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Concept Testing of a Simple Floating Offshore Vertical Axis Wind Turbine

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Abstract

The wind energy community is researching new concepts for deeper sea offshore wind turbines. One such concept is the DeepWind concept. The concept is being assessed in a EU-FP7 project, called DeepWind. Objectives of this project are to assess large size wind turbines (5-20MW) based on the concept. One task in the project is to test a 1kW concept rotor (not a scaled down MW size rotor) partly under field conditions in a fjord in Denmark, partly in a water tank under controlled conditions in Netherlands. The objective of testing the 1kW concept turbine is to verify the dynamical behaviour under varying wind and wave conditions, and to compare such behaviour with computer code calculations. The concept turbine was designed and constructed by the project task partners, and all parts were assembled and installed at sea in the Roskilde fjord right next to DTU Risø campus. The turbine is under a testing program of which the initial tests have been completed, and a testing program with various wind and wave conditions are being carried out. The design ideas and the offshore implementation will be demonstrated, and some of the initial testing results of the testing program will be shown.

1. Introduction

The DeepWind wind turbine concept [1-4] is based on a very simple idea. The vertical-axis rotor shaft that carries a Darrieus rotor is extended deep into the sea. The long shaft then has two tasks: to provide buoyancy against weight to keep the rotor upright in the water, and to transfer the torque through the rotating rotor to the bottom. The generator is mounted deep in the sea at the bottom of the shaft, to convert shaft torque to electric power and to provide sufficient ballast. A mooring system is keeping the turbine in place and transfers rotor thrust and rotor torque to the sea bed.

The European Commission granted FP7 project DeepWind [5] has a task 7 of proof of principle experiments of this type of design. The objectives of task 7 is to demonstrate the dynamic behaviour under different operating conditions, partly under field testing conditions, partly under controlled water tank conditions. The dynamic behaviour is studied by simulations and measurements of dynamic movements under different wind, wave and current conditions. The concept testing is based on a 1kW DeepWind concept demonstrator wind turbine. This paper describes the testing of the turbine under realistic field conditions.

2. Demonstrator design

The demonstrator was designed as a concept wind turbine. It was on purpose not designed as a scaled model of a 2 or 5MW size wind turbine, which might have otherwise provided good evidence for a large size turbine. The design philosophy was to make a turbine that was able to provide evidence that the concept can work as expected. Another design philosophy was that the activities at sea should be safe and controllable without the need of work at the sea bottom. The mooring configuration was selected as configuration 2 in ref [2], the torque arm fixed configuration, which restricts the degrees of freedom of the rotor so that it is fixed in position over the seabed, but still floating, and the generator cannot rotate. The basic test setup ideas are shown in Figure 1. A three legged foundation with concrete feet is used to support a lattice mast and a torque arm that can move up and down.

The rotor tube with the Darrieus rotor in the top is in the bottom flanged to a generator box. The generator box is mounted on a gimbal joint that is connected to the torque arm, giving the rotor freedom to move in heave, pitch and role. The torque arm transfers the rotor torque to the foundation, and keeps the rotor in position. The torque arm can also be raised to sea level for mounting and dismantling of the rotor for changing rotor configuration etc. A raft to lift the foundation for transportation to position of test site and for servicing the test setup is also part of the test setup.

Figure 1 Principle test setup of 1kW DeepWind demonstrator wind turbine

The detailed design of the demonstrator was not far from the original basic sketch in figure 1. The Darrieus rotor was designed as a 2x2m Troposkien shaped rotor made of glasfiber with 0.10m chord and a Delft DU 06-W-200 asymmetrical airfoil [6]. Unfortunately, the first blades produced had production faults that lead to a decision to use alternative blades. The Darrieus rotor with these alternative blades were also 2x2m, but with circular shape and made of extruded aluminium profiles with 0.12m symmetric Sandia SAND 0018/50 profile [7]. The total length of the rotor is 5.00m, diameter 0.15m and wall thickness 5mm. The tube is made of standard extruded aluminium AW 6082 T6, and the flanges for blade attachment are welded on. The rotor flanges were made to take two or three blades.

The generator box was made with a standard 1kW asynchronous motor with a fail-safe disc brake that needs a voltage signal to detach before operation can start. A belt drive with a gearing ratio of 1:3.41 is used to increase wind turbine rotor speed from nominal 400rpm to nominal 1500rpm of generator.

The 1kW demonstrator turbine has been modelled with the HAWC2 program to simulate the behaviour for given wind, current and wave conditions [4]. However, the simulations are not made for the final design with the alternative blades. The power curve with two alternative blades is made, though, and is shown for three rotational speeds in figure 2.

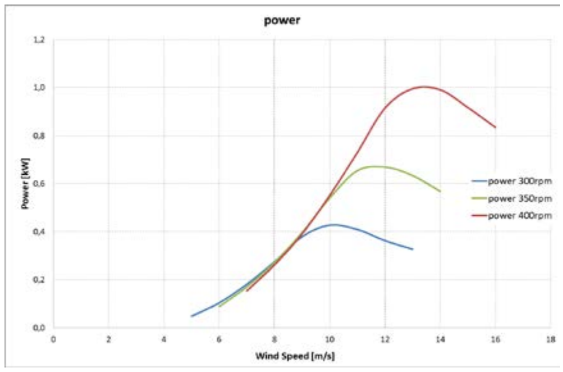

Figure 2 Power curve of demonstrator with alternative blades (2 blades, 0.12m chord, SAND 0018/50 profiles, al-blades)

3. Instrumentation

The instrumentation of the rotor was based on the objectives of measurement of movements of the rotor. For this reason and to keep the weight low no load measurements were made on the rotor or the rotor blades. The instrumentation in the rotor consisted in the bottom of a National Instruments measurement system, powered by a power supply through the generator box. A 3D accelerometer and a gyroscope was also mounted in the bottom. Additionally a 3D accelerometer was mounted in the rotor top. Data were transmitted wirelessly from the top of the rotor to the mast. The mast was instrumented with a 3D sonic, and a temperature and pressure sensor. Rotor and mast data were connected at the mast and transmitted wirelessly to land. A Sentinel ADCP was installed at sea bed on the site to measure sea currents and wave heights. The ADCP was connected via cable to the measurement system in a container at the pier. A video camera was installed above the container on the pier in order to visually record the behaviour of the turbine.

4. Manufacture of demonstrator turbine

The foundation, torque arm, gimbal support, and the rotor tube was designed and manufactured by Vestas. The blades were made by WindPowerTree Aps. The generator box and control system was designed and manufactured by Aalborg University. The barge, the concrete feet, the mast, the instrumentation in rotor and mast and on seabed, were designed and manufactured by DTU. The assembly of the foundation with concrete feet, generator box and torque arm with air barrels for lifting are shown in Figure 3.

Figure 3 Foundation with concrete feet, generator box and torque arm with air barrels

5. Modal analysis of demonstrator rotor

Modal testing has been carried out on the demonstrator and comparisons are conducted on the basis of a finite element model analysis of the wind turbine. The purpose is to have a good representation of the demonstrator in terms of safety and controls. Three configurations were studied: tube alone, tube with blades and tube with blades and generator box (the rigid structure rotating around the main vertical axis), see Figure 4. The two first configurations see Figure 5, correspond to the configurations that have been tested experimentally with the B&K PULSE Modal test and analysis package. The modal testing has been conducted by hammering at a fixed point of the rotor top and simultaneously measuring the accelerations at different positions on the structure. With the method the systems transfer function is found and allowing to derive the modal shapes.

The finite element model has been setup consisting with machine drawings of the demonstrator. The tube, flanges for blade support and blades were modelled in ANSYS with shell elements.

Figure 4 Model of 3rd configuration (tube, blade and generator) for modal testing

The third configuration is similar to the operating configuration of the demonstrator and it has the same mass and centre of mass as the hinged support of the wind turbine. The two clamped models are used to tune the FEM model to match the experimental results. For the third configuration no experimental validation is available.

In the 1st configuration the eigen frequencies of the first, second and third modes are shown in table 1. They are predicted 6-8% higher than the measured frequencies.

In Table 2, the frequencies of the fixed support model are compared to the frequencies of the hinged support model.

From Table 2 it is seen that the side-side mode disappears because of the hinged, zero-stiffness support. The measured frequencies of the fore-aft bending modes are increased because the hinged support is supported in the hinges and zero hinge displacement is prescribed. The torsional frequency disappears because the tube-blade assembly is free to rotate.

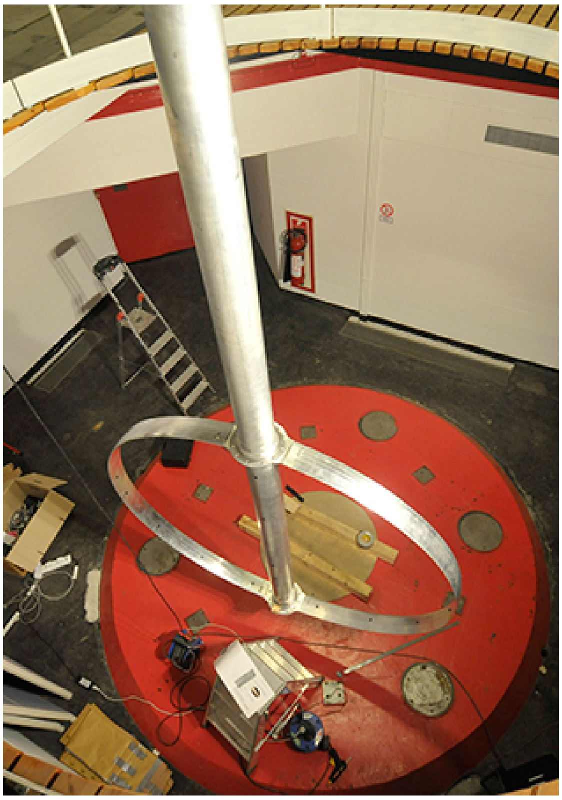

Figure 5 Setup of 1kW demonstrator rotor for modal testing

Table 1 Comparison of FEM modeling and modal testing the tube

FEM Frequency	Modal test Frequency	Mode shape
2.78 Hz	2.75 Hz	First bending
23.61 Hz	21.75 Hz	Second bending
69.4 Hz	68.25 Hz	Third bending

The Campbell diagram of the hinged pipe and blade assembly is estimated and shown in Figure 6. As seen from the figure, there are 4 potentially critical rotational frequencies: The 1P, 2P and 3P crossing of the first Eigen frequency (fore-aft), and the 3P crossing of the second Eigen frequency (side 2nd pipe bending).

Table 2: Eigen frequencies of the fixed support model compared to Eigen frequencies of the hinged support model.

Fixed support frequency [Hz]	Hinged support frequency [Hz]	Mode shape	Key
2.29	4.52	Fore-aft	Blue
2.33	-	Side-side	
19.73	16.04	2nd tube bending side-side	Green
20.41	-	Torsion	
21.45	30.4	2nd tube bending fore-aft	Red
30.12	31.56	1st blade flap bending assym.	Azur
32.58	32.95	1st blade flap bending sym.	Purple
49.34	50.23	1st blade edge bending sym.	Black
62.41	44.16	3rd tube bending side-side	Lime

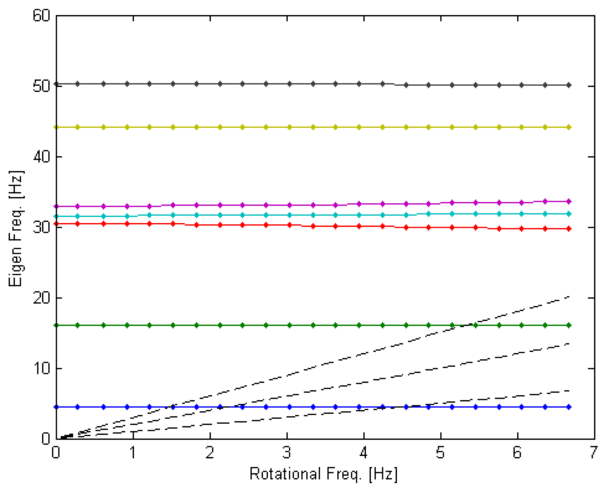

Figure 6 Campbell diagram for demonstrator rotor

6. The test site

The test site was chosen to be in Roskilde fjord at the Risø campus site with easily access with the barge or sea vessels from the small harbour behind the pier. The test site is positioned 50m west of the pier at a water depth of 4.5m, see Figure 7. At the position there is about 0.5m soft mud at the bottom. The foundation feet were specifically designed to sink through the mud and to stabilize on the solid seabed below. The torque arm was then still moving freely above the mud. The foundation was positioned so that the torque arm was pointing towards south. The ADCP was mounted on the seabed 25m north of the demonstrator. A yellow sea mark was deployed about 25m west of the demonstrator. In the directions west to north-west of the test site there was an open sea sector for about 6km. Winds from this direction generates relatively high waves, while winds from the south to south-east generates relatively low waves. This was used in the test matrix to achieve various combinations of wind speeds and wave heights. More details of the expected wave characteristics can be found in [7] p88.

Figure 7 Test site 50m west of pier at Risø marked at left of yellow line. Sea depth at site 4.5m

7. Deployment at test site

The sea operations were carried out with a special purpose sea vessel, the barge. The whole turbine construction without the rotor was lifted onto the seabed next to the pier with a mobile crane on 13 August 2012. With the sea vessel it was lifted one meter up from the seabed and then transported to the site, where it was sunk down in position. The construction weight is about 1.9ton. To alleviate the construction three air bags were installed on the foundation legs, and were each inflated with 250 litres of air. The torque arm was also supplied with two barrels that can be inflated from the mast. These were used to lift the rotor and generator box up to sea level for mounting and dismantling of the rotor, and also for adjustment of the rotor height above sea level, see Figure 3. The demonstrator setup without rotor is shown in position in Figure 8.

Figure 8 Demonstrator foundation with mast in position 50m from pier, torque arm is lifted with generator box above sea level and sea vessel surrounds mast

8. Measurement program

The measurements that were performed were all campaign measurements. The wind turbine was not supported with a regular safety system. There were no other overspeeding protection mechanisms than the failsafe mechanical brake. Measurements were typically performed for one hour. For a measurement campaign the following parameters were measured:

- Data from rotor (Gyroscope data, 3D accelerometer at bottom, 3D accelerometer at top, rotor position)
- Data from mast (3 wind components from 3D sonic anemometer, air temperature, air pressure)
- Data from ADCP (sea currents, wave heights)
- Data from control system (electric data to derive electric power and rotational speed)
- Video of demonstrator viewed from pier

Prior to testing the turbine in normal operation the brakes should be tested in order to ensure safe operation.

The test plan for operation of the turbine included winds and waves of different strength. The different wind directions are related to different wave heights due to the distance to shore. The longer the distance the higher the waves. The wind directions were then used to generate different wind and wave conditions according to the test matrix shown in Table 3.

Table 3 Test matrix for winds and waves

Wind and wave matrix	Low wind below 8m/s	Average wind 8m/s to 11m/s	High wind 11m/s to 16m/s
Winds from E, SE and S (low waves)	Case 1	Case 3	Case 5
Winds from W and NW (high waves)	Case 2	Case 4	Case 6

9. Database test results

The testing program was performed in the period October-November 2012. A database has been established with tests from brake tests and with operation for different wind speeds and waves according to the test matrix in Table 3.

Brake tests

Brake tests were first made without blades. Four braking tests were performed for different initial rotational speed of the generator: 300, 600, 900, 1100rpm. Then brake tests were made with two blades attached. Again four braking tests were performed, starting from different initial rotational speed of the generator: 300, 600, 900, 1100rpm. The braking tests provided evidence that the rotor can be stopped in overspeeding situations.

Tests during operation

The test matrix in Table 3 was fulfilled with 1 hour measurement campaigns. No data have been analysed yet and no comparison have been made with simulations. Some results of the tests will be shown here for illustration of the database. Figure 9 shows the DeepWind demonstrator in operation. The rotor is seen tilted towards the mast due to a medium wind but with low waves due to the southern wind.

Figure 9 DeepWind demonstrator in operation and tilting towards mast with medium wind from south and low waves

One test is rather illustrative. It is a test from 25 October 2012 at 13:57, a stormy day at Roskilde Fjord, under a case 6 measurement campaign. The wind direction was from north-west, average wind speed over 1 hour was 10m/s and waves were high. The upper two plots of Figure 10 show 10min time series of the wind speed and wind direction. The horizontal component of the wind speed is shown in the first plot. The X-axis shows the time in seconds. The average value for this ten minutes record is 11,4m/s. The wind direction is shown in the second plot. The average value is 30deg, but it is un-calibrated. The right value should be around 290deg, west to northwest. The third plot shows the rotational speed. The X-axis shows the time in seconds, while on the ordinate the angular speed is shown in volts. The upper value of 4.2V corresponds to approximately to 1300rpm, while at rotor standstill, the value is about 2.5V. The average generator speed over 1 hour is 1300rpm.

A big wave hits the rotor in several occasions, well documented both in the time series and video. The third plot shows 6 clear sudden drops in the rotational speed, corresponding to wave hits. The most serious hit occurs at around 10s from the start of the time series, when the voltage drops to 3V corresponding to 500rpm. The turbine is seen to recover to nominal speed within about 20 seconds.

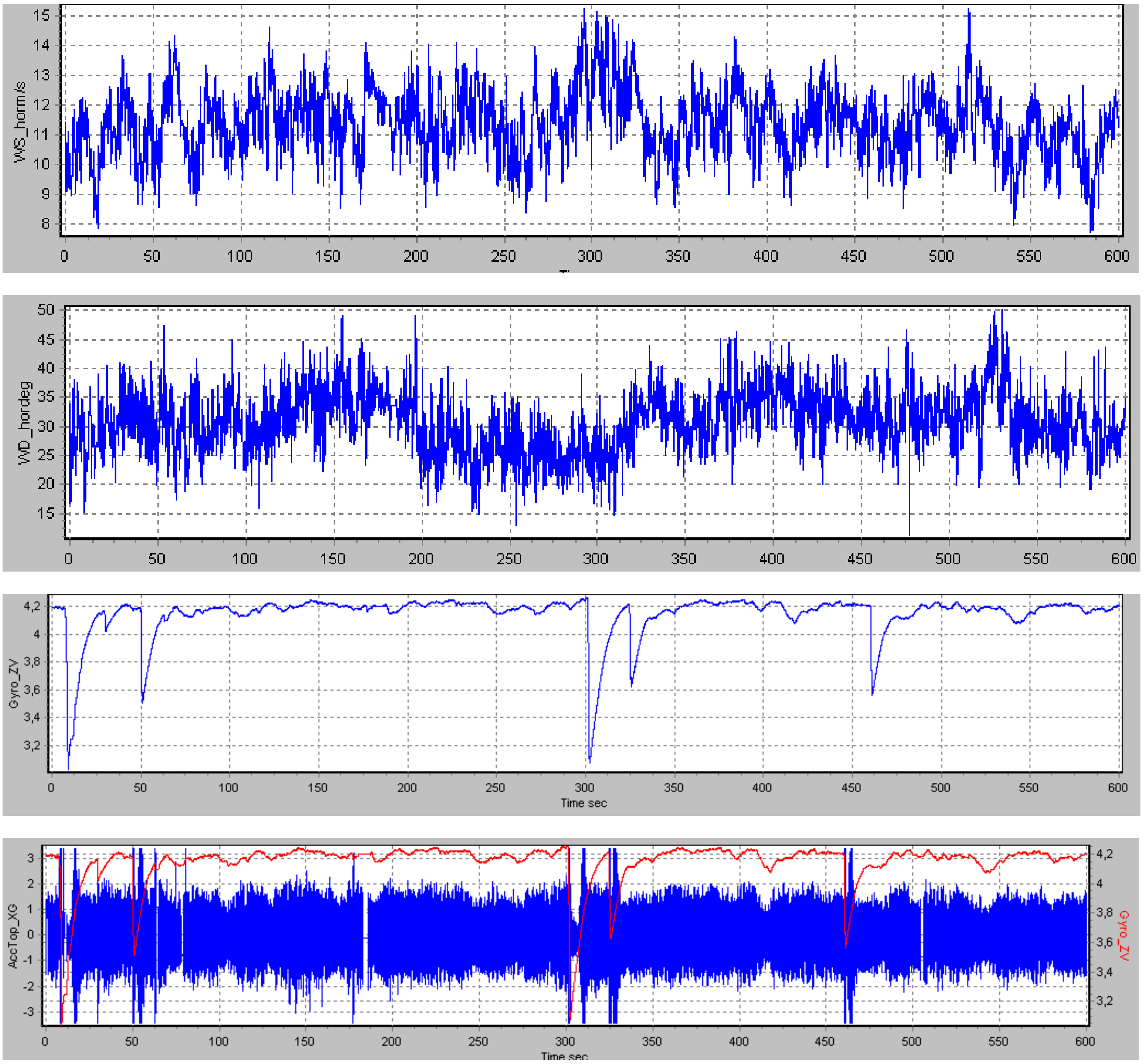

Figure 10 Example of measured data from 25 October 2012 13:57 with an average wind speed of 11.4m/s and winds from west to northwest and high waves. First plot shows wind speed. Second plot shows wind direction (un-calibrated – should show about 290deg. Third plot shows rotational speed of generator (un-calibrated). Fourth plot shows transversal acceleration in top of rotor.

The same "hits" can be seen in the acceleration normal to the tube at the top of the rotor measured by the 3D accelerometer. Here the normal acceleration on the top of the tube is shown in the fourth plot, where the rotational speed is superimposed on the graph (now in red). The uppermost point of the rotating turbine normally feels acceleration limited between +2g and -2g (on the left axis), but when the blades hit the water, +/-3,5g are felt.

10. Discussion

The measurements shown in Figure 10 were made with a rotor that was adjusted lower than shown in Figure 9. The rotor was lowered to try to get more buoyancy to raise the rotor closer to vertical. Unfortunately, this was too much to avoid the blades to hit the waves. The shape of the rotor was also originally designed for Troposkien shape. This shape will have less tendency to hit the waves because the blades are attached to the shaft with an angle upwards. The hits that are shown in Figure 10 actually occur at quite high blade radius and this gives a rather high torque spike that reduces rotational speed immediately.

11. Conclusions

A demonstrator DeepWind concept wind turbine was designed and built. The rotor was not built as originally designed, but alternative blades were provided, and these have functioned successfully on the rotor. Safety tests have been made on the mechanical brake to assure that safe operation could be made. A test matrix of combinations of winds and waves was setup, and tests have been made according to the test matrix. The wind turbine have operated smoothly during the tests with which has and an infrastructure for demonstration and testing of the turbine under real field conditions has been established.

The further plans of the database is to start analysis of data, and to compare data with simulations. March 2013 it is planned to test the turbine in a water tank under controlled conditions where well-controlled wind and waves will be applied to the 1kW concept demonstrator. Later in 2013 new tests in Roskilde Fjord are expected to be performed, applying other rotor configurations on the turbine.

12. Acknowledgements

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13. References

1. A Novel floating offshore wind turbine concept, *EWEC 2009* Vita L, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F
2. A novel floating offshore wind turbine concept: new developments, EWEC 2010 Vita L, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F
3. A novel concept for floating offshore wind turbines: Recent developments in the concept and investigation on fluid interaction with the rotating foundation, *OMAE2010-20357* Vita L, Zahle, F., Paulsen US, Pedersen TF, Madsen HA, Rasmussen F
4. Offshore Floating Vertical Axis Wind Turbines with Rotating Platform, Risø-PhD-80(EN) August 2011, Luca Vita
5. DeepWind – An innovative wind turbine concept for offshore, EWEA 2011, Paulsen US, Pedersen TF, Madsen HA, Enevoldsen K, Nielsen PH, Hattel J, Zanne L, Battisti L, Brighenti A, Lacaze M, Lim V, Wedell-Heinen J, Berthelsen PA, Carstensen S, de Ridder EJ, van Bussel G, Tescione G
6. The Design and Testing of Airfoils for Application in small Vertical Axis Wind Turbines, Master thesis TU Delft November 9 2006, M.C. Claessens
7. Tailored Airfoils for Vertical Axis Wind Turbines, Sandia Report SAND84-1062 UC-60, February 1992 Paul C. Klimas
8. Modal analysis of 1kW vertical axis rotor, Knud Abildgaard Kragh, DTU report (to be issued)