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Published in:

Conference proceedings of the 3rd International Operational Modal Analysis Conference

Publication date:

2009

[Link back to DTU Orbit](#)

Citation (APA):

Schmidt Paulsen, U., Erne, O., & Klein, M. (2009). Modal Analysis on a 500 kW Wind Turbine with Stereo Camera Technique. In Conference proceedings of the 3rd International Operational Modal Analysis Conference IOMAC.

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Modal Analysis on a 500 kW Wind Turbine with Stereo Camera Technique

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ABSTRACT: A new measurement technique of retrieving 3D positions in time and space has been developed at GOM, Germany and tested in collaboration with RISØ DTU on a 500 kW wind turbine. The technique is based on that multiple cameras are observing distant light reflecting markers which enable optical, dynamic 3D analysis to determine position, motion and deformation calculation of structures and components. The paper describes the technique, how the initial tests were conducted on the wind turbine and preliminary test results showing the potential of the new method to monitor dynamics and predict modal shapes.

1 INTRODUCTION

A review of literature within experimental testing of structures sensible to excitation of resonances shows in brief that analysis have advanced from signal- or system analysis techniques towards operational modal analysis. Analysis approaches such as physical modeling (mainly FEM) and system identification techniques: *non-parametric*, e.g. frequency peak picking, frequency domain decomposition, and *parametric*, e.g. ARMA, correlative function estimation, state space identification) are elements of modal testing (Andersen, Overschee, Ventura, Andersen). Though a flexible structure such as a 19 m wind turbine rotor blade can be modal analyzed by using acoustic or force excitation (Gade, Larsen) and carrying out post simulations with software tools (such as ME'scope), accounting for noise input and robust estimation of modal frequencies, damping and mode shapes. However, there is still the entire wind turbine to consider under operational conditions. The structure is assembled from numerous flexible components, which makes the complete vibrant picture complex and a testing of the structure quite extensive in sensor instrumentation and analysis effort. A system analysis approach can provide answers in particular low frequency modes of the vibrant components. The technique of using the stroboscopic light effect on cam shafts triggered the idea to use this on wind turbines. (Døssing) analyzed rotating shafts w.r.t. operating deflection shapes, and ways were identified to carry out this on the complete wind turbine structure when under normal operation. Laser vibrometry (Gatzwiller) has been used on rotating shafts for torsional deflection mode shape analysis.

GOM, with expertise in the field of optical and 3D measurement technique and digital image processing, has developed a method for measuring 3D motion of components with visible light (PONTOS) and improved this technique further for wind turbines of 100 m height during 2007. The present paper addresses on the potential with this method to obtain a modal signature of the wind turbine (height x width: 40m x 40m) in terms of dynamic behavior and vibration parameters and to describe first impressions with this experimental method. A photo of the optical system for object sizes (2-10 m) is given in Fig. 2.

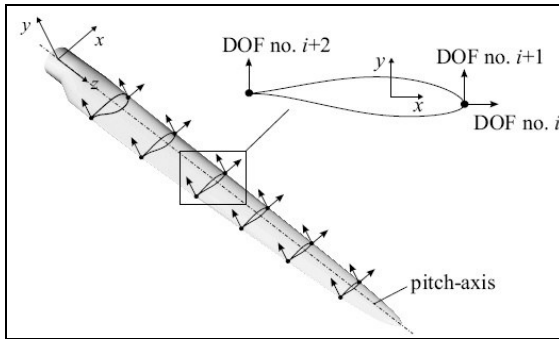


Figure 1 : Sensor positions (DOFs) (Larsen)



Figure 2 : Stereo Camera system PONTOS, with tripod, cameras and flashes

2 CONCEPT

In the absence of measured damping-, mass- and stiffness matrices we apply the mathematical notation, that the structure's vibrant response Z is a result of a mechanical load with associated displacement X : $Z=H \cdot X$ (Bendat). With measured 3D coordinate \mathbf{y} on a wind turbine component, displacements of points relative to a reference point \mathbf{x} could be used for applying modal analysis techniques (McHargue, Richardson), e.g. transmissibility functions, operating deflection shapes, parameter estimation of damping and resonances, and mode shapes. For the instrumented blade shown in Fig. 1, Origo is regarded as a reference position w.r.t. to other sensor positions on the blade. The blade is interpreted as a lumped system with DOF elements, each represented as a SDOF system. With the reference position moving in space, the response functions (Mod, Arg) for the vector displacement $\mathbf{z}=\mathbf{y}-\mathbf{x}$ typically looks as in Fig. 3. For the wind turbine under normal (e.g. non-transient) conditions, transmissibility functions contain responses excited by Gaussian stochastic wind. Calculating 3D positions with an optical system is based on, that two cameras have their slightly angled picture plane fixed at a mutual distance and on a line connecting each. The line is perpendicular to the line from the object to the optical system. The digital stereo camera system records different load or movement states, and the software assigns 3D coordinates to the image pixels. The digital images are compared and the displacement of the reference points is computed.

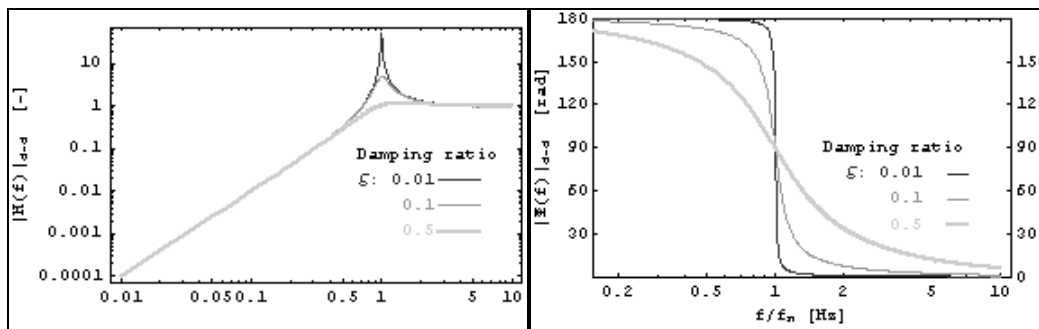


Figure 3 Frequency response functions, SDOF

3 THE EXPERIMENT

3.1 Description

The optical system setup for measuring deflections on a wind turbine is seen in Fig. 4. The distances from the 40 m rotor to the cameras is approximately 100 m. The optical system is capable to measure objects of 100 m rotor diameter. The reflective light from the targets are recorded at a speed of 100 Hz.

Special reflective targets of diameter D are applied on the turbine in a way as visually seen in Fig. 4.

Following 'rules of thumb' are applied:

- The markers are distributed as many as possible on the surface at sufficient intervals.
- Between spots: a distance of 2-3 D .
- The domain surrounding the target contains significant contrast compared
- to the target for calculating torsion.
- A line consisting of at least 3 markers defines a pitch deflection axis.

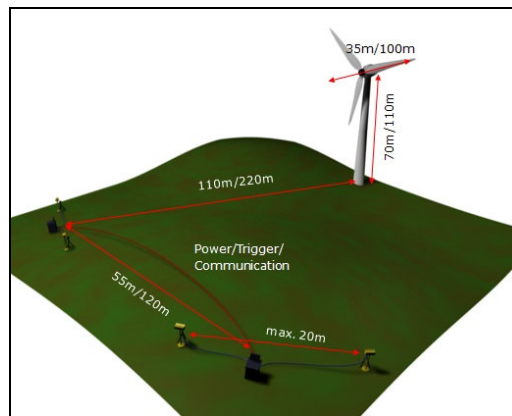


Figure 4 Experimental layout of camera system

(Larsen, p16) concluded on the accelerometer positioning in terms of uncertainty for the mode shape calculation (see Fig. 1 on the relative variation of DOF_{i+2} and DOF_{i+1}):

- The distance between two targets measuring the flap wise accelerations should be as large as (practical) possible
- The angle between their measuring axes should be as close as possible to zero.

The wind turbine is instrumented with a variety of sensors on the rotor, nacelle and tower and measurement equipment for 35Hz to 10 kHz sampling. Measurement records are stored for post analysis in a data base. (Helgesen, Paulsen) describe recent development and activities carried out with this wind turbine. Analysis of the data is carried out on the basis of the 35 Hz sampled records.



Figure 5 The effect of flash on the reflective markers.
Wind turbine at campus, Dec 2007.

3.2 Calibration

The optical system is self-calibrating for effects influencing the optical quality and consistency. In general these effects are non-linear and dependent on the lens quality and the CMOS system. Once calibrated the cameras are able to detect positions when flash light bursts illuminate the targets and the pixels are stored on the CMOS plate, row by row.

A proper selection of the reference target is a key issue for determination of mobility. The camera settings shall match the condition, that all targets are captured and recognized.

4 RESULTS

4.1 Lessons learned

During the setting up the optical system, as a field experiment, experiences due to weather impact on soil conditions, on hardware and wind turbine testing conditions were made. Firstly the wind changed in direction and dropped down to conditions where the turbine could not operate under steady conditions. This condition is not ideally for the analysis of the vibration of the wind turbine, in particular the condition provides a major impact on the assumption of the analysis methods of modal analysis. The loads are less energetic than under high wind conditions, which have in particular impact on the operating deflection shapes (McHargue). The excitation of the lightly damped structure practically exists for impacts with frequencies close to resonance (e.g. operating deflection shape~modal shape). Secondly the cameras, computers and flashes were placed on ploughed land. The soil-softness changed accordingly with precipitation and frost. However, a fixed position of the optical system was achieved.

Because of lack of high wind conditions during the initial tests, preventing access to responses at normal operation and at standstill, it was decided to follow up on the present concept at a later stage.

The test wind turbine rotor is mounted in upwind position, which makes the markers applied on the tower 'blind' for the cameras at the blade position is pointing downward. In this situation no data can be extracted from these targets, but this window lacking data is very narrow compared to one revolution.

4.2 Test cases

Despite the low wind speeds, some results from the conducted tests are presented. The rotor speed was increased by means of forcing the asynchronous generator works as a motor, and then let the wind turn the wind turbine rotor. Following tests were carried out under these conditions:

- rotor idling, RPM varying
- stop sequences (e.g. grid loss simulation)

To provide some results for the edgewise blade bending, rotor shaft torsion and tower bending at the bottom, Fig. 6 shows a comparison of measured spectral load responses.

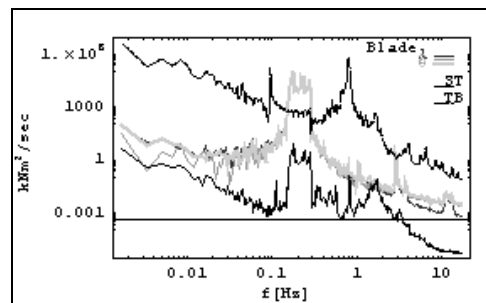


Figure 6 PSD of edgewise bending moments, tower base bending moment and rotor shaft torsion

Here at this atypical operating condition the turbine is rotating slowly at a speed of 0.17-0.29 Hz, demonstrating the edgewise blade vibration and in the rotor shaft. Furthermore the blade

masses rotating with the rotor plane excite the tower natural frequency at about 0.8 Hz, and the 1st symmetrical mode of the edgewise blade frequency at around 3.0 Hz.

The wind power spectrum is a straight sloping line following the main trend of the signals in the Fig. 6. A similar explanation on the influence of this ambient exciter is applicable for Fig. 7, which also reveals a similar result as in Fig. 6 on the coupled vibrations in the structure with a major flap wise motion correlated to the tower bending response and rotor shaft bending.

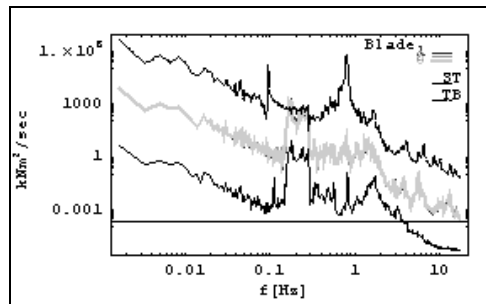


Figure 7 PSD of flap wise bending moments, tower base bending moment and rotor shaft torsion

The 1st symmetrical flapwise blade frequency mode is found at 1.5 Hz. In comparison, the optical displacement offers the ability to investigate on the vibrations which occur in the structure, as seen in Fig. 8. In the figure the Cartesian co-ordinate system is oriented as indicated, with a positive axis co-parallel with the wind. Furthermore mainly 1 Hz sinusoidal cycles from out-of-plane deflections correlated and synchronized with the 1st bending mode of the main shaft are also observed from the spectral load response results. Phase information is seen from Fig. 8, when comparing deflections at the indicated radial position on the different blades.

The flapwise deflection of a cantilevered 19 m blade is measured and computed in (Larsen) and consists of a relative measure of the deflection shape along the blade for the different modes. The operational deflection measured here is by magnitude superimposed with the wind loading and the mode shapes at this operating condition. To decouple these effects, detailed analysis of the test data are planned for the next measurement. The analysis of 3D motion requires static points to be referenced to. In the following part of the rotor plane has been used for developing a surface.

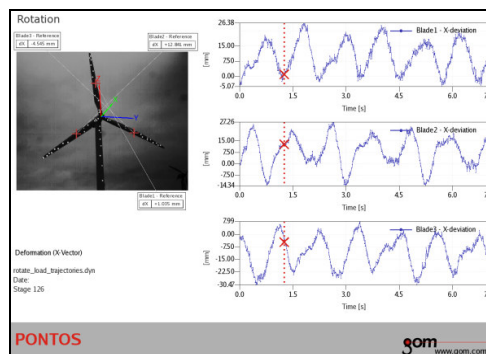


Figure 8 Optical measurement results, deflection in wind ward direction

Fig. 8 shows the out-of-plane movement of selected markers on the rotating blades. The signals contain several harmonics and show a proper resolution compared to the level of what can be detected (0.1-1 mm). The result is quite remarkable because the information regarding into the optical plane almost vanishes (still the view is slightly from below).

Fig. 9 visualizes the conditions during stopping of the rotor (grid loss simulation). The turbine is slowed down from 27 rpm to standstill. Again a lot of dynamics is developing when the rotor slows down.

In Fig. 10 it is seen, that the tower deflects up to 15 mm at this stage.

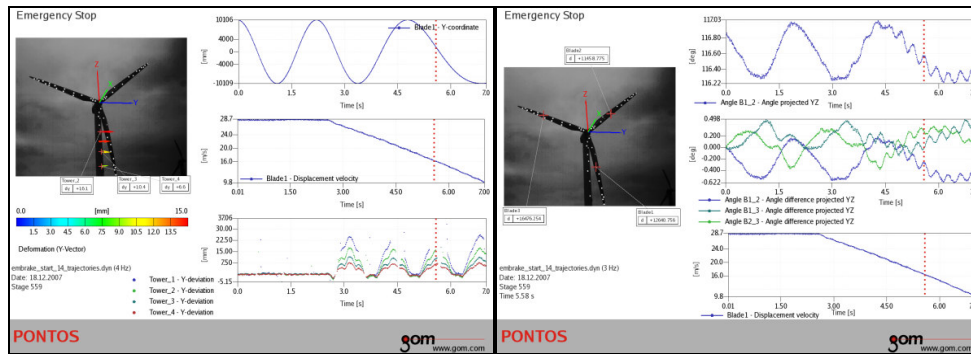


Figure 9 Phase angles and deflections during emergency shut down

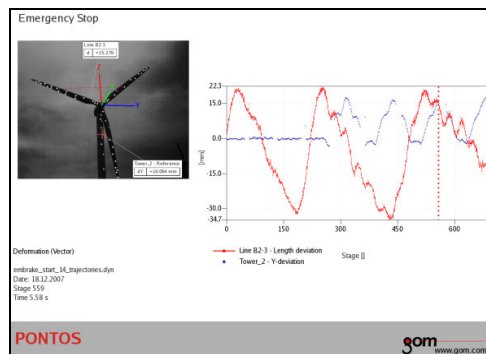


Figure 10 Blade and tower motion at the beginning of the emergency shut down

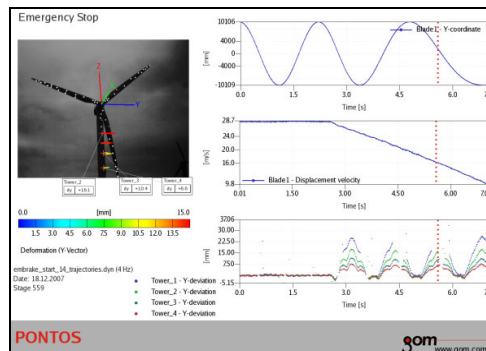


Figure 11 Tower deflections

At the end of the stop, the rotor is pitching back and forth due to backlash in the gearbox. This motion can be seen in Fig. 10, where the distance between the markers on two blades is monitored.

For the two blades in upside position as indicated on the image, the blades bend downwards causing an elongation. At the opposite position the situation has reversed to a shortening of the distance between the markers. Fig.11 shows the in-plane deflection of the tower.

5 CONCLUSION

A novel method of measuring 3D positions of wind turbine components during operation has been introduced. The method is applicable for wind turbines of 100 m in size and is capable to measure 3D position, motion and acceleration with sufficient resolution and bandwidth. In the paper the analysis has been limited to results from the optical analysis and to a comparison with load measurements, carried out with traditional acquisition system hardware.

With this method works has to be continued in analysis of the load responses:

- determination of deflection shapes and modal shapes, and the comparison
- analysis at standstill and at normal operation conditions
- impacts(emergency stop)

ACKNOWLEDGEMENTS

Jeppe Herbsgaard Laursen, Zebicon A/S is greatly appreciated for bringing people from GOM and RISØ DTU together, and for bringing valuable, practical and encouraging support and input into success.

GOM is gratefully acknowledged for support, to participate in the experiment and assisting with analysis, in particular Dirk Behring, Oliver Erne, Markus Klein, Gunther Sanow and Theodor Möller.

The technical staff at RISØ DTU campus (BAS), in particular Anders B. Møller and Oluf Høst are acknowledged for their technical assistance prior, during and after the tests and Kirsten A. Frydensberg for valuable help with necessary approvals concerning air flight safety and car traffic issues.

Finally the wind energy division, test and measurement program at RISØ DTU is gratefully acknowledged for financial support of the testing and work carried out.

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