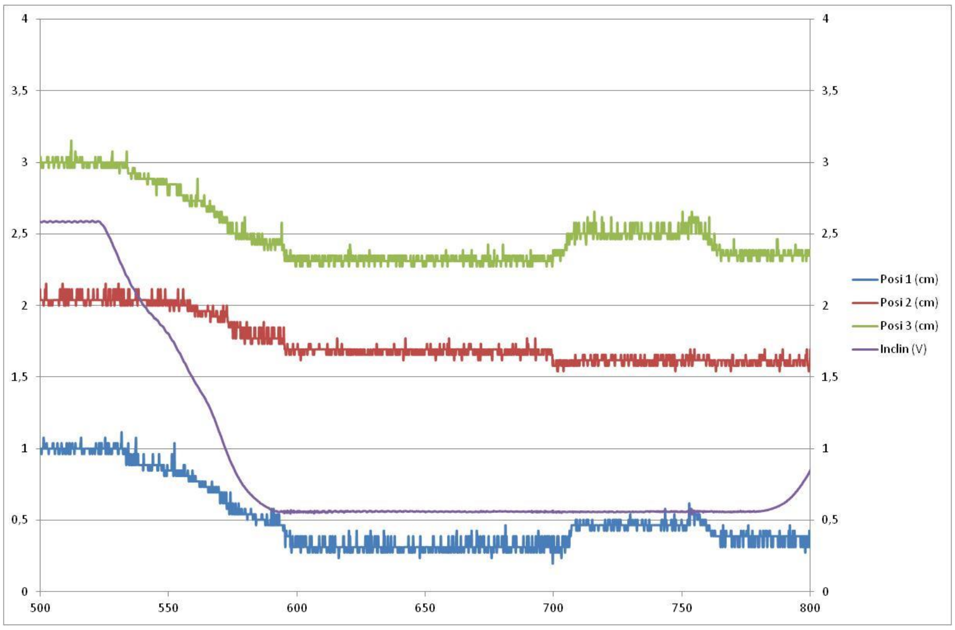

Fig. 50 - Detail from posiwire showing the blade rotating to the 90° position where the pitch is cycled from 90 deg to 0 deg and then back again

Note that the output from the displacement sensors has been normalised so that Posi 1 starts the measurement with an output of 1cm, Posi 2 (2cm) and Posi 3 (3cm). At 600s the blade is locked in the 90° position, the blade is then pitched from 90 deg to 0 deg at 700s and then pitched from 0 deg back to 90 deg at 750s. Posiwire 1 and 3 behave in a similar way, flexing slightly outwards when the blade is pitched the first time, and in again when pitched back to 0 deg. However Posiwire 2 contracts at the first pitch change, and shows no response when the blade is pitched back to 0 deg.

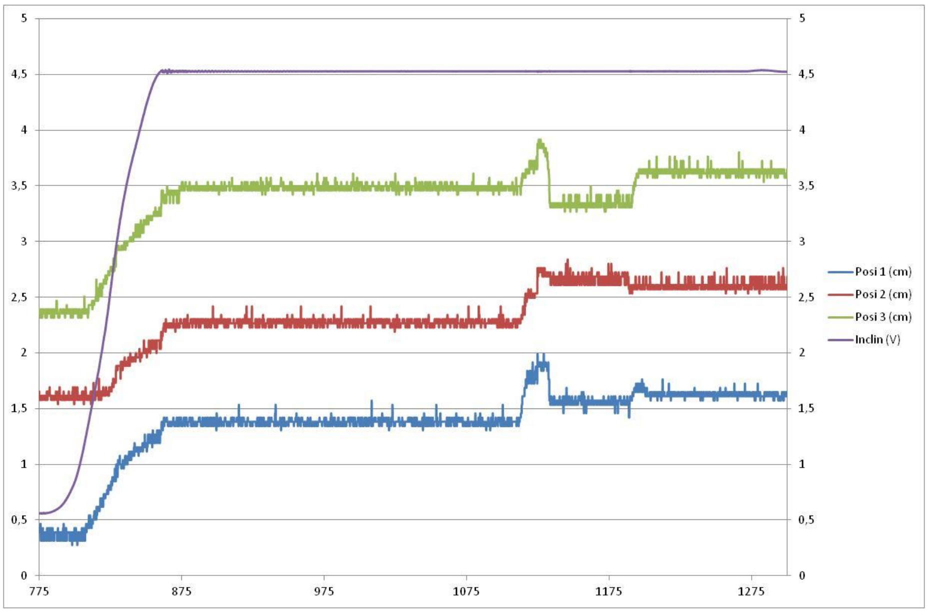

Fig. 51 - Detail from posiwire showing the blade rotating to the 270° position where the pitch is cycled from 90 deg to 0 deg and then back again

By 875s the blade has been locked in the position 270°. At 1110s Blade A is pitched from 90 deg to 0 deg, and at 1190s pitched back to 90 deg again. On this occasion the Posiwire output shows that the trailing edge flexes out as the blade is pitched towards 0 deg, but that a sudden contraction occurs when fully pitched to 0 deg. The posiwires show the trailing edge flexes out again when the blade is pitched back to 90 deg.

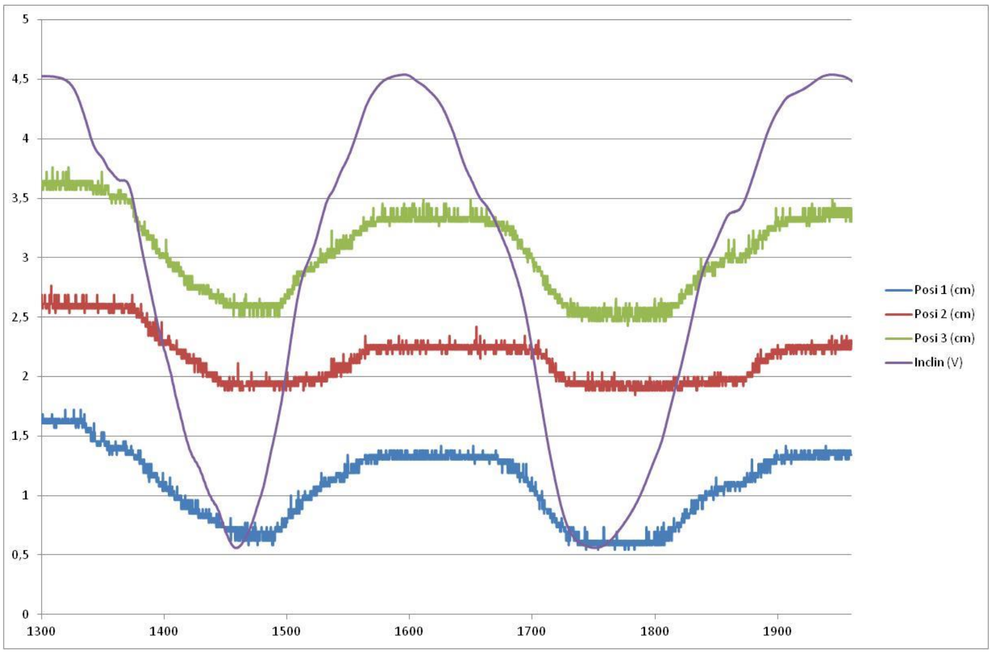

Fig. 52 - Detail from Posiwire showing the rotation while at blade pitch 85 deg

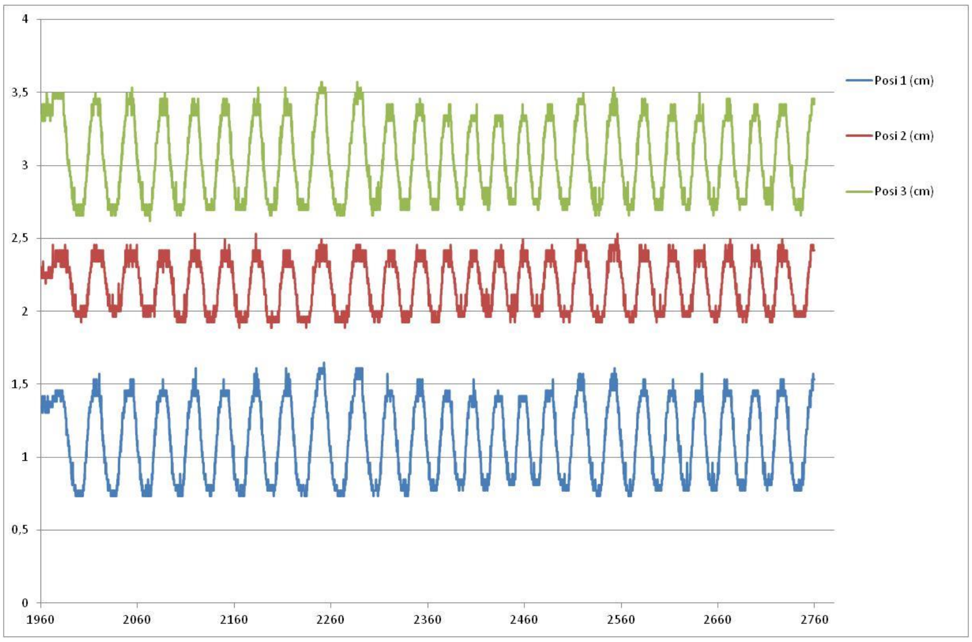

Fig. 53 - Detail from Posiwire showing the rotation while at blade pitch 45 deg

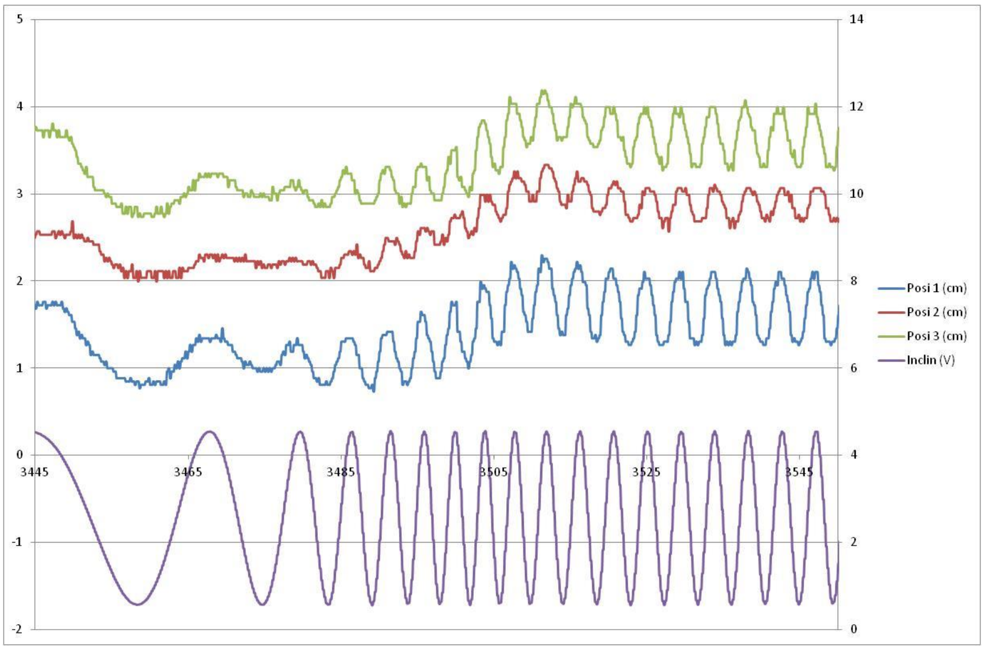

Fig. 54 - Detail from Posiwire showing the rotation while the blade accelerates at blade pitch 0 deg

Note that the posiwire response ramps upwards while the blade is accelerating to full rotation speed at 0 deg pitch.

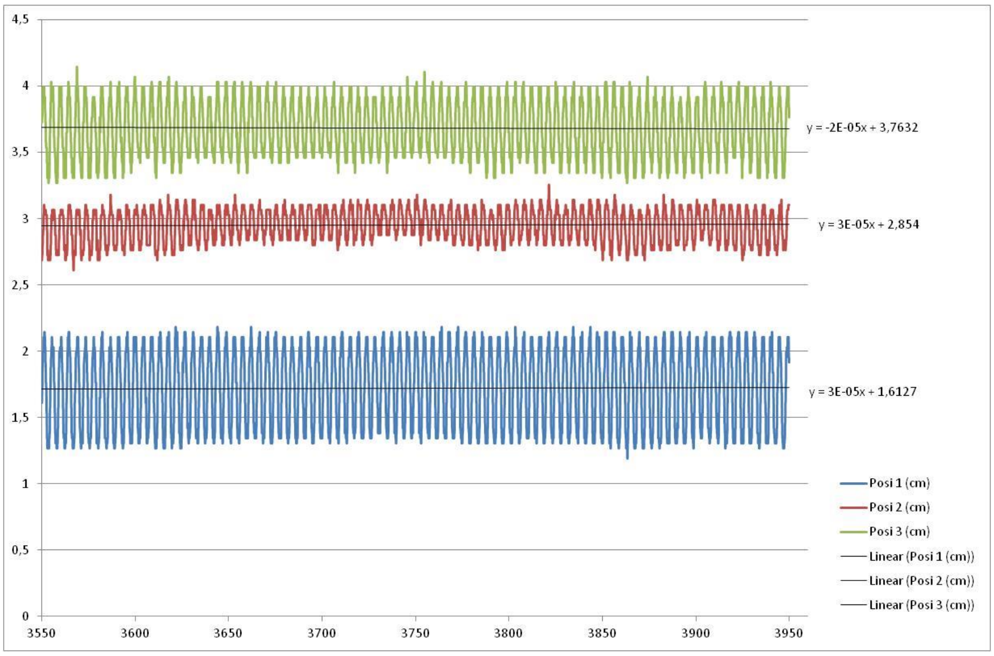

Fig. 55 - Detail from Posiwire showing the rotation while at blade pitch 0 deg

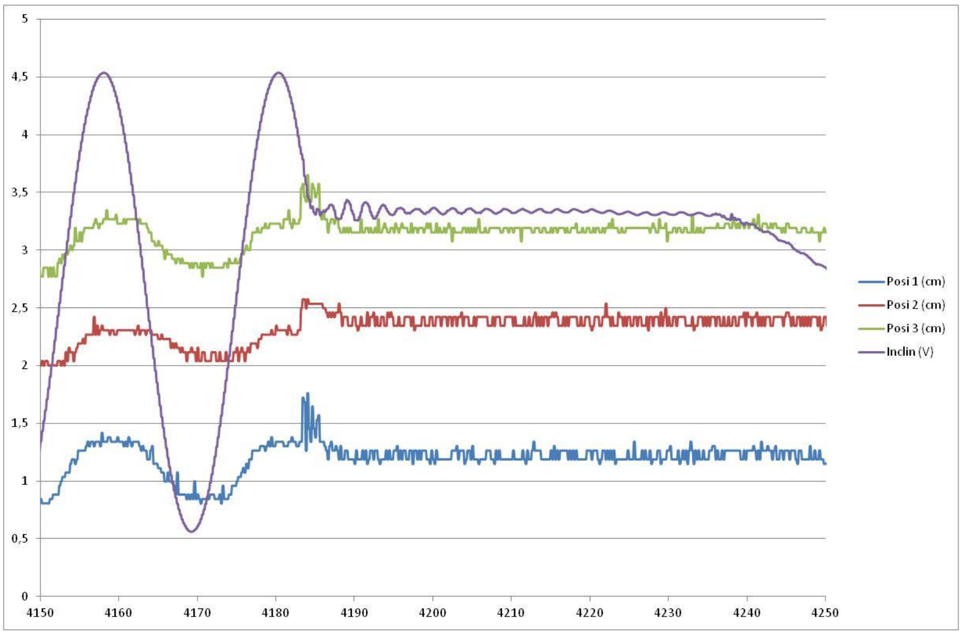

Fig. 56 - Detail from Posiwire showing the “emergency” stop while at blade pitch 30 deg

Table 4 - Posiwire test table of measurement output

Test event	Posiwire 1 (cm)			Posiwire 2 (cm)			Posiwire 3 (cm)		
	start	Δ	end	start	Δ	end	start	Δ	end
Position 0° to position 90°	1.00	***-0.69***	0.31	2.00	***-0.34***	1.66	3.00	***-0.69***	2.31
Pitch change (90 to 0 deg)	0.31	***+0.16***	0.47	1.66	***-0.08***	1.58	2.31	***+0.19***	2.50
Pitch change (0 to 90 deg)	0.47	***(+0.11)*** ***-0.08***	(0.58!) 0.39	1.58	***(+0.08!)*** ***-***	(1.66!) 1.58	2.50	***(+0.12!)*** ***-0.15***	(2.62!) 2.35
Position from 90° to 270°	0.39	***+0.99***	1.38	1.58	***+0.69***	2.27	2.35	***+1.15***	3.50
Pitch change (90 to 0 deg)	1.38	***(+0.62!)*** ***+0.19***	(2.00!) 1.57	2.27	***(+0.49!)*** ***+0.42***	(2.76!) 2.69	3.50	***(+0.42!)*** ***-0.16***	(3.92!) 3.34
Pitch change (0 to 90 deg)	1.57	***(+0.19!)*** ***+0.08***	(1.76!) 1.65	2.69	***-0.08***	2.61	3.34	***+0.31***	3.65
	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.
Slow rotation (85 deg) - data from 1300 to 1900s	0.54 (-0.55)	1.09	1.72 (+0.63)	1.85 (-0.31)	2.16	2.76 (+0.60)	2.43 (-0.61)	3.04	3.76 (+0.72)
Medium rotation (45 deg) - data from 2000 to 2500s	0.73 (-0.39)	1.12	1.65 (+0.53)	1.89 (-0.29)	2.18	2.53 (+0.35)	2.62 (-0.43)	3.05	3.57 (+0.52)
Autorun (0 deg) - data from 3550 to 3950s	1.19 (-0.42)	1.61	2.18 (+0.57)	2.61 (-0.24)	2.85	3.26 (+0.41)	3.27 (-0.49)	3.76	4.14 (+0.38)
Total displacement	10mm			6,5mm			8,7mm		
	Peak displacement			Peak displacement			Peak displacement		
Emergency stop at 30 deg	+0.42			0.30			+0.41		

! – Value peaks before dropping to the new value

7.3 Displacement measurements for cross wires mounted inside the spar (Blade C)

Internal beam displacement measurement:-
from corner to corner at approximately Radius 10 of blade C

Two measurements were taken for this configuration on the afternoon of October the 25th.

Beam test 1 - Wind 8-12m/s from West (0 to 3 deg)

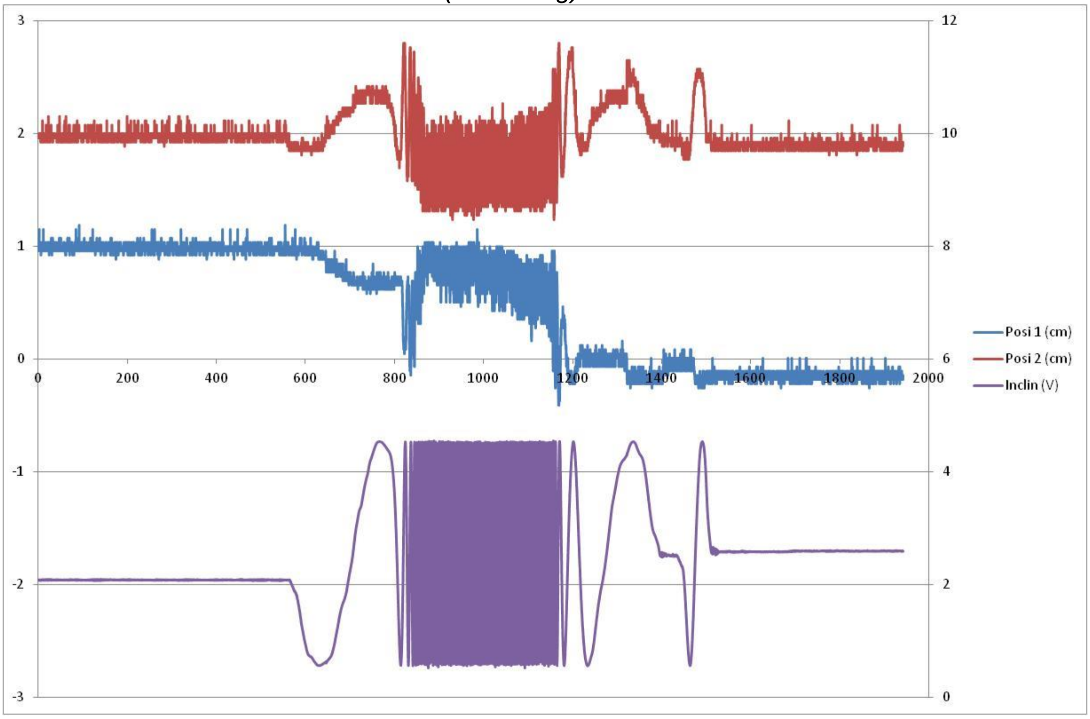

Fig. 57 - Full trace for posiwire beam test 1 (25/Oct)

550s after data acquisition begins the turbine is placed in autorun condition and begins a slow rotation in “idle” condition as the slip ring heats up. At 775s the turbine automatically goes into production condition and runs at between 0 and 3 deg pitch angle. After 1150s the turbine is placed in manual control and the pitch changed to 90 deg at which point the turbine slows. At 1500s the turbine is halted and at 1950s the data acquisition is stopped.

Note also that Posiwire 1 does not return to the original displacement condition (normalised to 1 cm) but ends the measurement around -0.14 cm. And to a lesser degree Posiwire 2 ends the measurement series slightly below its’ normalised 2 cm start condition at 1.89 cm.

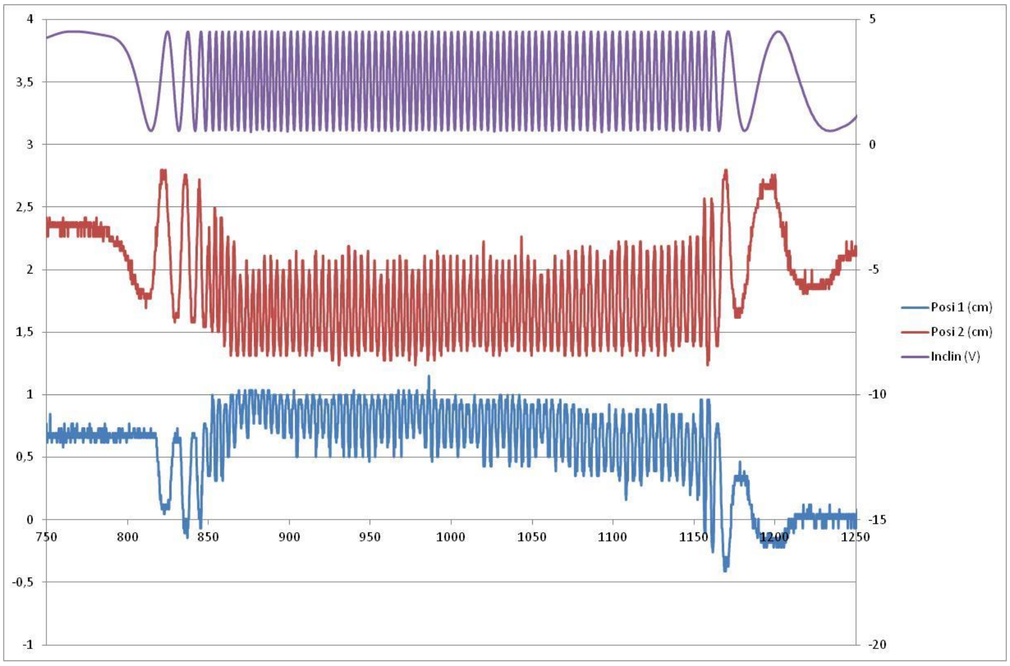

Fig. 58 - Detail from Posiwire beam test 1 showing the main data acquisition period

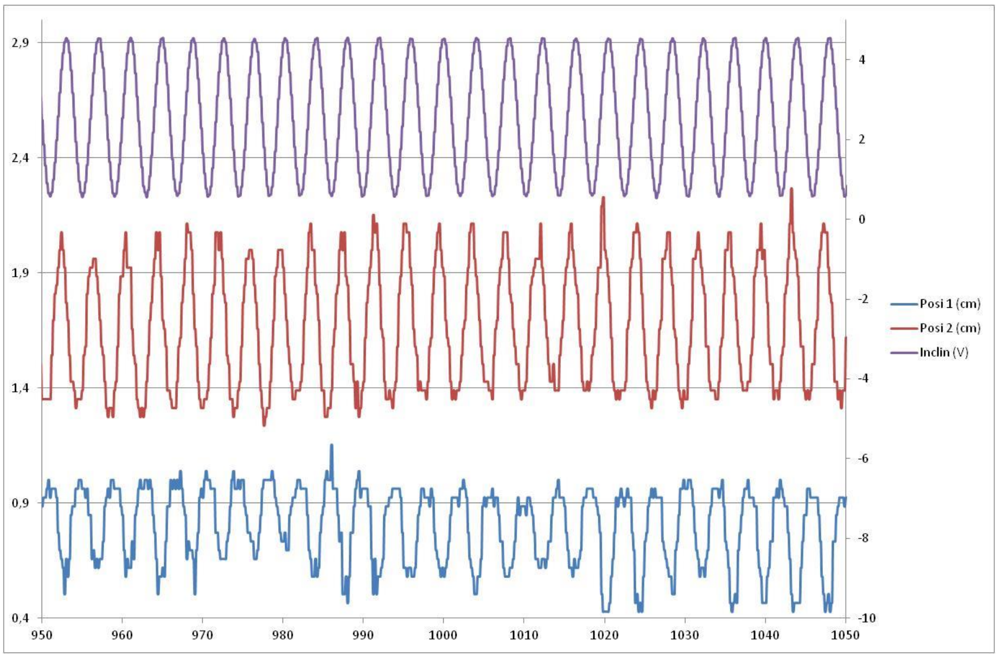

Fig. 59 - Close up detail from Beam test 1 showing the shear behaviour

Test 2 - Wind 10-12m/s from West (0 to 5 deg)

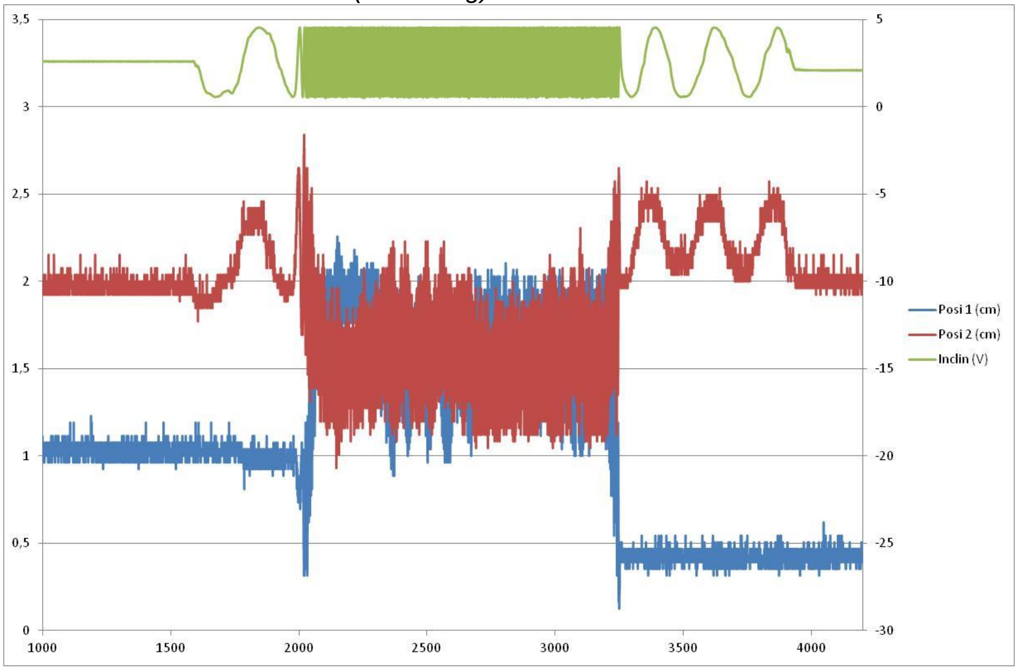

Fig. 60 - Main trace for the Posiwire Beam Test 2 showing the full acquisition period

Around 1575s after data acquisition begins the turbine is placed in autorun condition and begins a slow rotation in “idle” condition as the slip ring heats up. At 2000s seconds the turbine automatically goes into production and accelerates to run at between 0 and 5 deg pitch angle. At 3250s the turbine is placed under manual control again and the pitch changed to 90 deg causing the turbine to slow. At 3950s the turbine is halted. Between 4300 and 5700s the system was dismounted from the box beam while the data acquisition system is still running, the data from this period has been excised from the output graph show here.

Note that Posiwire 1 shows no displacement during the slow rotation “idle” periods at the start and end of the main run, whereas Posiwire 2 responds with a 0.5cm displacement during each rotation. Posiwire 1 does respond to the full speed rotation period.

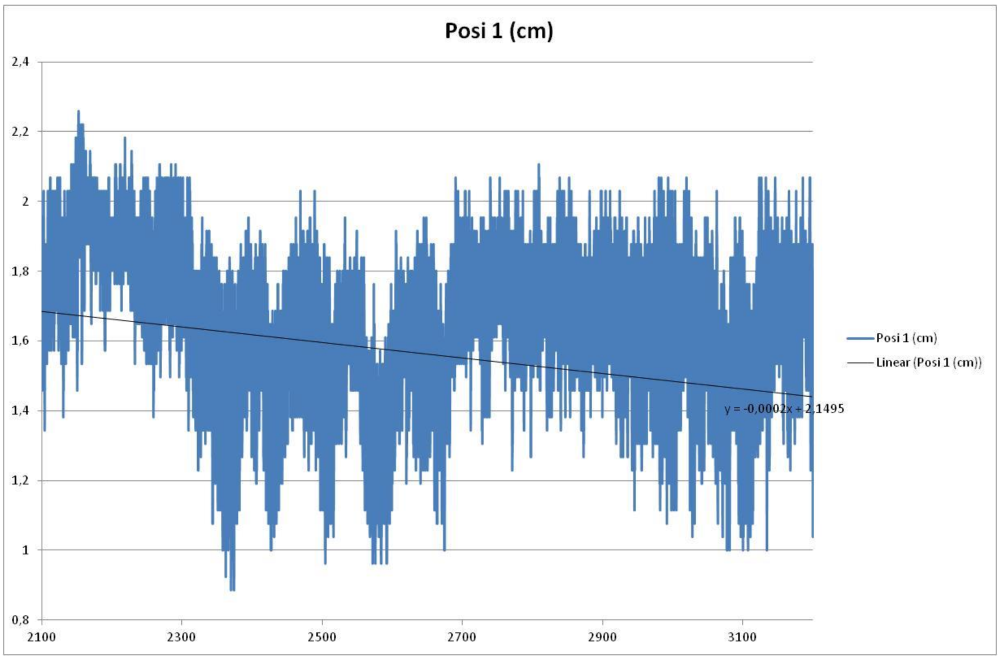

Fig. 61 - Detail from Posiwre Beam Test 2 showing the response of Posiwire 1 only

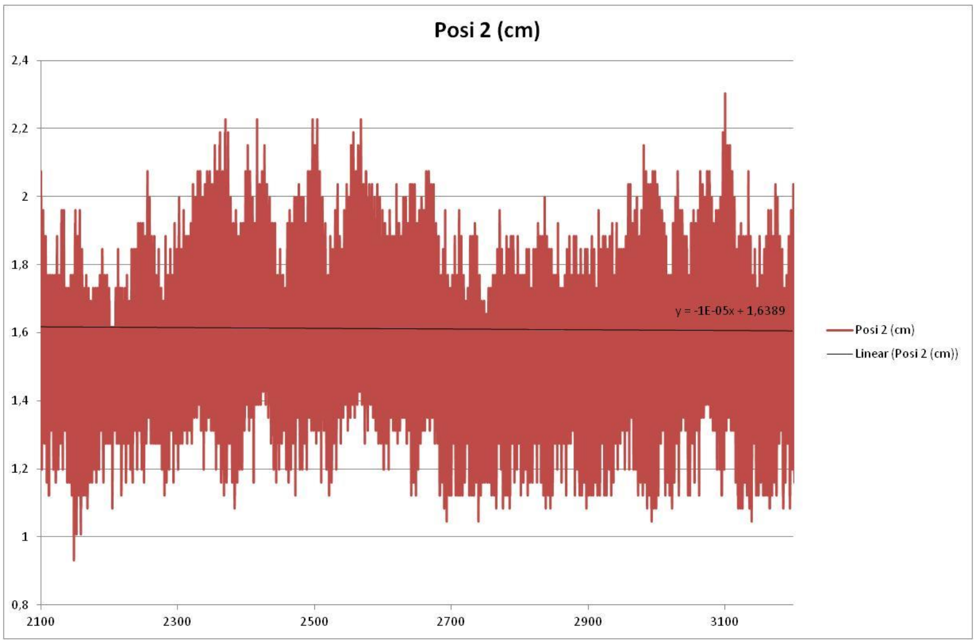

Fig. 62 - Detail from Posiwre Beam Test 2 showing the response of Posiwire 2 only

These graphs show that whereas the response from Posiwire 2 is stable over the duration of the main rotation period, the output from posiwire 1 is ramping downwards.

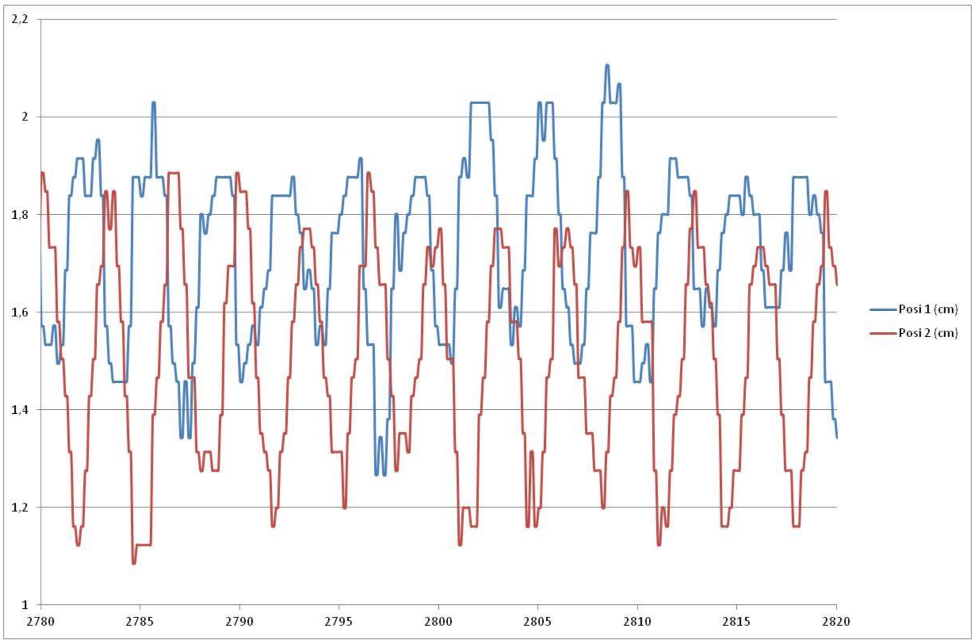

Fig. 63 - Close up detail of the Posiwire output from Beam Test 2

In this trace it is possible to see the shear response of the beam during normal loading by comparing the period of the displacement measurements on Posiwire 1 and 2.

Table 5 - Posiwire beam tests 1 and 2 table of measurement output

Test event		Posiwire 1 (cm)			Posiwire 2 (cm)		
		Min.	Average	Max.	Min.	Average	Max.
Beam test 1	Start Measurement		1.00			1.96	
	Full autorun condition - data from 950 to 1050s	0.43 ***(-0.37)***	***0.80***	1.15 ***(+0.35)***	1.24 ***(-0.43)***	***1.67***	2.27 ***(+0.60)***
	End measurement		-0.14 ***(-1.14)***			1.89 ***(-0.07)***	
Beam test 2	Start Measurement		1.00			1.96	
	Full autorun condition -data from 2700 to 2900s	1.23 ***(-0.50)***	***1.73***	2.11 ***(+0.38)***	1.05 ***(-0.45)***	***1.50***	2.00 ***(+0.50)***
	End measurement		0.43 ***(-0.57)***			2.00 ***(+0.04)***	

Beam cross shear distortion during autorun condition average 9mm

7.4 Displacement measurements between the shell elements of the reinforced trailing edge (Blade A)

See table 2 – red highlighted positions
Posiwire 1 – Position E (R9,2m)
Posiwire 2 – Position G (10,2m)
Posiwire 3 – Position I (11,2m)

Two measurement acquisition periods took place on the afternoon of Thursday 10th January

130110 Test 01 - Wind 9m/s from North-East

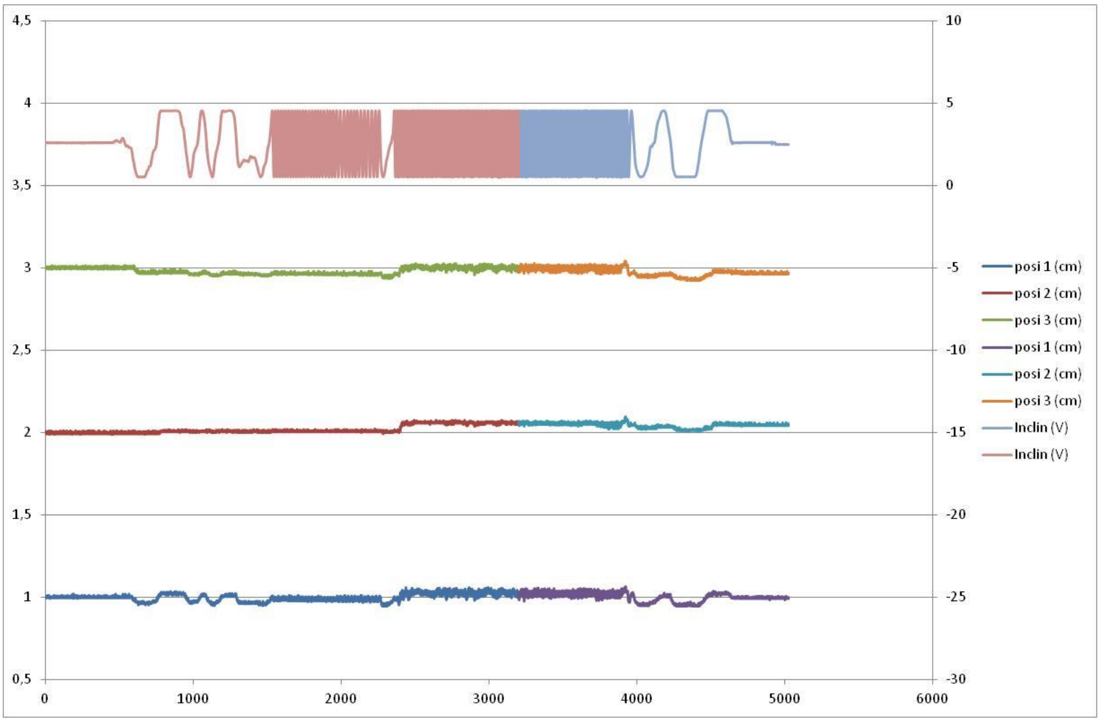

Fig. 64 - Main trace for the 130110 Test 1 showing the full acquisition period

At around 500s the blade is rotated from the 0° to 90°, and then on to 270°. After a brief start up period the turbine is rotated at a pitch angle of 50 deg between 1500 and 2300s. The blade is then placed in full run condition with a pitch value between -1 and 2 deg until approximately 4000s. At the switch to autorun condition there is an approximately 1mm step up observed in all the posiwire outputs. After the autorun condition is over the blade is again cycled to hold periods at 90°, 270°, and then 0°. Pitch changes at the horizontal blade holds caused no effect on the poiswire outputs.

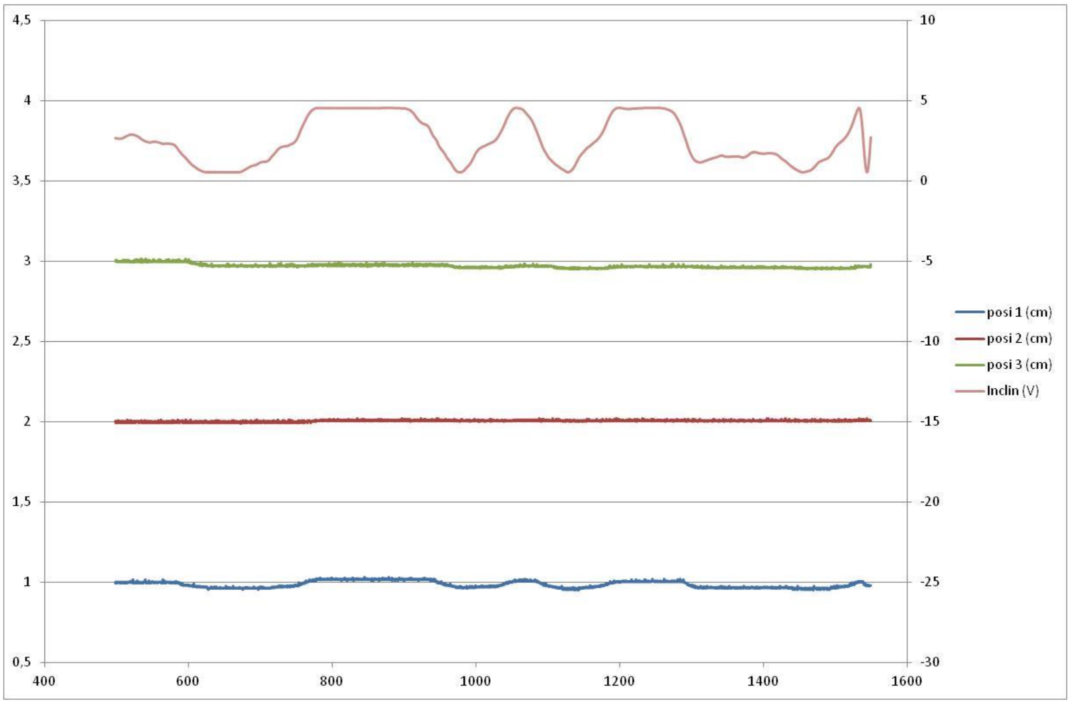

Fig. 65 – Detail from 130110 Test 1 showing the start up

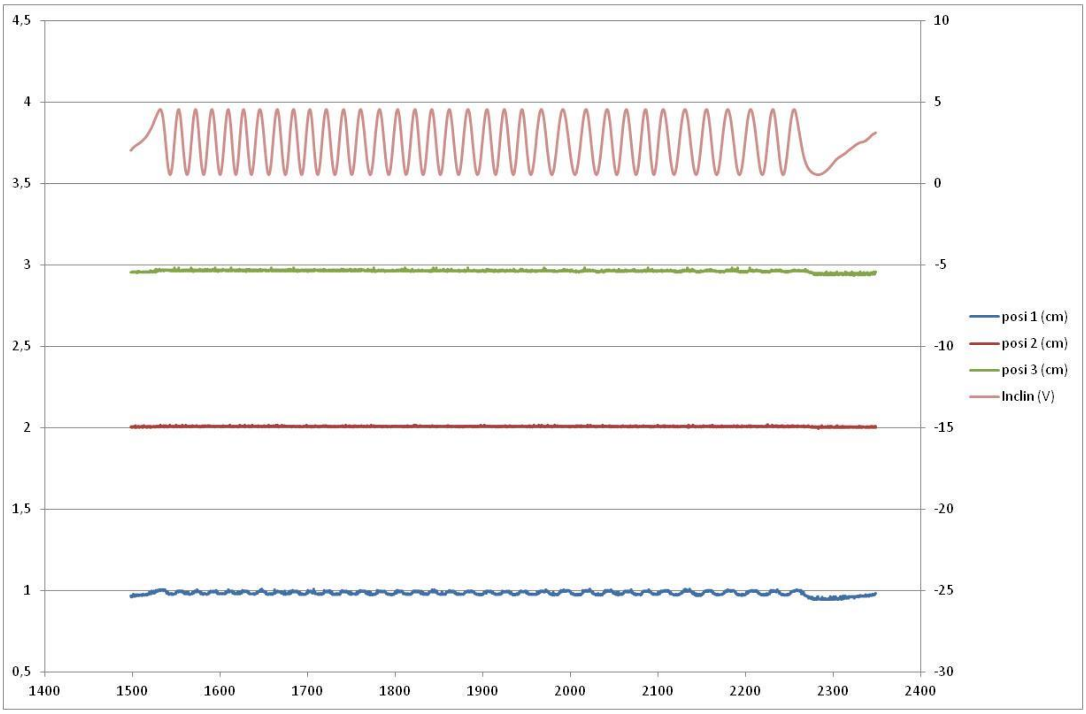

Fig. 66 – Detail from 130110 Test 1 showing turbine running at 50 deg pitch angle

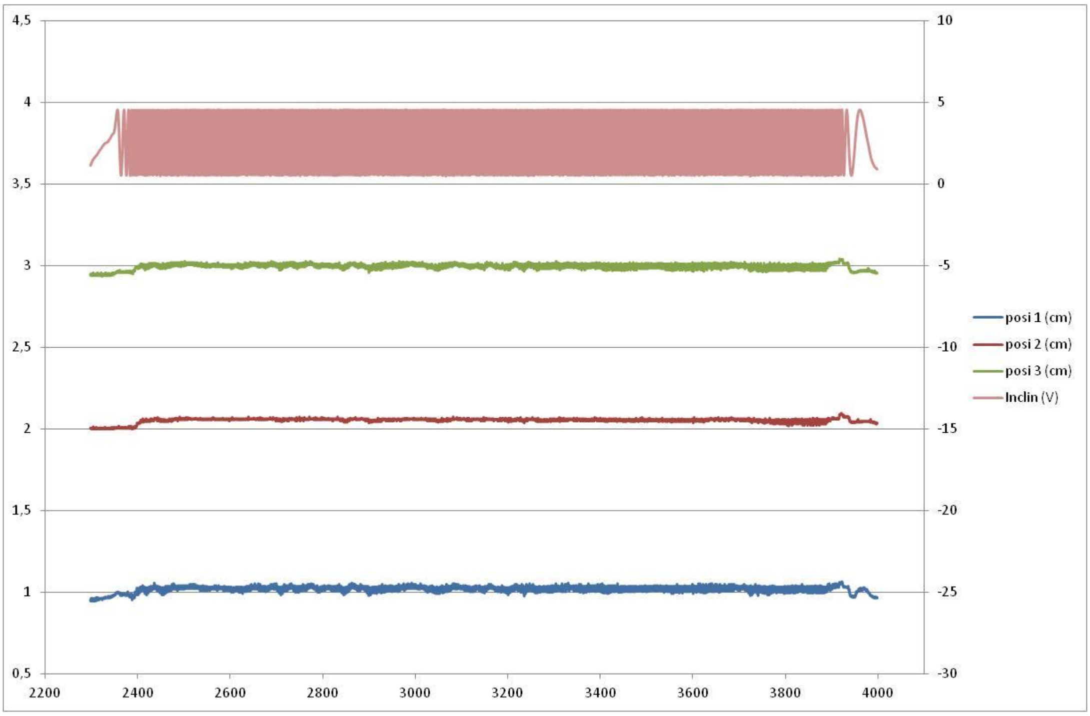

Fig. 67 – Detail from 130110 Test 1 showing turbine during autorun at -1 to 2 deg pitch angle

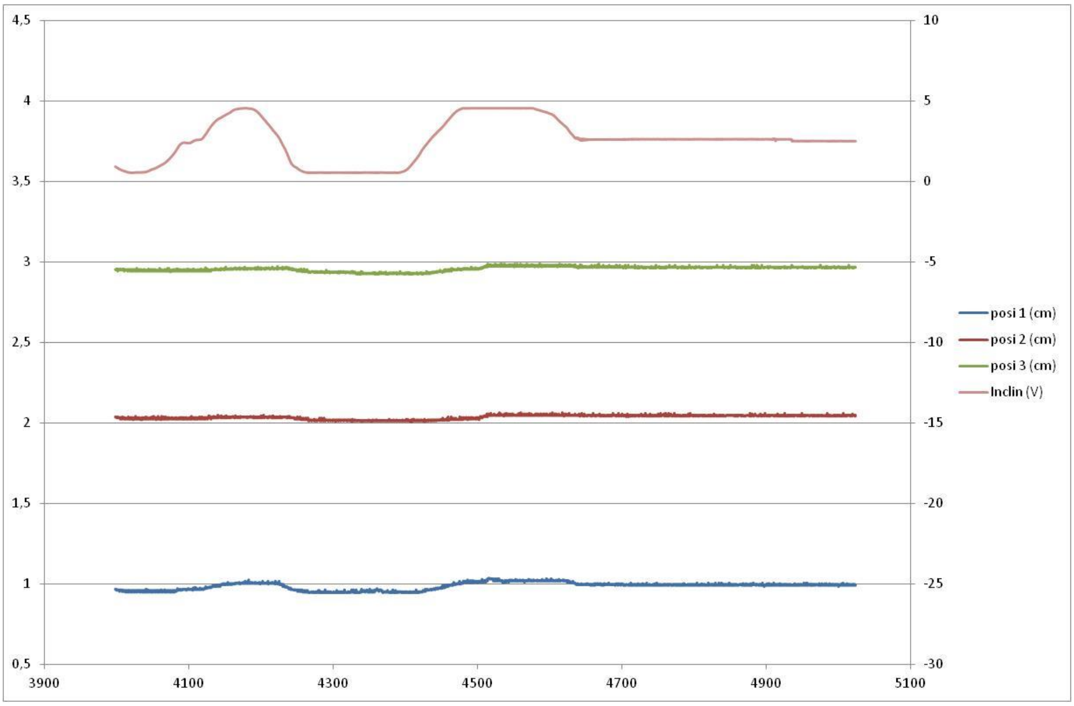

Fig. 68 – Detail from 130110 Test 1 showing effect of pitch change (0-90-0 deg) during horizontal blade hold

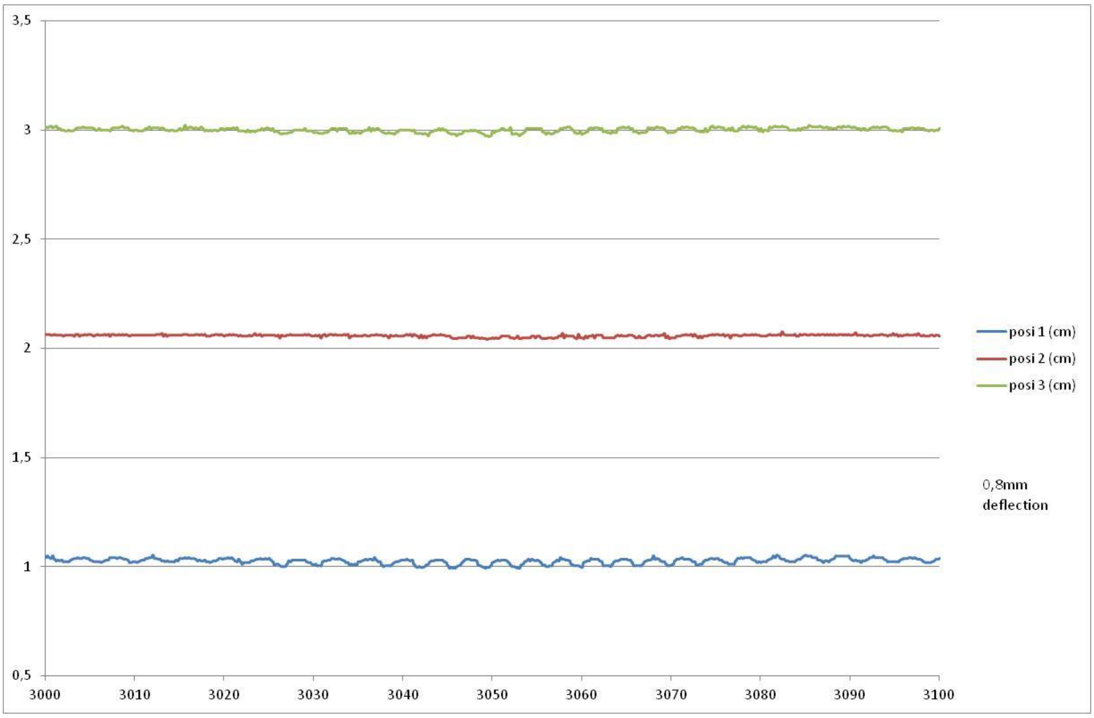

Fig. 69 – Close up detail from 130110 Test 1 showing posiwire response during autorun (-1 to 2 deg)

During autorun condition the posiwire response is very limited (under 1 mm total deflection) although in detail it is possible to see the cyclic response due to the blade rotation.

130110 Test 02 - Wind 9m/s from North-East (production pitch angle -1 to 2 deg)

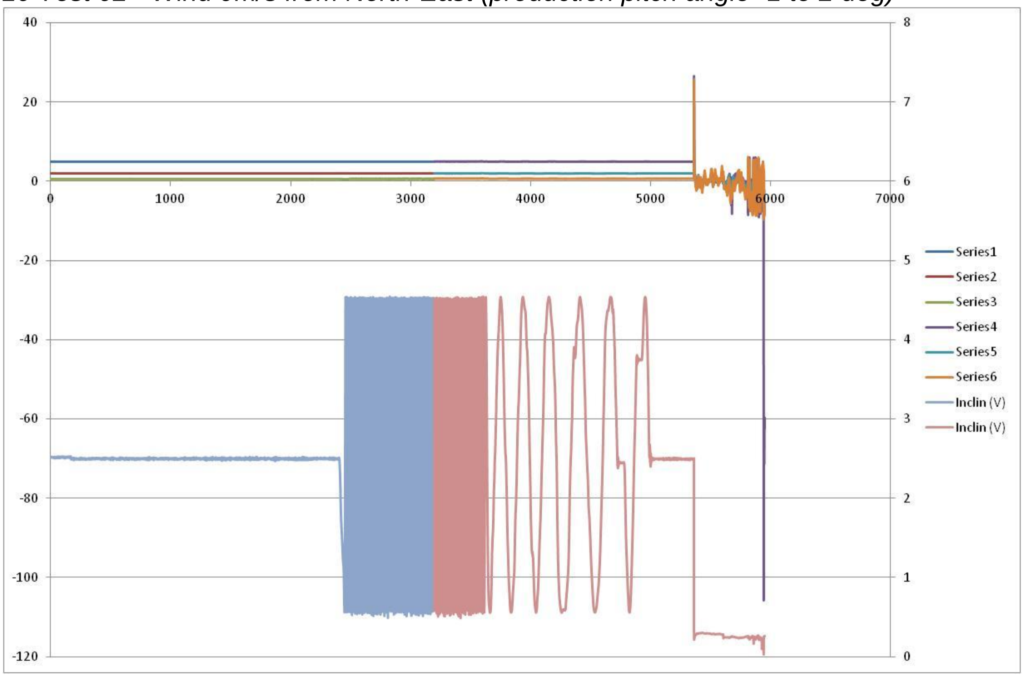

Fig. 70 – Main trace for the 130110 Test 2 showing the full acquisition period

There is a long pause before the turbine begins at autorun condition about 2400s into the acquisition period. When the autorun stops at about 3600s the turbine idles for some time before rotation is halted at 0° and the instrumentation system removed.

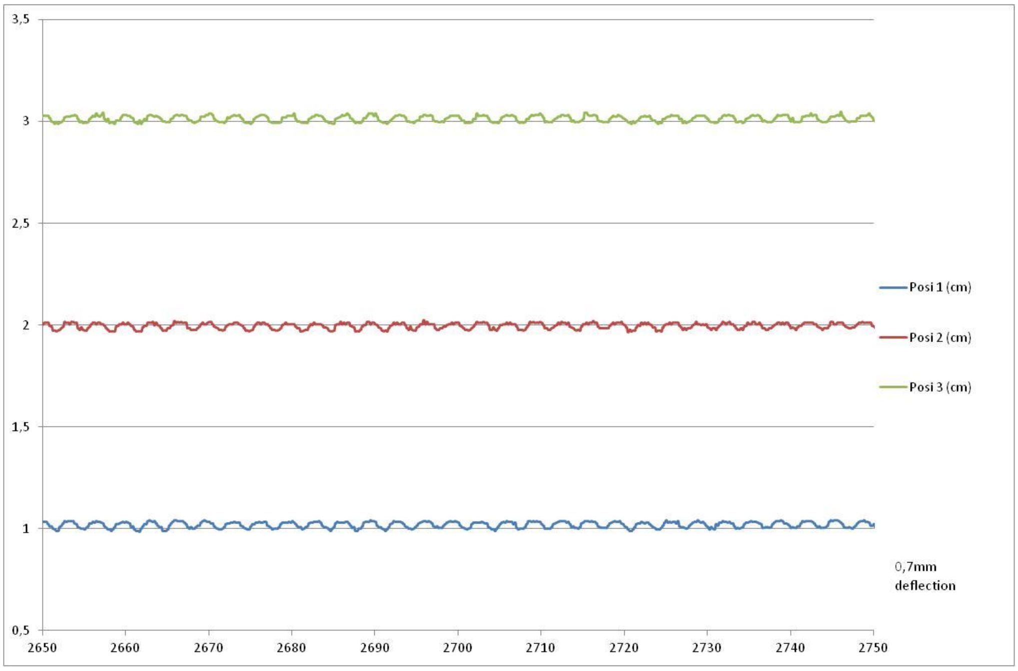

Fig. 71 – Close up detail of the posiwire response during autorun condition

8. Conclusion

The Bondlines consortium has successfully assembled a sensor system that allows the measurement of local structural deformations and loading in an operating wind turbine blade. Over a period of three days in October 2012, measurements were taken from the trailing edge and internal beam of blades on a V80 wind turbine at Tjærborg near Esbjerg. In January 2013 a retrofit structural reinforcement to prevent displacement of the trailing edge panels was effected and the measurements repeated.

A reduction in total deformation of 6.5 to 10mm between the two trailing edge panels to below 1mm in the reinforced blade was measured by these trials. The load value fluctuations measured between the trailing edge panels varied between 100 and 200N during autorun condition. And a cross shear beam distortion averaging 9mm was measured by the position wires at blade R 10m.

This data will now be used in the continuing development of retrofit reinforcements by the Bondlines project, as well as updating current models for structural behaviour used to describe blade response. A sub-component mechanical test series planned in Work Package 4 of the Bondlines project will calibrate the mechanical testing around the values measured here. The final report in WP2 will assess the measurement system used here, and propose improvements to assist future on-site monitoring work based on input from the rest of the consortium.

All data available on the Bondlines project sharesite:-
https://tdch1016781.sharepoint.com/EUDP-Bondline/SitePages/Home.aspx

Alternatively on request from

Malcolm McGugan mamc@dtu.dk (WP2 – measurement systems)

or Raphael Sajous res@bladena.com (WP3- On-site measurement)

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- define the requirements of the system
- source and integrate the various sensors, data acquisition, control, and power components
- develop and approve the instrumentation procedures
- safely and effectively conduct the on-site installation and measurement
- provide notes from their observations
- feedback regarding the data output

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DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

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