Final report

1.1 Project details

Project title	Costeffective offshore monopole foundation by joint applied research
Project identification (program abbrev. and file)	64010-0124
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Vestas Wind Systems A/S Hedeager 42 8200 Aarhus N
Project partners	LIC Engineering Aalborg University Technical University of Denmark (DTU) FORCE Technology
CVR (central business register)	10403782
Date for submission	2015.01.16

1.2 Short description of project objective and results

English Version

The project was initiated as the means to reduce the levelized Cost of Energy [LCoE] for offshore wind in order to compete with existing fossil solutions.

There is an estimated cost-out potential of 10% of the foundations since the design is based on the rather conservative approach from the Oil & Gas industry.

The foundations contribute with a big lump of the CAPEX and a reduction of 3% of the LCoE can be reached by optimizing the design.

The well-known concept of monopiles has been chosen to be optimized and this also enables the monopiles to stretch the design to greater water depths and/or poorer soil conditions.

Dansk Version

Projektet blev igangsat som et middel til at reducere levelized Cost of Energy [LCoE] for offshore vind for at være i stand til at konkurrere mod eksisterende fossile løsninger.

Det er vurderet at der er et cost-out potentiale på ca. 10% for vindmøllefundamenterne, idet designet er baseret på den mere konservative olie og gas industri.

Fundamenter udgør en stor del af de samlede anlægsomkostninger of det er vurderet at det er muligt at reducere LCoE med 3% ved at optimere fundaments designet.

Det velkendte monopælsfundaments koncept er udvalgt til optimeringsprocessen og muliggøre også at bruge monopælskonceptet på størrer vanddybder og/eller dårligere jordbundsforhold.

1.3 Executive summary

The project has been divided into 4 work packages as follows:

- Work Package 1: Improved Soil Modelling (headed by AAU)
- Work Package 2: Laser/Hybrid welding (headed by FORCE)
- Work Package 3: Improved Design Basis for Welded Joints in Seawater (headed by DTU)
- Work Package 4: Damping of Wind Turbine Tower Vibrations (headed by DTU)

Work packages 1, 2 and 3 has all shown cost-out potential – work package 4 has still not matured enough to present a viable business case. The total cost-out is calculated to 240 kEUR for the Northwind project – that is approximately 11% for the full value-chain of the foundation.

1.4 Project objectives

The project has suffered several setbacks, such as LORC exiting the project after 1 year (Luckily FORCE entered instead as a project partner) and also Vestas had to dial down the ambitions due to laydown of the entire offshore foundation department and laidoff of general project management. A lot of internal relocation took place (LIC took a large piece of the general system design and effects of optimization results) but all-in-all the scope of the different workpackages remained the same as originally described in the application.

1.5 Project results and dissemination of results

1.5.1 Work Package 1: Improved Soil Modelling (headed by AAU)

More than 1000 monopile structure have been erected in offshore wind parks in Northern and western Europe. The monopile has turned out to be a cost effective structure to produce and install, but there are still possibilities for further improving the cost effectiveness. The technical challenges have been to increase the size of the monopiles as much as possible in order to accommodate the increasing size of wind turbine generators and at the same time to minimise the steel consuption.

The monopiles are driven with larger and larger diameters in order to accommodate deeper, waters, more severe environment and the increase in the size of the wind turbine generators. Pile diameters greater than 6.5 m are in use for the moment and diameters beyond 7 m are on the drawing board. Hammers and anvils have far smaller diameters. Diameters around the sea level also have to be small in order to reduce the in-place loading of waves. This has led to introduction of piles with submerged conical sections. Driving this kind of pile means that water internally has to be displaced for each blow. Part of the driving energy is hereby diverted and is reducing the energy transferred to the pile toe. The loss in energy can be quite large and will have an impact on selection of hammers. Very large hammers are in short supply so an accurate estimate of energy consumption is essential.

A method of analysis for determining the effect has been developed. The predictions have been compared with actual experiences for the driving of piles in offshore wind parks. Agreement between measurements and theory is good. Even conical sections with a small slope will course considerable losses in driving energy.

The behaviour of the surrounding soil is very important as demonstrated in Work Package 1 of the project. Here it is demonstrated that sandy marine soils are considerably stiffer than predicted by the traditional p-y-curves (10% - 20%). Also the damping contributions for the soils are considerably higher than specified in the current Codes of Practices. Including these effects in design will have a high influence in reducing the dimensions of the primary steel.

1.5.2 Work Package 2: Laser/Hybrid welding (headed by FORCE)

The primary effort in work package 2 has been to introduce the laser hybrid welding process as a promising path to reducing the cost of production of monopoles and similar intended for offshore usage. This work included a thorough study of laser hybrid welding process parameters as well as a study of chemical compositions resulting in a recommendation of suitable steel. To some extent inspiration and finding from shipyard industry was taking into use and pushed further.

The main result are qualification according to applicable standard of the laser hybrid welding process in three sheet thicknesses. This qualification includes NDT, mechanical test and visual inspection. The tested sheet had the thickness of 12.5 mm, 25 mm, 40 mm and welded as a butt joint. This was done in a two-pass step process for 12.5 and 25 mm. The 40 mm sheet was made with 8 passes. When comparing with the industry used process and focusing process velocity and consumables, an up to 80% cost reduction is achievable when using the two-pass approach.

The 32 kW laser installation combined with a traditional MAG torch invites to high-speed welding production of thick steels. However, as the steel grow in thickness, the chance of solidification cracks simultaneously increases to some extent. This indicating that the work of two-pass process with 40 mm and higher is not concluded at this point.

The secondary activity, a corrosion study of monopiles initiated as the knowledge of this limited.It was realized early in the project that hydrogen Induced stress cracking (HISC) could become a problem when future attempts for cost-savings are applied. Consequently, a HISC test setup has been developed and initial testing of laser welded specimens is ongoing. The test setup takes into account the environment, cathodic protection (and consequences of over protection), mechanical loads and hydrogen uptake in the steel. The hydrogen uptake is measured by hydrogen sensors. This allows for a global frame of reference between all experiments. Redesign of the FORCE Technology hydrogen sensor for this purpose is currently ongoing. The test method and hydrogen sensor is relevant to a wide range of industries concerned with hydrogen cracking, such as offshore wind, oil & gas and maritime industries. Furthermore, a method for testing corrosion fatigue has been established with support from the project.

Extensive knowledge and experience on corrosion and environmental monitoring has been established during the project. This experience is to some extent based on surveys or systems provided to clients, also abroad. Today, FT can specify and supply tailored configurations for monitoring inside any monopile structure, irrespective of the corrosion protection that implies either airtight design or cathodic protection. The supplied systems are mainly built from commercial sensor types that are adapted to meet the special requirements in monopiles. The provided sensors include measurements of pH, corrosion potential, corrosion rate, temperature, conductivity and dissolved oxygen.

Coordinated and integrated with the activities above, a draft system for Integrity management of WTG foundations has been developed. In this context, offshore repair of protective paint coatings is an effort where substantial cost-savings may be obtained as demonstrated in the performed study on repair methods.

The work package has led to strong collaboration with DTU and feed the project PhD student with SAW and laser hybrid welded test pieces, who study the fatigue properties of welded joints. Also in respect of fatigue and corrosion aspects have supported DTU in alignment of tests setup etc.

This project has a significant interaction with FORCE Technology's business strategy, including LORC and LWT, and other overlapping project activities. The dissemination of activities and results have quite comprehensive through papers, articles, seminars, conferences and especially a group of relevant industry professionals, which main purpose are to evaluate FORCE Technology's technical actions as well as the relevance.

1.5.3 Work Package 3: Improved Design Basis for Welded Joints in Seawater (headed by DTU)

The work package was divided into three sections in order to achieve the abovementioned goals. Each section involves a series of fatigue tests where the validation of fatigue resistance is the main objective.

Test series 1, is the experimental investigation of the thickness effect, often termed size effect, for SAW welded joints. This section concerns challenging conservatism in the present guidelines and design solutions which were inherited from the oil and gas industry. The basis for this research is the state of the art literature investigation of fatigue resistance of SAW welded joints, which confirmed and demonstrated the trend of thickness effect for larger joints, but also indicated that the thickness correction might be too conservative. The debatable "conservative" thickness effect of welded joints has led to truly thick welded structures, and following the current trend they will only grow even larger in dimensions in the near future. This increases the already problematic process of manufacturing, transporting and installing the offshore wind turbine structures due to immense sizes. The thickness correction factor is applied in design codes for all welded joints above 25 mm thickness. The influence of thickness on the fatigue resistance of the welded joint is well established theoretically and experimentally, however if proven too conservative implies a great potential to reduce the cost of energy.

Test series 2, concerns validating the fatigue resistance of laser-hybrid welded butt joints and comparing the subsequent results with the conventional and reliable SAW welding method. SAW welding is currently accountable for more than 90% of tubular wind turbine welds. The laser-hybrid welding method is very beneficial when compared to the SAW welding, especially concerning cost optimization, automation, weld quality, weld consistency and energy efficiency. The laser-hybrid welding industry is rapidly moving forward, working its way towards truly thick sections, however there is a long way to go until the laser-hybrid method can weld steel sections ranging above 100 mm flawlessly and repetitively for the offshore wind turbine industry. However combining the possibility of reducing the recommended thicknesses for the structures in addition to introducing a new technology and more powerful lasers it could become a feasible and cost effective solution in the near future.

Test series 3, relates to in-situ fatigue testing of "larger" SAW welded joints in a corrosive environment in order to investigate the influence of corrosion fatigue on as-welded joints. Corrosion fatigue is another field of study with great dispute and controversy where the available experimental results are completely contradictive of one another. Most available articles concerning experimental corrosion fatigue have been conducted on small scale samples which have been post-weld treated to fit perfectly into a test setup, resulting in e.g. compressive residual stresses that have beneficial influences the results. Experimental testing is therefore lacking, and truly lacking for "larger" scale testing of submerged welded joints. An experimental setup has been constructed with a circulating seawater environment and a 500 kN loading capacity. The test facility allows control of temperature, circulation speed, pH level with open access to oxygen, making it very efficient for corrosion fatigue testing. Initial testing of SAW welded joints allowing free corrosion of the samples confirmed a reduction of fatigue life by a factor close to 3.

1.5.4 Work Package 4: Damping of Wind Turbine Tower Vibrations

The present work package investigates the possibility of introducing additional damping to the critical vibration modes of monopole supported offshore wind turbines by the application of supplemental damping and/or control systems. The common approach described in the literature involves a mechanical mass damper, placed at the top of the turbine tower, where the authority of the mass damper is largest. The theory behind the performance of mass dampers is fairly well described and the present project has therefore investigated alternative damper strategies.

When having dampers acting on the relative displacement of the turbine tower, the optimal location of the damper system is at the bottom of the tower near the transition to the monopole where the bending curvature is largest. It is found that the attainable damping associated with a single viscous damper system, acting directly on the deformation of the tower wall, is around 1% critical damping [1], and that the magnitude can more or less be increased proportionally with the number of damper systems. Thus, the attainable damping from the pure viscous damper systems meets the desired level for the offshore wind turbines. The challenge associated with this concept is the very small damper stroke that is available across the tower wall, and a toggle-braces amplification system is therefore proposed in [1], which increases the damper stroke by a factor 5 with the same damper performance.

The damper stroke can also be improved by introducing an active actuator in series with the passive viscous unit [2-4], where the motion of the actuator is controlled by an integral force feedback (IFF) procedure based on the measured damper force, which is easily determined although the corresponding damper stroke is insignificant. It is found that the desired attainable damping from the passive viscous damper is retained (1% critical), with a much larger stroke across the passive viscous damper, depending on the active control effort [2]. The IFF can also be suitably filtered so that the apparent damper phase moves ahead of the damper velocity, whereby improved damping performance is obtained [3]. It is found that this filtered IFF yields damping levels that are two to three times larger than for the pure viscous damper [3], and thereby more than meets the requirements for damping of large offshore wind turbines. The filtered IFF has been tested experimentally using the real-time hybrid testing facilities at Purdue University, Indiana, USA [4]. The results produced in collaboration with the group of Professor Shirley J. Dyke show that the filtered IFF can be realized in an operational setting, which is the basis for future implementation of the IFF concept in actual wind turbines. The active-passive damper format can be extended by placing a spring element in parallel with the viscous dashpot, whereby the IFF control must only create the inertia term to create a resonant damper concept, which is effective for damping of resonant vibration modes [5]. Resonant damping is also proposed in the form of an active tuned mass damper, where an active actuator is placed in parallel with the spring and dashpot of the classic mechanical tuned mass damper. The actuator is controlled by a simple feedback control loop, where the aim is to reduce the amount of damper mass needed to achieve the desired damping level [6].

As a conclusion the present work package proposes new and alternative passive/active damper concepts suitable for damping of offshore wind turbines, and it demonstrates that damping levels from one percent (passive viscous) to several percent critical damping (active-passive) can be obtained based on an integral force feedback control, which is suitable at damper locations at the bottom of the turbine tower, where damper strokes are otherwise insignificant.

1.6 Utilization of project results

Through the strategy plan and the involved industry partners the implementation of laser hybrid welding process in the heavy industry will be a long-term investment for FORCE Technology. Three qualified welding procedures has been matured, but the need for deeper penetration and lowered production cost is called for. The development work will indeed proceed in close collaboration with the relevant industry targeting variety of different designs foundations. Parallel to these actions, the classification companies will be involved.

Corrosion fatigue and HISC are both items of major concern for the offshore WTG business. Along with this, other issues have been identified and evaluated, such as cathodic protection in closed compartments. A systematic review of such corrosion-related topics has been performed with some coordination from international corrosion societies, EFC and NACE. The results will be presented at the NACE 2015 conference.

The commercial aspects of corrosion monitoring and integrity management are very promising at this point, and have and will translate into specific commercial assignments. The commercial angle of laser hybrid welding process will achieved a long-term impact in the producing industry. On the short-term basis it will generate more company based R&D.

Introduction of the weight savings due to the improved geotechnical analyses methods and the improved design of the welded connections have been initiated in the current practice.

1.7 Project conclusion and perspective

The papers produced in this project can be used to persuade the certifying agencies in adopting different damping model in soil as well as better S-N curve for welded steel monopile. This will drive the cost down on off-shore wind in accordance to the overall project goal.

Furthermore the laser-hybrid studies performed under this project will enable manufactures to utilize this efficient and cost-out production method in the future.

Lastly the corrosion studies performed under this project will enable offshore operators to have reliable data on structure lifetime – this is essential when extending the overall lifetime of the offshore turbines. The effect here is quite substantial.

Annex A – List of Project Publications (Articels/Papers/Presentations)

1. Damgaard M. An introduction to operational modal identification of offshore wind turbine structures, DCE Technical Memorandum, Aalborg University, 2011, 13.

2. Damgaard M., Ibsen L.B., Andersen L.V., Andersen J.K.F. Natural frequency and damping estimation of an offshore wind turbine structure. Proceedings of the Twenty-second International Offshore and Polar Engineering Conference. International Society of Offshore & Polar Engineers, 2012, 22:. 300-307.

3. Damgaard M., Ibsen L. B., Andersen L. V., Andersen J. K. F. Cross–wind modal properties of offshore wind turbines Identified by full scale testing. Journal of Wind Engineering and Industrial Aerodynamics 2013; 116: 94–108.

4. Damgaard M., Ibsen L. B., Andersen L. V., Andersen J. K. F , Andersen, P. Damping estimation of a prototype bucket foundation for offshore wind turbines identified by full scale testing. 5th International Operational Modal Analysis Conference 2013, May 13-15 Guimarães, Portugal, 2013.

5. Lisbeth Hilbert, Havvindmøller og korrosion. Præsentation ved Spuns & Rammedag, DSI, København 23 maj 2013

6. Lisbeth Hilbert, Corrosion control inside offshore wind farm monopile foundations, Præsentation ved Danish Wind Power Research, 27. Maj 2013, Fredericia

7. L. R. Hilbert, T. Mathiesen, A. R. Black, C. Christensen, Mud zone corrosion in offshore renewable energy structures, presentation and paper for EuroCorr 2013, 1.-5.September 2013, Estoril, Portugal

8. Lisbeth Hilbert, Draft overview of GAP analysis for submerged sections, Præstentation ved NACE TG 476 meeting, Estoril, 1.-5. September, 2013

9. Anders Rosborg Black, Monitoring and inspection for documentation and early warning– technical options focused on the inside of monopile foundations. Presentation at Offshore Wind Corrosion Protection, Esbjerg, Sept. 26th 2013

10. Troels Mathiesen, Cathodic Corrosion Protection of foundation structures - CP strategies, solutions and challenges. Presentation at Offshore Wind Corrosion Protection, Esbjerg, Sept. 26th 2013

11. Morgan Troedsson, Inspection, repair and maintenance, Presentation at Offshore Wind Corrosion Protection, Esbjerg, Sept. 26th 2013

12. Lisbeth Hilbert, Forebyggelse af korrosion - Korrosion indvendigt i monopæle. Præsentation ved Dansk Ståldag, Allerød 14 Nov. 2013

13. Anders Rosborg Black, Corrosion monitoring of offshore wind foundation structures, Poster and paper for EWEA Offshore, Frankfurt, 19-21 November 2013

14. Michel Honoré, Study of the welding characteristics of a 32 kW disc-laser system delivering up to 2x16 kW in a common melt pool, NOLAMP14 Conference, Göteborg, 26-28 August 2013

15. S. Ussing, K. H. Christensen, M.Honoré, Adaptive control of weld process in wind turbine tower manufacturing, JOM Conference, Helsingør, 5-8 May 2013

16. Michel Honoré, Future Production Methods for Offshore Foundations, Præsentation ved Danish Wind Power Research, Fredericia, 27-28 May 2013

17. Michel Honoré, Laser Safety for High-Power Industrial Lasers, Præsentation ved ATV-SEMAPP Dansk-Svensk Laserdag, Lindø, 29 October 2013

18. Michel Honoré, Laser/hybridsvejsning, Præsentation ved Grønne Offshore Netværksdag, Lindø, 3 December 2013.

19. Kim H. Christensen, Avanceret Automatisering, Præsentation ved Grønne Offshore Netværksdag, Lindø, 3 December 2013.

20. L. Rasmussen, K., Hansen, M., Kirk Wolf, T., Ibsen, L. B., & Roesen, H. R. (2013). A Literature Study on the Effects of Cyclic Lateral Loading of Monopiles in Cohesionless Soils. Aalborg: Aalborg University. Department of Civil Engineering. (DCE Technical Memorandum; No. 025).

21. Ibsen, L. B., Roesen, H. R., Wolf, T. K., Hansen, M., & Rasmussen, K. L. (2013). Assessment of p-y Curves from Numerical Methods for a non-Slender Monopile in Cohesionless Soil. In The Proceedings of the Twentythird (2013) International Offshore and Polar Engineering Conference. (pp. 436-443). International Society of Offshore & Polar Engineers. (International Offshore and Polar Engineering Conference. Proceedings).

22. Roesen, H. R., Thomassen, K., Ibsen, L. B., & Sørensen, S. P. H. (2011). Evaluation of Small-Scale Laterally Loaded Monopiles in Sand. In Symposium Proceedings. Toronto, Ontario: Pan-AM CGS Geotechnical Conference.

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27. Bayat, M., Andersen, L. V., Andersen, S., & Ibsen, L. B. (2013). Numerical Calculation of Damping for Monopile Foundations under Cyclic Load During Steady-State Vibration. In A. Zingoni (Ed.), Research and Applications in Structural Engineering, Mechanics and Computation. (pp. 2497-2502). London: C R C Press LLC.

28. Poulsen, R., Nielsen, B. N., & Ibsen, L. B. (2013). Correlation Between Cone Penetration Rate And Measured Cone Penetration Parameters In Silty Soils. In P. Delage, J.

Desrues, R. Frank, A. Puech, & F. Schlosser (Eds.), Challenges And Innovations In Geotechnics. Chapter 102.(pp. 603-606). Presses des Ponts.

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36. Laier-Brodersen, M., Design of stroke amplifying brace concepts for damping of wind turbine tower vibrations, Proceedings of the 9th PhD seminar on Wind Energy in Europe, Uppsala University, September 2013

37. Jan Høgsberg and Mark L Brodersen,Hybrid viscous damper with filtered integral force feedback control, Journal of Vibration and Control published online 4 August 2014

38. Mark L. Brodersen, Jan Høgsberg, Damping of offshore wind turbine tower vibrations by a stroke amplifying brace, EERA DeepWind'2014, 11th Deep Sea Offshore Wind R&D Conference

39. Mark L. Brodersen & Jan Høgsberg, Hybrid damper concept for damping of offshore wind turbine tower vibrations through damper stroke amplification

40. Mark L. Brodersen1, Ge Ou2, Shirley J. Dyke3, Experimental validation of hybrid damper concept using real time hybrid simulations

41. Jan Høgsberg, Mark L. Brodersen and Steen Krenk, Passive-active damper with resonant integral force feedback control

42. Mark L. Brodersen, Ann-Sofie Bjørke and Jan Høgsberg, Active Tuned Mass Damper for damping of offshore wind turbine vibrations

43. M.M. Pedersen, Ó.M. Ólafsson, Investigation of the thickness effect for butt welded joints, International Institute of Welding, IIW conference in Aalto, Finland, 2012.

44. Ó.M. Ólafsson, S. Thöns, A. Michel, M.F. Faber, H. Stang, C. Berggreen, J. Jönssen, Fatigue performance of offshore wind turbine structures in corrosive environments, in preparation, 2015.

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48. Barauskis, Gatis, Fl. Jacobsen, 2012: "Drivability of large diameter piles with Submerged Conical Section". Proceedings of ISOPE 2012, Rhodes, Greece

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