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Direct approach to determine static and dynamic behaviour of wind turbine blades for health monitoring and pitch control purposes

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Abstract

Increasingly, health-monitoring of wind turbines is discussed to improve turbine reliability and turbine efficiency. This holds especially true for multi-megawatt plants in remote locations such as offshore [4]. Condition monitoring of blades may be used to detect and to monitor the progression of damages to the blade. This information may be used to either schedule maintenance (condition based maintenance) or to stop the turbine to prevent further damage. Turbine efficiency can also be increased by implementing individual pitch control.

There are several concepts on the market for blade monitoring. The most important ones are: strain gages to measure strain at the blade root, accelerometers in the blades, and fiber bragg gratings (FBG) laminated into the blade. All these concepts are severely limited by their underlying principles.

The herein presented novel approach to blade condition monitoring directly measures the time-resolved deflection and torsion at one or several positions. Due to this direct measurement, a unique combination of static accuracy and fast dynamic measurement is made possible. It allows for high band-width for natural-frequency analysis, while simultaneously attaining unprecedented resolution in the range of better than 0.0002 degree or +/-0.05 degree absolute angular accuracy for deflection and torsion measurement. The obtained information can also be used for individual pitch control. This is accomplished by using a combination of a specifically designed high-speed camera with active illumination and special reflectors (thus no cabling required) at the locations of deflection and torsion measurement.

In this poster-presentation we would like to share the results of test center and laboratory testing of this new sensor. First, we will give an overview over the system design and setup, to show how integration into a blade can be accomplished, and what the underlying physical principles are. Second, examples of some tests that have been conducted will be shown and an overview over the results is given. The data include natural frequency measurements, and deflection and torsion measurement. These results show the superior resolution and accuracy of our system, in both frequency and spatial domain.

Introduction

In recent years, condition monitoring (CMS) of wind turbines has gained significance. Known critical components like e.g. bearings and gear box are monitored using sensor elements. Very often data from strain gages and accelerometers are transmitted to remote monitoring bodies. Damages to gears, bearings, and shafts are detected by comparing the frequency spectrum with reference data sets. Significant changes, associated with impending damages set off warnings or alarms to the operator (Fig. 2). Depending on the severity, immediate repair and even a shutdown is initiated, or the affected part is marked for the next maintenance [3].

This procedure enables the operator to make repairs on a planned basis and to pre-emptively (pre-emptive maintenance, or condition based maintenance) replace parts that are about to fail.

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Most repairs on wind turbines are relatively costly, as a lot of equipment has to be moved and access is sometimes limited during bad weather. This is especially true for offshore turbines.

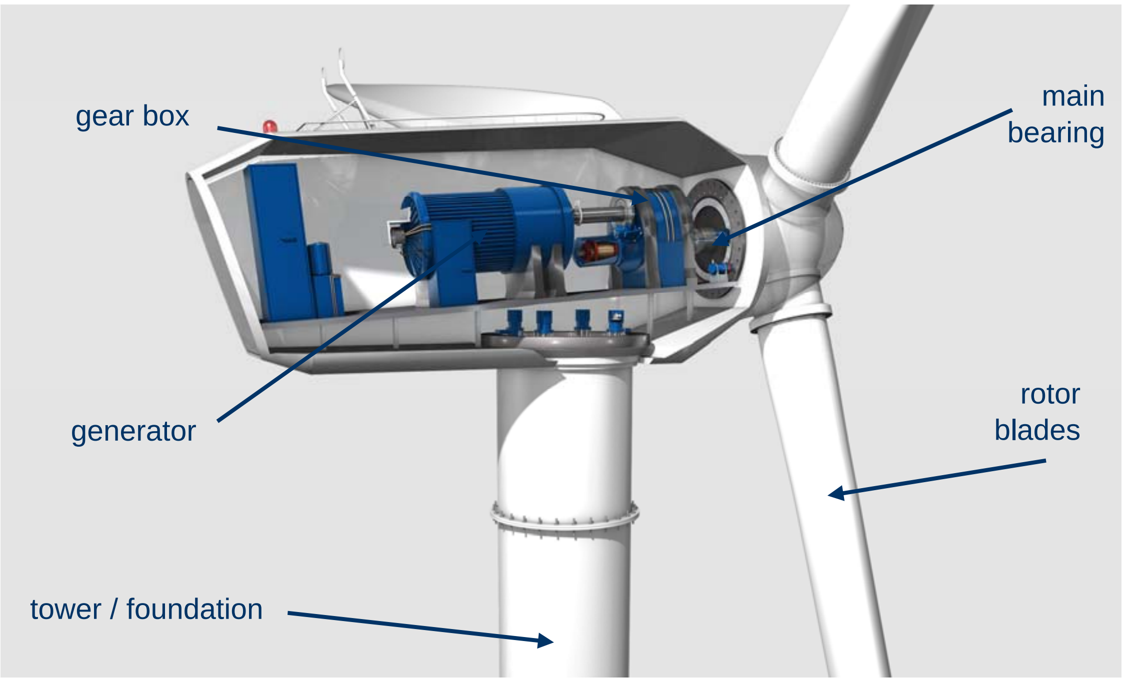


Fig. 1 Condition and Health Monitoring on Wind Turbines

Today CMS is mandatory for off-shore turbines and usually covers the drive-train only. Whereas future CMS will include according to GL [2]

- Blade Monitoring, (…)
- „Remaining Life-Time Estimation“, and will be
- recommended for all wind turbines

When sophisticated condition monitoring systems are put in place a lot more information is available on the operating control. Especially the blades, which are a sensitive part of the turbines, give many new perspectives for optimization of the turbine control and/or pitch control algorithms.

→ More information for operating control will be available which opens up new approaches for turbine control algorithms

→ Local data pre-processing within the CMS will be available to reduce field bus load and to optimize input for control loop tasks

Several blade monitoring concepts are on the market. The most important ones are: strain gages to measure strain at the blade root, accelerometers in the blades, and fiber bragg gratings (FBG) laminated into the blade. All these concepts are severely limited by their underlying principles. Strain gages, when laminated directly to the blade, tend to develop fatigue fractures [1, 5], and have to be replaced. Fiber bragg gratings are expensive [5] and get easily damaged during the manufacturing process, or the patches get loose after some time. For damage detection it is desirable to be able to directly measure small deflection and torsion amplitudes. These solutions do not directly measure deflection and torsion, but rather indirectly measure it, either by double integration of the acceleration, or deduction from strain-deflection models. Table 1 shows an overview of advantages and disadvantages of the available technologies.

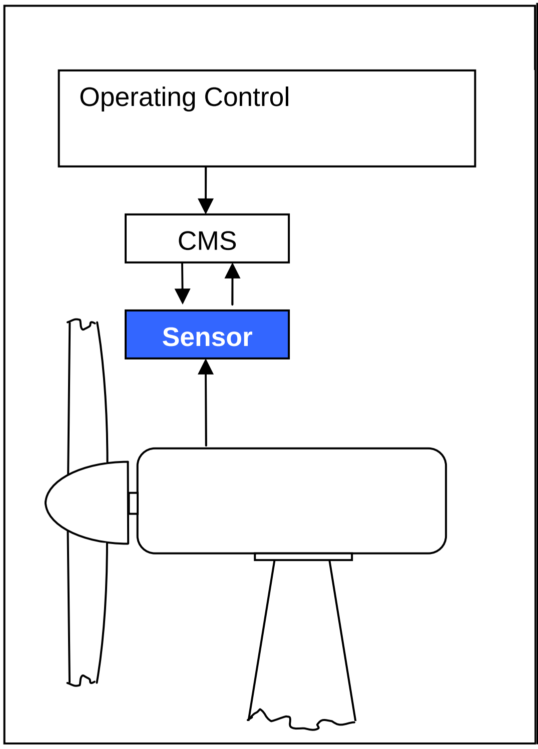


Fig. 2 CMS Today: Warning and Alarm only

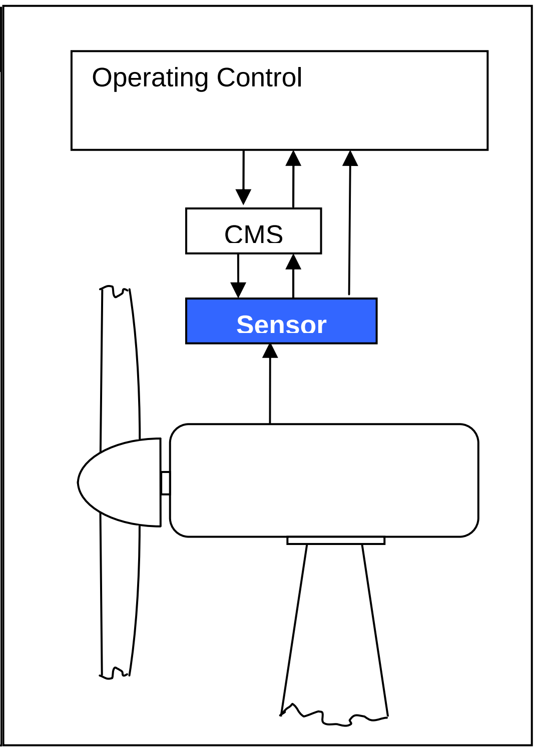
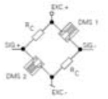
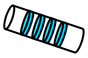


Fig. 3 Future CMS: Operating Control uses CMS sensor information and local data pre-processing

Features	Strain Gage	Accelerometers	Fiber Bragg Gratings	Optical Blade Monitor Baumer
Sensor	Change in resistance when force is applied 	2 or 3 axis acceleration sensor per rotor blade 	Optical temperature and strain gage sensor (Fiber-Bragg-Grating) 	Optical camera system 
Frequency analysis	-	+++	-	++
Deflection, Torsion	+	-	++	+++
Disadvantages	• cabling effort • EMC - susceptibility • low load cycles stability when laminated directly to blade • no direct deflection / torsion measurement	• cabling effort • EMC susceptibility • measures deflection and torsion not directly • no direct deflection / torsion measurement	• mounting issues • strong temperature dependence of refractive index • temperature compensation is necessary • no direct deflection / torsion measurement	• no direct strain measurement
Advantages	• simple measurement principle	• bandwidth up to kHz • temperature range	• load cycles (+) • accuracy (+)	• window heating prevents fogging • direct measurement of deflection and torsion • High accuracy for both large and small amplitudes (+++) • bandwidth up to 100Hz • Independent of load cycles

Tab. 1 Blade Monitoring Technologies Comparison Chart

Measurement Principles

The Baumer Blade Monitor uses an active illumination camera approach. At the measurement distances retro-reflectors are attached to the blade. The active illumination of the camera causes a strong reflection towards the receiver optics of the camera. The reflectors are reproduced as spots on the CMOS or CCD detector. The positions of these spots are proportional to the angle of the retro-reflectors and the optical axis of the camera. The principle is shown in Fig. 4. This figure also indicates the algorithms used to deduce deflection and torsion. The illumination and receiving optics use a large area. This makes it very robust regarding fogging and staining. To further enhance robustness a window heating device is being used to remove condensation.

The setup contains no moving parts. The optical principal allows for the very high accuracy for small and large positional changes of the reflectors. The achieved absolute and relative accuracy is much better than the pixel resolution. A sub-pixel resolution of better than 30 can be accomplished. The actual achievable deflection and torsion accuracy depends on the distance of the reflector. Angular values are given in Table 2. This table also contains key performance characteristics.

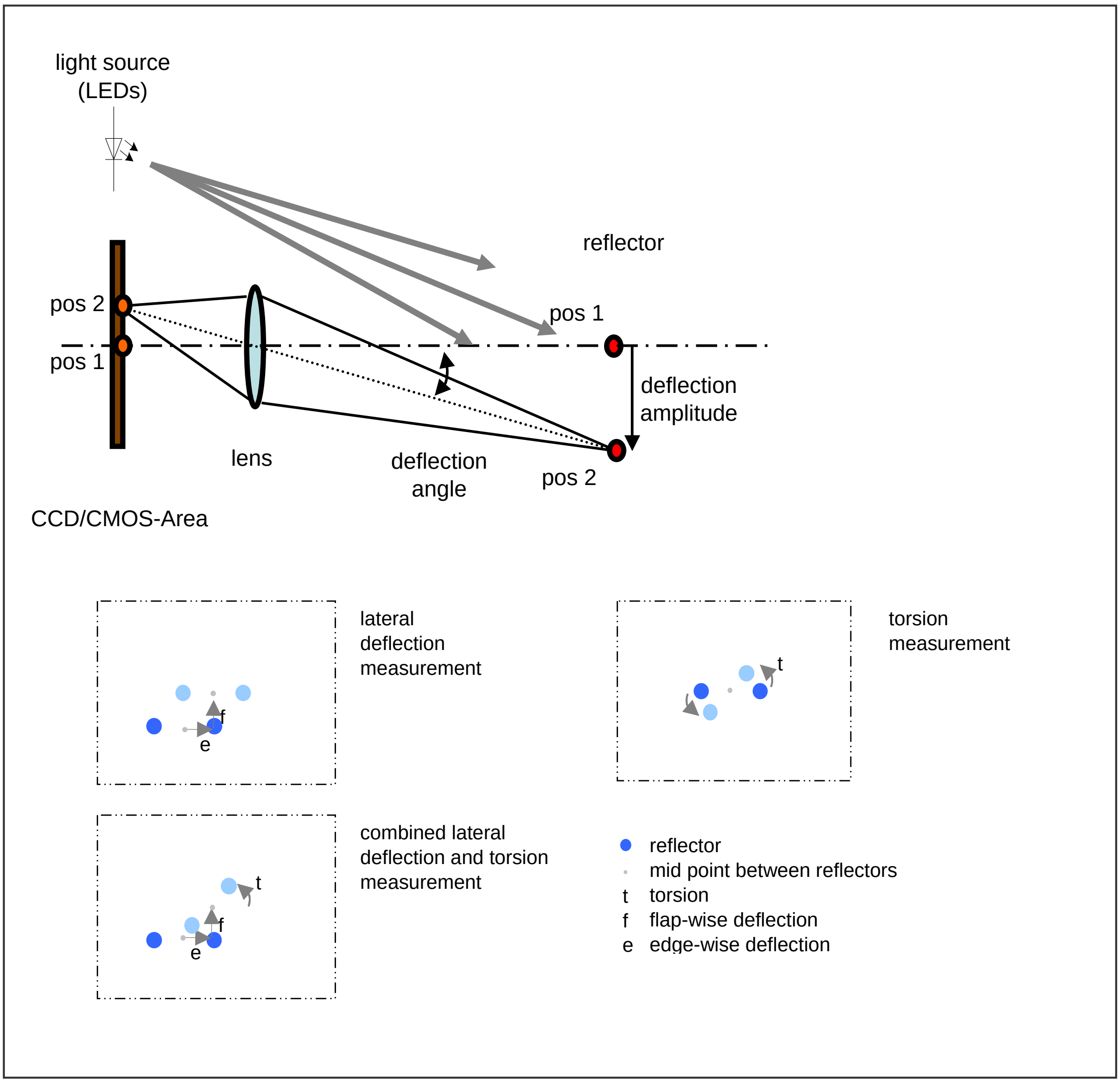


Fig. 4 Baumer Blade Monitor: Measurement principle

Fig. 5 illustrates schematically the integration into a blade. It shows the sensor measuring towards reflector positions. The reflectors have to be positioned in a way that they are visible during maximum blade deflections. Depending on the blade type the optimal mechanical coupling influences the positioning of the reflector holders.

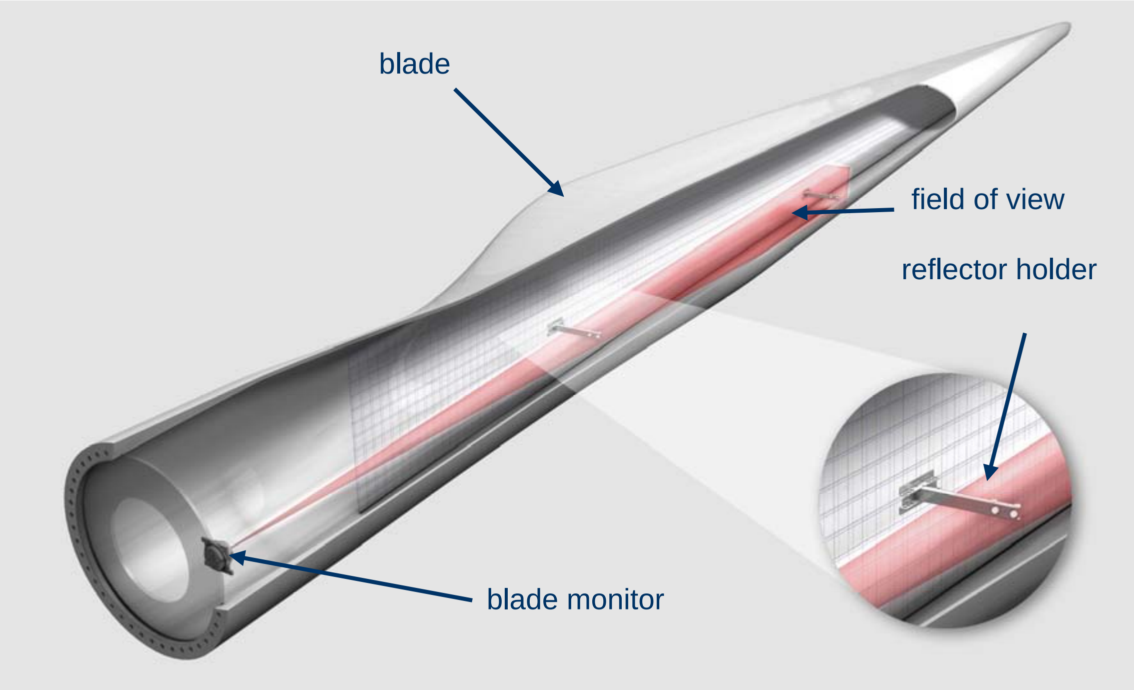


Fig. 5 Baumer Blade Monitor: Schematical setup in a blade (no actual positioning, principle only)

Results

Table 2 shows results from Baumer laboratory design validation testing. Besides lab testing comparative tests have been conducted at manufacturer test centers. For example FFT and deflection values have been compared to reference measurements.

Tests have been conducted together with Risø at the "Experimental Research Facility for Blade Structure" in Roskilde, Denmark. The blade used for these tests is a SSP 34m blade from SSP Technology A/S (cut to approx. 25m length). The reflectors (reflector pairs 1 and 2) have been placed on the outside for better access in a test environment. Excitation occurred at position FT-1. The blade was mounted with a 30 degree angle between the edgewise direction and the floor.

The following section shows some capabilities of the sensor in a case study at the test center in Roskilde. The examples have been chosen to illustrate the usability for e.g. pitch-control and/or health monitoring purposes. The data presented does not imply that the product has been explicitly validated for this usage, but rather shows its usability for usual blade monitoring approaches known from literature. With this kind of high-resolution (deflection and torsion accuracy, time and frequency domain) data, very minute effects (e.g. 10-50µm at >20m reflector distance) and large deflections (e.g. >1m at >20m distance reflector) can be simultaneously measured.

Parameter	Implemented in functional model	Note
Operating distance on a retro-reflector	2…50m	The range may be extended by using suitable retro-reflector material
Field of view		
Focal length of camera optics	60mm	Defines field of view
flap wise maximum field of view	+/- 2.08 deg	The usable field of view is reduced by approx. two times the angular dimension of the retroreflector operating distance has some influence
edge wise maximum field of view	+/- 1.33 deg	
maximum edge-wise deflection amplitude for fast read-out	+/- 0.40 deg	
Angular resolution	<0.0002 deg	
Timing		
illumination time	<1-200 µs	
measurement rate	<=200Hz	
Position repeatability (angular resolution)	<0.0002 deg	Limits angular resolution
Position accuracy / linearity (f(Temp.))	approx. < +/-0.05°	Temperature offset of measured position; does not affect frequency analysis
Frequency resolution fres (@ t_{sample}=60s)	< 16.67mHz	Can be improved in the serial product by at least a factor of ten through interpolation; frequency resolution depends on sample time tsampl

Tab. 2 Key Performance Parameters of functional model (results from validation testing)

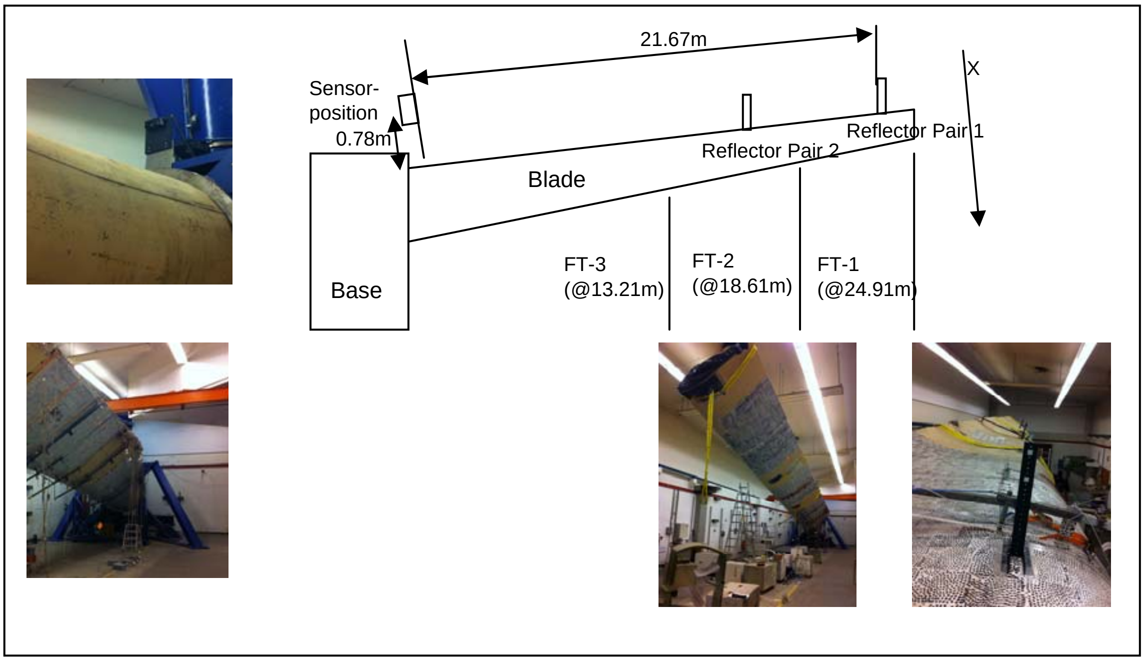
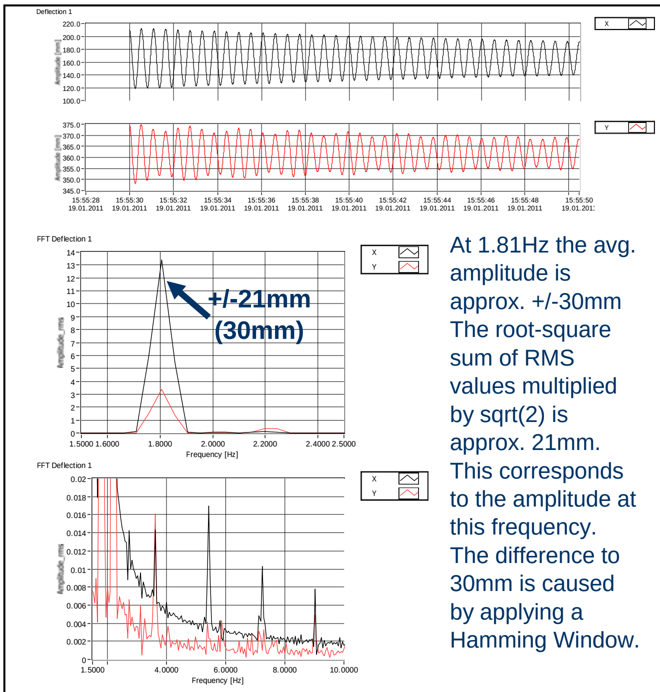


Fig. 6 Test setup at Risø test center

The excitation was accomplished by knocking the blade with a hammer at FT-1 or by pulling at FT-1 with a string. While the results are quite similar, some deviations can be seen. This poster does not give an explanation for the blade's eigenfrequency phenomena seen, but rather connects possible measured with calculated (FEM simulation) eigenfrequencies. The frequency resolution of the FFT is 48.8mHz (20.48s sampling with 200Hz sampling frequency). A Hamming window has been applied, which reduces the actual bandwidth and the intensity of the amplitudes. The FFT is given in the units Amplitude [mm] RMS. From this, amplitudes in a certain frequency interval can be estimated.

Fig. 7 and Fig. 8 show large and small scale effects giving some indications on the amplitudes involved. The following figures compare simulated eigen-modes of the 34m SSP blade (cut to 25m) with measurements made with the Blade Monitor.

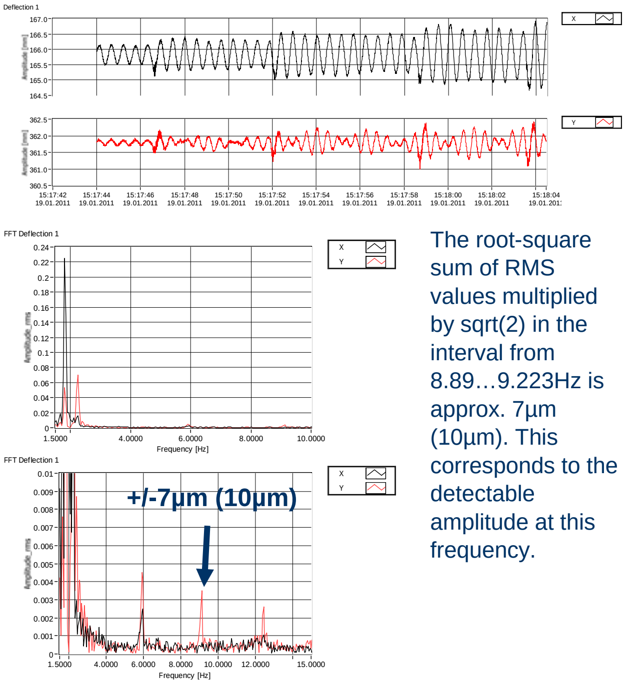


At 1.81Hz the avg. amplitude is approx. +/-30mm The root-square sum of RMS values multiplied by sqrt(2) is approx. 21mm. This corresponds to the amplitude at this frequency. The difference to 30mm is caused by applying a Hamming Window.

„Macro-Scale“
large amplitudes > 1m
(magnitude of meters)

Fig. 7 Excitation by Pulling at the Blade (C95CAB9E-13630)

>100dB
“dynamics”



The root-square sum of RMS values multiplied by sqrt(2) in the interval from 8.89…9.223Hz is approx. 7µm (10µm). This corresponds to the detectable amplitude at this frequency.

„Micro-Scale“
very small amplitudes 10-50µm
(magnitude of micro-meters)

Fig. 8 Excitation with Hammer (C95CA305-700)

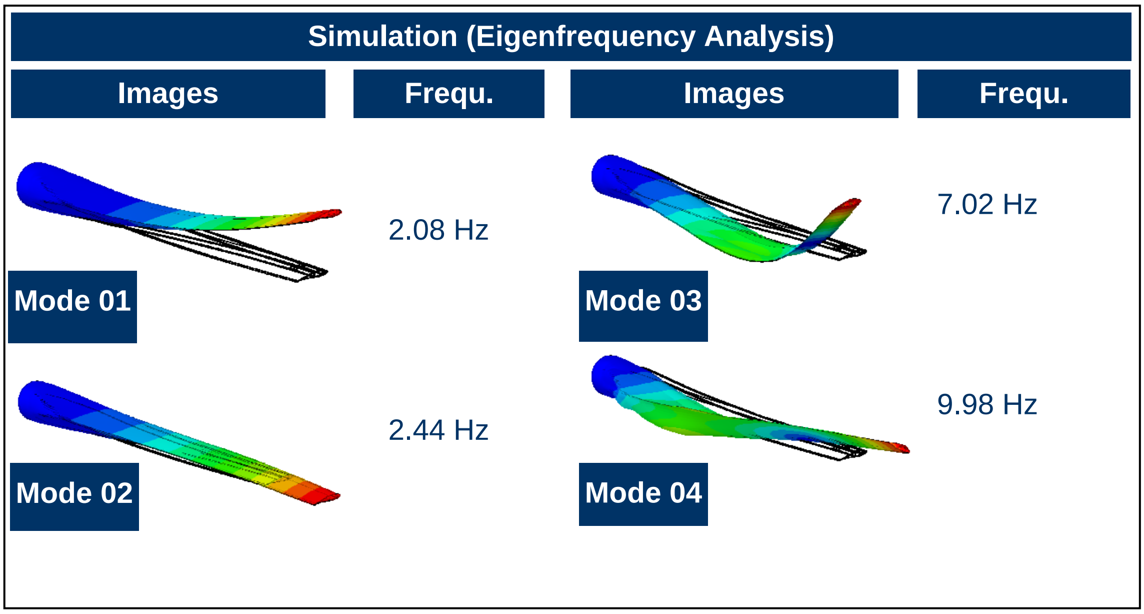


Fig. 9 Eigenfrequency Analysis – FEM Simulation

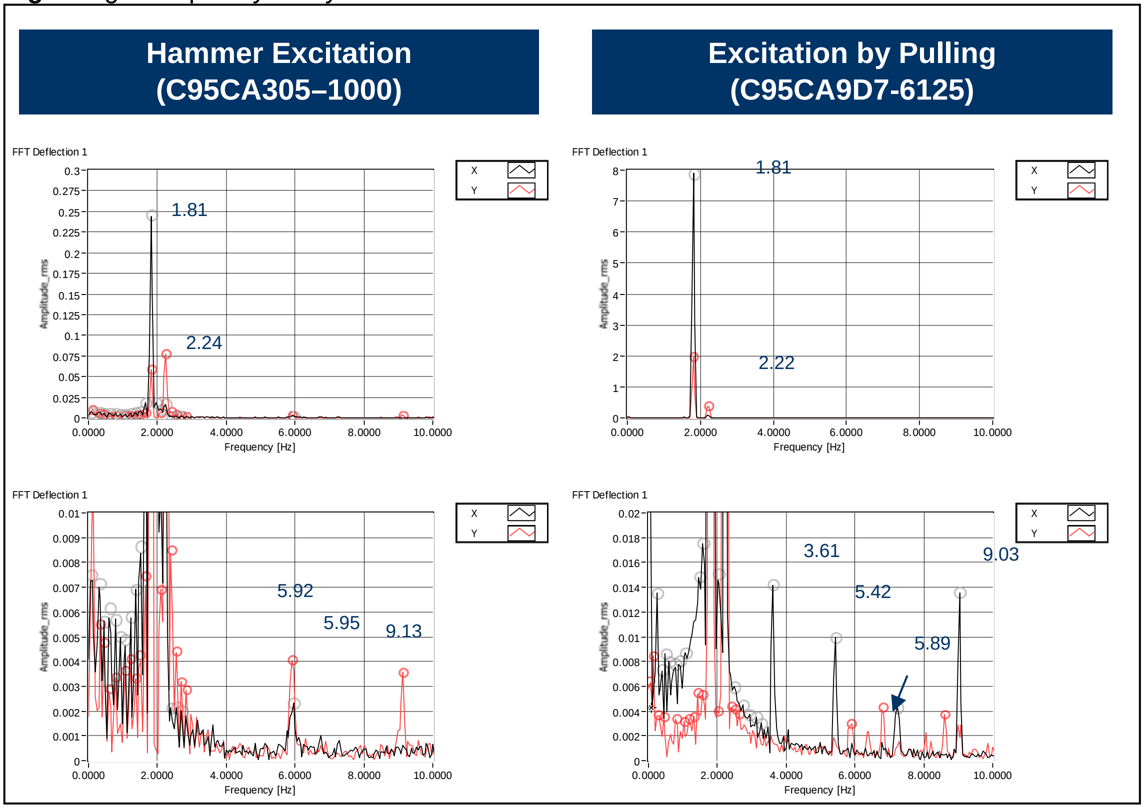


Fig. 10 FFT Results Comparison and Examples

Figure 9 shows in a summary the simulation results of some of the natural frequencies of the blade under test. Figure 10 shows some of the measurement results with the Baumer Blade Monitor. Since the blade has been mounted with a 30° angle (combined load) setup, the axes in the diagram do not match flap- and edge-wise orientation. There are for example X and Y components at the first mode at 1.81Hz. The axis definition is shown in Fig. 6.

During testing, various measurement equipment was attached to the blade, increasing the blade's mass. As this additional mass was not accounted for in the finite element simulations a deviation between the measurements and simulation results is to be expected. The clearly flap-wise (softer) directions seem to be affected more. A likely correlation is:

- 2.08Hz seems to correlate to 1.81Hz (-13% frequency shift)
- 2.44Hz seems to correlate to 2.24Hz (-8% frequency shift)
- 7.02Hz seems to correlate to 5.9Hz (-16% frequency shift)
- 9.98Hz seems to correlate to 9.0…9.1Hz (-9% frequency shift)
- The strong peaks at 5.4 and 3.6Hz may be harmonics of 1.8Hz. These peaks appear when excitation by pulling has been done.

Conclusions

The Baumer Blade Monitor is a powerful tool to be used for condition and health monitoring, and pitch control purposes. Its main features are:

- Powerful combination of static and dynamic accuracy
- Precise measurement of both large amplitudes and small amplitudes at the same time
- The angular accuracy is better than +/-0.05° (+/-17mm at 20m reflector distance) over the whole temperature range
  → static accuracy
- The angular resolution is better than 0.0002° (70µm single shot at 20m reflector distance). This gives superior detection capabilities for very small amplitudes.
  → dynamic accuracy
- With a sensor like this it is possible to go beyond simple eigenfrequency analysis.
  → more information for turbine control
  → new approaches for turbine control and pitch system algorithms
  → local data pre-processing possible

These features are accomplished while avoiding disadvantages of many of the approaches with available sensors. For condition monitoring and pitch control suppliers this sensor technology will open up opportunities that have not existed so far.
Possible applications in the blade may include:

- Ice detection
- Structural damage detection
- Recognize excessive wind load
- Optimization of pitch control

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