CODE COMPARISON OF A NREL-FAST MODEL OF THE LEVENMOUTH WIND TURBINE WITH THE GH BLADED COMMISSIONING RESULTS

Jordi Serret*
University of Edinbugh
Edinburgh, EH9 3BF, UK

Carlos Rodriguez
Offshore Renewable Energy Catapult
Blyth, NE24 1LZ, UK

Tahsin Tezdogan
University of Strathclyde
Glasgow, G4 0LZ, UK

Tim Stratford
University of Edinburgh
Edinburgh, EH9 3FG, UK

Philipp Thies
University of Exeter
Penryn, TR10 9FE, UK

ABSTRACT

This paper describes the process adopted to set up a FAST model to produce relevant design load cases (DLCs) for the Levenmouth (Samsung Heavy Industries - S7.0-171) demonstration foreshore wind turbine owned by the Offshore Renewable Energy Catapult (ORE Catapult). The paper does not take into account hydrodynamic forces.

Existing literature has carried out FAST studies predominantly using reference turbines (e.g. NREL-5MW, DTU-10MW) instead of real prototype or commercial turbines. This paper presents the results for the Levenmouth wind turbine, a real, operating demonstration wind turbine. The paper explores and simulates the critical loads for the turbine, which will be very valuable validation case for industrial and academic use. Moreover, the Levenmouth wind turbine exhibits a new generation of extremely flexible blades that conflict with the previous approaches used by most common aero-elastic codes and makes this simulation a challenge.

The study is divided into three steps. It starts with building the model and fine-tuning it until it matches the natural frequencies of the blades and tower. The second step encompasses the comparison of the commissioning results with the relevant NREL FAST simulations to match the dynamic behaviour of the turbine. The final step comprises a load comparison for the interface between the tower and transition piece, in order to validate the new aero-elastic model with the commissioning loads.

The results of the study show 98% agreement in the natural frequencies and dynamic performance, and a 78% agreement in the loads between the aero-servo-elastic model and the certification results.

The present study is framed into an engineering doctorate project and a more comprehensive turbine virtualisation project. We anticipate that our work to be the initial point for more sophisticated aero-elastic models adapted to the unique properties of the Levenmouth demonstration wind turbine.

1 INTRODUCTION

The ORE Catapult's 7MW foreshore wind turbine is a demonstration wind turbine dedicated to research. It enables testing, verification and validation of future technologies that will help to improve reliability and performance for the next generation of offshore wind turbines. ORE Catapult is working on a project to virtualise their Levenmouth wind turbine. The project's objective is to create a digital 'Clone of the Levenmouth Wind Turbine' (CLOWT) following the recommendations of the IEC 61400-1 and 61400-3 standards. It involves setting up and validating aero-hydro-servo-elastic numerical models for enhanced use of the monitoring instrumentation.

The overall aim is to advance the industry's understanding of how large megawatt turbines behave and to identify cost reduction opportunities through design optimisation [1]. The present work is the starting point of this more comprehensive turbine virtualisation project. The paper aims to set up the

*Corresponding author. Email: J.Serret@ed.ac.uk or J.Serret@fwtltd.co.uk

starting point for the CLOWT project by building an open-source aero-elastic model of the Levenmouth wind turbine and calculating the Levenmouth wind turbine interface loads. The controller set up is out of the scope of this study and will be developed in future studies. The Levenmouth wind turbine loads will be the initial point for the subsequent development of a new floating wind concept.

The analysis conducted with NREL FAST v8.16.00a-bjj is verified with the turbine technical specifications and the available Original Equipment Manufacturer (OEM) physical testing. The analysis is also compared to the commissioning results.

The definition of commissioning covers all activities after all components of the wind turbine are installed. Hence, it comprises all the testing leading to the operational stage. It is the most reliable information on the operation of the wind turbine, besides Supervisory Control And Data Acquisition (SCADA) data. GH Bladed, the industry aero-elastic standard modelling tool, was used during the commissioning of the Levenmouth turbine.

It should be noted that a considerable part of the data presented in this paper is either normalised or given without magnitudes to protect proprietary information.

2 SIMULATION TOOLS

There are several theories and models capable of capturing the aero-hydro-servo-elastic behaviour of an offshore wind turbine. The numerical implementation can be carried out by advanced codes using i) finite element modelling (FEM), ii) multibody system dynamics (MBS) or iii) an assumed modes approach. As stated before, NREL FAST was chosen in this study, to carry out the simulations as it is a very common and well-documented open access code in the scientific community. Some other alternative codes utilised for simulating offshore wind turbines are ANSYS Workbench, Technical University of Denmark (DTU) HAWC2, and GH Bladed (DNV-GL) to name a few.

2.1 The NREL FAST simulation tool

NREL FAST [2] is a glue code that uses the results of several pre-processors (e.g. BModes, IECWind, TurbSim and ModeShapePolyFitting), and combines them within several simulations (e.g., ElastoDyn, BeamDyn, InflowWind, AeroDyn, ServoDyn, and SubDyn).

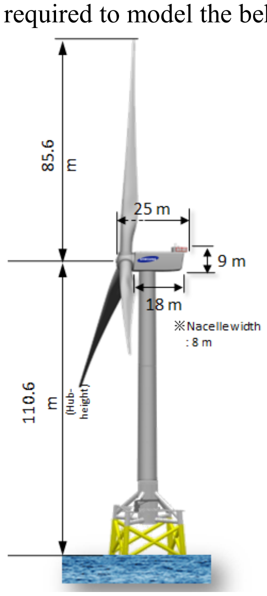
The pre-processors are tools helping to create aero-elastic models. They produce relevant information needed to feed the simulation tools. BModes is a finite-element code that provides coupled modes for a turbine blade or a tower [3]. IECWind is a utility program used to create wind files that model the extreme conditions outlined in IEC 61400-1 and IEC 61400-3 for AeroDyn-based programs [4]. TurbSim is a stochastic, full-field, turbulent-wind simulator using a statistical model to generate time series of three-component wind speed for AeroDyn-based codes such as NREL FAST [5]. Finally, ModeShapePolyFitting is a spreadsheet capable of producing polynomial coefficients for mode shapes given BModes results.

NREL FAST couples results from different simulations. ElastoDyn is a dynamic structural model able to model the rotor, drivetrain, nacelle, tower, and platform. It computes displacement, velocities, accelerations and reactions from the acting loads taking into account the controller and the substructure reactions. In this study, ElastoDyn is used to model the blades until the BeamDyn simulator is implemented. BeamDyn is an improved time-domain structural-dynamics module to analyse beams that are made of composite materials, initially curved and twisted, and subject to large displacement and rotation deformations [6]. InflowWind is a module for processing wind-inflow data coming from IECWind or TurbSim pre-processors. AeroDyn is a time-domain module that computes aerodynamic loads of horizontal axis wind turbines [7]. ServoDyn is a control and electrical drive model for blade pitch, generator torque, nacelle yaw, high-speed shaft brake and blade tip brake [8]. HydroDyn deals with the hydrodynamic loading. However, if FAST-OrcaFlex Interface is used, all hydrodynamic and mooring loads will be computed using OrcaFlex [9]. SubDyn is a structural dynamics module for simulating multi-member substructures [10].

The workflow to set up a NREL FAST model consists of the generation of several input files, section properties files (for tower, blades and airfoils), airfoil coordinate records and a controller.

3 MODEL DESCRIPTION

The main properties of the Levenmouth turbine are given in Fig.1. The rest of the parameters needed to create the model are confidential. Therefore, they are not provided in this paper. It is worth highlighting that a detailed geometry and the complete distribution of properties along the blades and the tower are required to model the behaviour of the wind turbine adequately.



Wind Class	IEC Class 1A
Rotor diameter	171.2 m
Capacity	7 MW
Hub height	110.6 m
Blade length	83.5 m
Generator	Medium (3.3kV), PMG
Converter	Full power conversion
Drivetrain	400 rpm
Rated frequency	50 Hz
Rotor speed	5.9 – 10.6 rpm
Wind speed	3.5 – 25 ms^{-1}
Rated wind speed	10.9 ms^{-1}
Design life	25 years
Certification	DNV
Control System • Independent and collective pitch control modes • Active drive train damping • Active load control • Blade load monitoring	

FIGURE 1 LEVENMOUTH TURBINE LAYOUT [11].

4 SIMULATION

The system model includes three blades, hub, drivetrain, gearbox, generator, nacelle, tower and a jacket substructure. The model accounts for the flexibility of the blades, drivetrain, tower and jacket substructure. Meanwhile, the hub, gearbox, generator, and nacelle are assumed to be rigid bodies. Therefore, the distributed mechanical and aerodynamic attributes of the blades and tower must be input in NREL FAST along with the mechanical features and mass properties of the drivetrain, gearbox, hub, generator, nacelle and substructure. Additionally, several parameters regarding the operation of the pitch and yaw systems, drivetrain and generator must be introduced into NREL FAST. This is done by adjusting an open source DLL controller from the DTU to match the Levenmouth turbine characteristics.

4.1 Wind/aerodynamics

InflowWind manages IECWind and TurbSim wind files to be used by NREL FAST. IECWind and TurbSim simulate non-turbulent and turbulent wind files depending on the design load case (DLC) to be simulated. IECWind and TurbSim meet the conditions outlined in IEC 61400-1 and IEC 61400-3 standards. The DLCs considered in this study are listed in Table 1.

TABLE 1 DLCs CONSIDERED IN THIS STUDY.

	DLC	Wind Condition	Wind Speed	Grid loss
Power production	1.1a	NTM	V_{rated}-2	No
	1.1b	NTM	V_{rated}	No
	1.1c	NTM	V_{rated}+2	No
	1.3a	ETM	V_{rated}-2	No
	1.3b	ETM	V_{rated}	No
	1.3c	ETM	V_{rated}+2	No
PP + Fault	2.2a	NTM	V_{rated}-2	Yes
	2.2b	NTM	V_{rated}	Yes
	2.2c	NTM	V_{rated}+2	Yes
	2.3a	EOG	V_{rated}-2	Yes
	2.3b	EOG	V_{rated}	Yes
	2.3c	EOG	V_{rated}+2	Yes
Normal shut down	4.2a	EOG	V_{rated}-2	Yes
	4.2b	EOG	V_{rated}	Yes
	4.2c	EOG	V_{rated}+2	Yes
Parked	6.1	EWM	$V_{10min,50\text{-}yr}$	Yes
	6.2			Yes

More explanations regarding the different DLCs will be provided in the later sections. The most sensitive parameters to set up in TurbSim are the ones related to the wind grid. Table 2 shows the selected parameters for the present study. Further explanation of the wind condition, faults and grid loss conditions can be found in the IEC 61400-1 [12] and IEC 61400-3 [13] standards.

AeroDyn v15.03.00 is the aerodynamics simulator used in NREL FAST. The aerodynamics is the most significant model uncertainty, and it is based on the Blade Element Momentum (BEM) theory. The AeroDyn module requires information regarding the aerofoils, the aerodynamic properties of the blades and the aerodynamic influence of the tower. The aerofoils must be defined in terms of aerodynamic constants and coordinates of the aerofoil shape.

TABLE 2 GRID PARAMETERS USED IN TURBSIM TO GENERATE THE TURBULENT WIND FILES.

NumGrid_Z	41
NumGrid_Y	41
GridHeight [m]	181
GridWidth [m]	181

4.2 Blades/tower

The BModes pre-processor is used to calculate the rotating blade frequencies and the flap (fore-aft) and lag (side-to-side) blades (and tower) mode shapes. The calculated mode shapes are fitted into the ElastoDyn structural simulator by using a sixth order polynomial. The ModeShapePolyFitting spreadsheet fits BModes mode shapes given deflection data along a flexible non-cantilevered beam.

ModeShapePolyFitting offers three different methods to calculate the polynomial. The Projection method has been chosen among the Direct and the Improved Direct methods because a broader range of factors can be specified (i.e. slope and deflection at the bottom of the beam, and a y-scaling factor) to perform the calculation. BModes provides the slope and deflection at the bottom of the beam, and the suggested y-scaling factors were used so that the ratio of the deflection to the beam length corresponds to the exact ratio for a deflected beam [14].

4.3 Controller

ServoDyn deals with the control of the machine. The Levenmouth NREL FAST model employs an open source Bladed-style Dynamic-Link Library (DLL) controller provided by DTU.

The DTU controller benefits from a useful input file allowing the adequate configuration of the controller [15]. Most of the data used in the controller input files are subject to confidentiality.

4.4 Substructure

The jacket substructure has been defined as a multimember structure from the bottom of the transition piece to the top of the pin piles. Therefore, joint positions, members' connectivity, and physical properties of the members must be introduced in SubDyn. The thickness and physical properties of the cylindrical members which make up the substructure are confidential information and are not disclosed in this study.

4.5 Known model differences

Although an attempt was made to replicate the conditions used in the commissioning model accurately, there are significant differences regarding both the aero-elastic code and the simulation itself:

- The structural analysis method used in GH Bladed is a combined modal and FEM approach whereas NREL FAST uses a combined modal and MBS formulation.
- Aero-elastic theories used by NREL FAST and GH Bladed are different. Therefore, differences are expected between the codes' outputs, e.g. FAST calculates aerodynamic forces orthogonal to the deflected blade, whereas GH Bladed calculates aerodynamic forces orthogonal to the undeflected blade regardless of deflection [16].
- Differing model aerodynamic loads discretisation's lead to differences among the code predictions [16].
- Due to IP issues, the controller used in the NREL FAST model is not the one used by the commissioning model.
- The substructure modelled is slightly different to the one used for commissioning, i.e. it is 150 tons lighter; in order to match the one installed in Levenmouth.
- The coordinate axes are different in both aero-elastic codes. The X direction in NREL FAST corresponds to Y in GH Bladed, the Y to Z, and the Z to X.

5 RESULTS

The blade and tower mode shapes calculated by BModes pre-processor are shown in Fig.2.

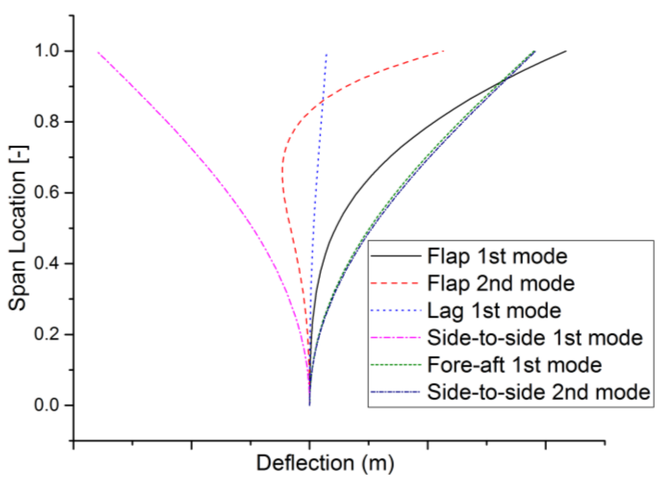


FIGURE 2 BLADE AND TOWER MODE SHAPES.

The coupled eigenfrequencies of the tower and substructure subsystems as calculated by BModes pre-processor are shown in Table 3.

TABLE 3 COUPLED TOWER AND SUBSTRUCTURE EIGENFREQUENCIES FOR THE LEVENMOUTH TURBINE.

Mode number	Tower (Hz)	Substructure (Hz)
1st	0.3675	0.7896
2nd	0.3918	0.7896
3rd	1.6466	0.8166

5.1 DLC1.1b

To check the dynamic behaviour, a regular power production DLC1.1 has been chosen. DLC1.1 presents the dynamic behaviour during power production using a Normal Turbulence Model (NTM) and active turbine control. Fig.3 shows the three components of the speed, the pitch angle and the rotor speed. This DLC has been chosen because it shows the genuine behaviour of the pitch control, increasing pitch angle when the wind speed is higher and reducing it when the wind moderates.

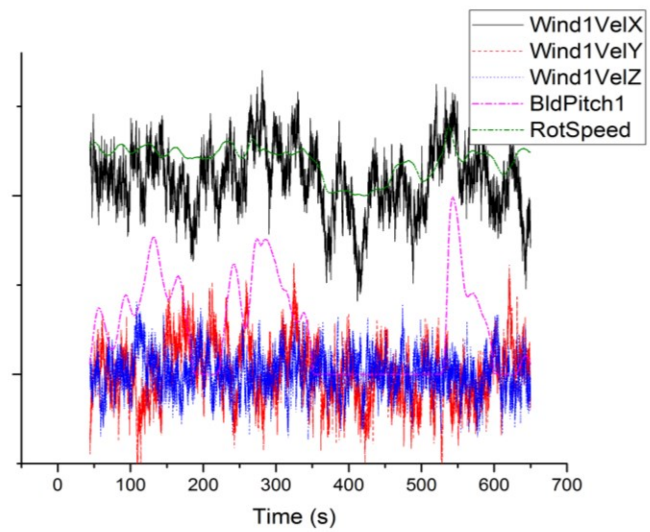


FIGURE 3 DLC1.1b WIND SPEED, BLADE PITCH, AND ROTOR SPEED.

As expected the rotor speed (Fig.4) is strongly linked to the wind speed as well as the generator speed, the generator torque (black axis) and the generated power (blue axis). Fig.5 shows forces and Fig.6 presents the moments for the DLC1.1b. The tower base force in the X direction (TwrBsFxt) shown in Fig.5 is the primary effect of the wind over the structure, and in the Y direction (TwrBsFyt) is residual because the wind speed in the X direction (Wind1VelX) is larger than in Y direction (Wind1VelY). The tower base force in the Z direction (TwrBsFzt) is the larger in magnitude because it is strongly influenced by the mass of the system. Tower base moments (Fig.6) exhibit the same behaviour shown in Fig.5, although here the larger magnitude corresponds to the Y direction

(TwrBsMyt) since this is the moment related to tower base force in the X direction.

TABLE 4 LOAD-MATRIX FOR THE LEVENMOUTH WIND TURBINE

		DLC	SF	Mx (kNm)	My (kNm)	Mz (kNm)	Fx (kN)	Fy (kN)	Fz (kN)
Mx	Max	DLC6.2	1.10	**42625**	15345	-226	653	-543	-8689
Mx	Min	DLC6.2	1.10	**-40689**	34122	-3832	985	518	-8701
My	Max	DLC2.2c	1.10	23573	**149050**	1166	1745	-275	-9050
My	Min	DLC2.3b	1.10	10315	**-248270**	-8159	-2522	-103	-9022
Mz	Max	DLC1.3b	1.35	14540	79582	**19062**	1033	59	-11155
Mz	Min	DLC1.3b	1.35	10500	77125	**-19346**	1018	-153	-11069
Fx	Max	DLC1.3c	1.35	-5107	177795	11883	**2430**	191	-11356
Fx	Min	DLC2.3b	1.10	10315	-248270	-8159	**-2522**	-103	-9022
Fy	Max	DLC6.2	1.10	-40678	34738	-4039	996	**527**	-8686
Fy	Min	DLC6.2	1.10	42625	15345	-226	653	**-543**	-8689
Fz	Max	DLC6.2	1.10	-599	33319	-619	852	20	**-8514**
Fz	Min	DLC1.3c	1.35	341	146610	3237	1898	135	**-11421**

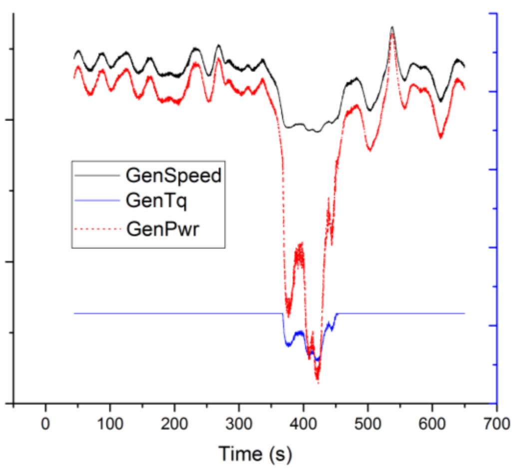


FIGURE 4 DLC1.1b GENERATOR SPEED AND TORQUE, AND GENERATED POWER.

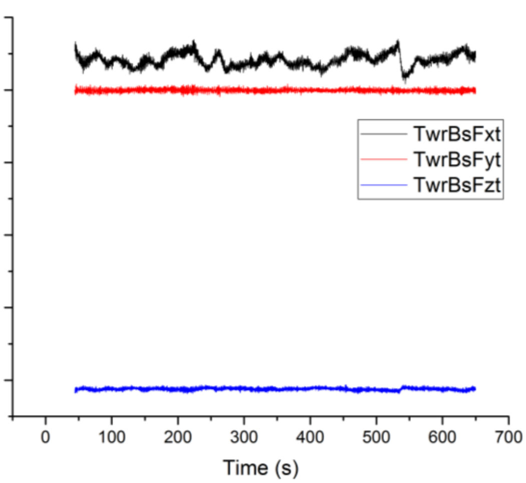


FIGURE 5 DLC1.1b TOWER BASE FORCES.

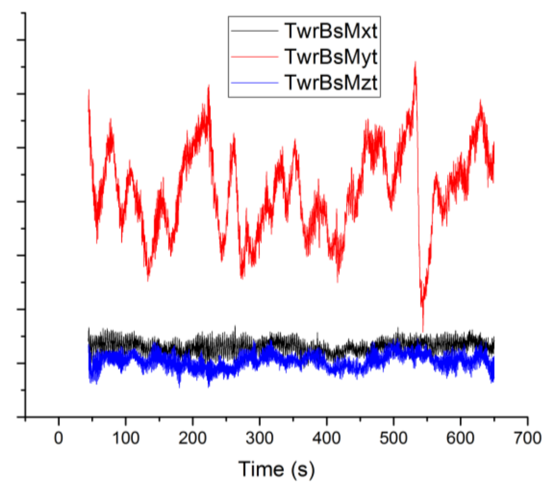


FIGURE 6 DLC1.1b TOWER BASE MOMENTS.

5.2 Summary

Table 4 shows the ultimate limit state load-matrix summarising the maximum forces and moments from all the simulations listed in Table 1. The elements on the diagonal of the matrix represent the worse situation possible regarding loading, even though the actual combination of loads never occur in a single simulation. Each of the elements on the diagonal is maximum or minimum coming from a simulation based on one of the DLCs shown in Table 1, e.g. 42,625 kN is the maximum moment in the X direction, and it occurs under DLC6.2. It is important to note that the values shown in Table 6 are already factorised using the suggested Safety Factor (SF) in [12] and [13]. The values accompanying a maximum or a minimum in the same row are the contemporary load results coming from the same simulation, e.g. 15,345 kN is the moment in the Y direction contemporary to the simulation DLC6.2 that has produced the maximum located in the diagonal.

On the other hand, the values accompanying a maximum or a minimum in the same column are moments or forces in the same direction but coming from different simulations, e.g. 23,573kN is a moment in the X direction, but it comes from DLC2.2c.

6 VERIFICATION

The NREL FAST code has been verified in the IEA Wind tasks 23 [17] and 30 [18], but case-by-case verification is needed here. Table 5 shows a comparison between the GH Bladed reference values and the eigenfrequencies resulting from BModes to model the mode shape of the blades. The first and second calculated flapwise modes of the blades agree with the referenced values to within 2.1% and 1.7% respectively. The first and second calculated edgewise modes were off by 1.4% and 1.1% respectively. The modes were not tuned.

TABLE 5 NORMALISED BLADE EIGENFREQUENCIES COMPARISON.

	NREL FAST	GH Bladed Reference
First Flapwise	0.979	1
Second Flapwise	0.983	1
First Edgewise	0.986	1
Second Edgewise	0.989	1

Since NREL FAST and GH Bladed use a different methodology to calculate tower eigenfrequencies, no further comparison regarding them is presented in this study.

Table 6 shows a comparison of the mass and dimensional properties calculated by NREL FAST versus the turbine technical specifications.

TABLE 6 COMPARISON OF THE CALCULATED AND REFERENCE NORMALISED MASS AND DIMENSIONAL PROPERTIES.

	NREL FAST Calculated	GH Bladed Reference
Hub-Height	1.004	1
Flexible Tower Length	0.916	1
Flexible Blade Length	0.997	1
Rotor Mass	0.985	1
Rotor Inertia	1.037	1
Blade Mass	0.973	1
Blade First Mass Moment	1.040	1
Blade Second Mass Moment	1.038	1
Blade Centre of Mass	1.034	1
Tower-top Mass	0.994	1
Tower Mass	1.009	1

The calculated values have shown an acceptable agreement with the commissioning results. The most substantial deviation is found in the calculated flexible tower length which is off by 8.4%. This disagreement is due to a different definition of the transition piece in both codes.

7 COMPARISON

7.1 Steady-state behaviour

A comparison of the steady-state behaviour has been performed by running several simulations with different constant wind speeds ranging from 3 to 25 m/s.

Fig.7 shows the power curve and the thrust force. The power curve is in good agreement until rated speed, but from there to cut-off speed NREL FAST underestimates the electrical power by 10% when compared with GH Bladed results. NREL FAST thrust force forecast is slightly overestimated on region 2, getting better in region 2½, and underestimating a bit on region 3.

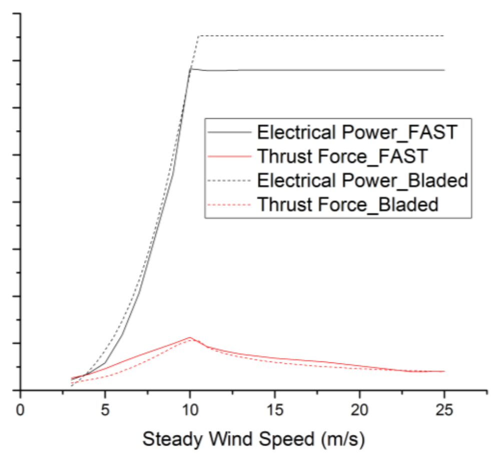


FIGURE 7 STEADY-STATE COMPARISON, GENERATED POWER AND THRUST FORCE.

Fig.8 shows the pitch angle and the rotor speed steady-state behaviour.

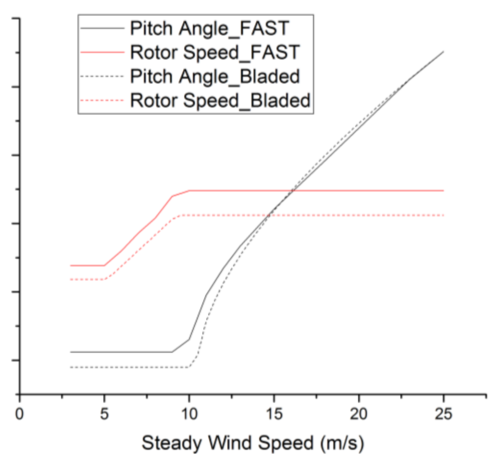


FIGURE 8 STEADY-STATE COMPARISON, PITCH ANGLE AND ROTOR SPEED.

The pitch angle curve fits well when compared with GH Bladed results. It starts a bit off until region 2½. Once rated speed has been reached, the results begin to be closer to the commissioning ones. Rotor speed results are overestimated by NREL FAST. The discrepancy increases as soon as the rated speed is reached, i.e. after region 2½.

Fig.9 shows the power coefficient versus the tip speed ratio comparison. NREL FAST and GH Bladed match this curve satisfactorily, although the discrepancy is more substantial at the beginning of region 3.

This behaviour changing between the regions indicates that the inaccurate tuning of the filters of the controller is the primary cause of the discrepancies.

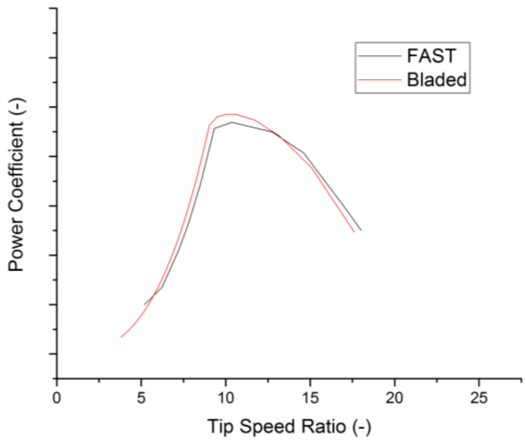


FIGURE 9 STEADY-STATE COMPARISON, POWER COEFFICIENT VS TIP SPEED RATIO.

7.2 Dynamic behaviour

In order to compare the dynamic behaviour, Table 9 presents the statistical differences between the NREL FAST results and the GH Bladed commissioning results combining all results of the DLCs 1.1, 2.3, and 6.2 shown in Table 1. The forces are transferred to the NREL FAST coordinate system for comparison.

TABLE 9 DIFFERENCES BETWEEN THE RESULTS.

	Mean	SD	Min	Max
Wind1VelX (ms^{-1})	1.67	4.58	10.67	4.32
BldPitch1 (˚)	13.60	6.66	0.76	2.80
RotSpeed (rpm)	10.20	63.88	7.90	21.30
GenSpeed (rpm)	10.20	63.88	7.89	21.43
TwrBsFxt (kN)	15.78	30.88	56.16	28.27
TwrBsFyt (kN)	38.91	18.75	45.21	21.76
TwrBsFzt (kN)	15.88	26.78	15.74	16.51
TwrBsMxt (kNm)	24.54	21.55	43.63	22.35
TwrBsMyt (kNm)	7.82	44.35	60.54	45.92
TwrBsMzt (kNm)	49.70	23.57	62.25	70.52
GenPwr (MW)	9.37	12.12	28.86	5.75
GenTq (kNm)	18.44	38.62	35.86	27.35

The Levenmouth model shows a good agreement with the commissioning results. Discrepancies in forces and moments are due to the different definitions of the transition piece and the substructure. As already mentioned, the controller used in the NREL FAST simulation is not the same as that used by the commissioning simulation. Therefore, the differences observed within the controller features i.e. pitch angle, rotor speed, generator speed, generator torque, and generated electrical power; were expected.

The behaviour of the pitch angle and rotor speed for DLC1.1b shows acceptable conformity (Fig.10) having into account that these results belong to the region 2½, where maximum discrepancies were found (Fig.8) with the commissioning results.

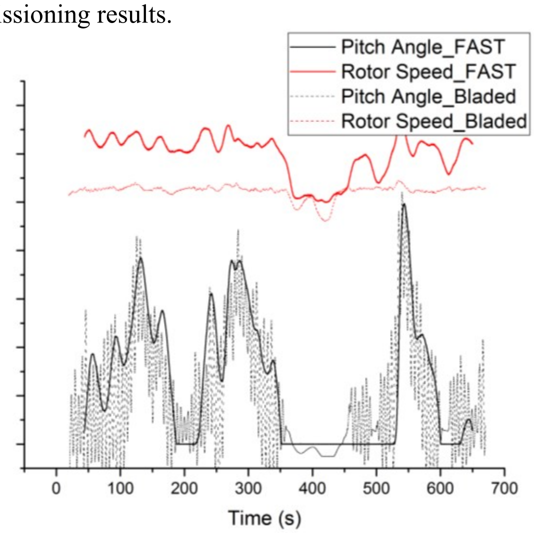


FIGURE 10 DLC1.1b CONTROLLER COMPARISON, PITCH ANGLE AND ROTOR SPEED.

The NREL-FAST model overestimates the rotor speed as well as the generator speed whereas underestimating generator torque and the power produced. Since the nominal values for rotor and generator speeds were correctly tuned, the differences must lie on the controller.

A comprehensive look at the pitch angle results shows that they follow the same general trend than commissioning results. The envelope of the blade pitch angle fits well with the commissioning results, but the inherent differences regarding the controller low-pass filters and gains, lead to significant statistical differences. Pitch mean values are slightly off due to the higher frequency of the commissioning results.

7.3 Summary

Fig.11 shows a comparison between the overall results of the NREL FAST simulation against the commissioning results. The discrepancies are within the expected ranges, and the more substantial differences are related to DLC6.2.

Those differences must be analysed within the framework established by Fig.12 which shows the discrepancies between the GH Bladed commissioning results in comparison to the GH Bladed Prototype analysis. This is based on the Levenmouth Class 1A conditions, i.e. a general Samsung S7.0-171 7MW wind turbine located in a given, but unknown, offshore site with wind conditions assimilated to IEC wind class IA, in comparison to the Samsung S7.0-171 7MW erected in Levenmouth, with its specific wind and sea state conditions.

Since this information is strictly confidential, a colour and pattern code has been used for the comparison. Green with vertical pattern means differences up to 10%; yellow with horizontal pattern means differences between 10% and 30%, and red with crossed pattern means differences higher than 30%.

		DLCs	Mx	My	Mz	Fx	Fy	Fz
Mx	Max	DLC6.2						
Mx	Min	DLC6.2						
My	Max	DLC2.2c						
My	Min	DLC2.3b						
Mz	Max	DLC1.3b						
Mz	Min	DLC1.3b						
Fx	Max	DLC1.3c						
Fx	Min	DLC2.3b						
Fy	Max	DLC6.2						
Fy	Min	DLC6.2						
Fz	Max	DLC6.2						
Fz	Min	DLC1.3c						

FIGURE 11 LOAD COMPARISON: NREL FAST VS GH BLADED

		DLCs	Mx	My	Mz	Fx	Fy	Fz
Mx	Max	DLC6.2						
Mx	Min	DLC6.2						
My	Max	DLC2.2c						
My	Min	DLC2.3b						
Mz	Max	DLC1.3b						
Mz	Min	DLC1.3b						
Fx	Max	DLC1.3c						
Fx	Min	DLC2.3b						
Fy	Max	DLC6.2						
Fy	Min	DLC6.2						
Fz	Max	DLC6.2						
Fz	Min	DLC1.3c						

FIGURE 12 LOAD COMPARISON: GH BLADED VS GH BLADED PROTOTYPE LEVENMOUTH CLASS 1A CONDITIONS

The differences observed between the NREL FAST and the GH Bladed commissioning load-matrixes are also related to the number of simulations executed. The commissioning results are based on approximately 3,000 simulations whereas the NREL FAST results are based on 90 simulations for the whole set of DLCs. Each simulation uses wind speeds created from different random seeds to produce variability. Indeed, increasing the number of simulations/seeds will produce peak loads reducing the differences between both load-matrices. GH Bladed commissioning load-matrix matches better with GH Bladed Prototype Levenmouth Class 1A conditions load-matrix because they both are based on thousands of simulations.

8 DISCUSSION AND CONCLUSION

Accurate numerical models able to simulate the coupled dynamic response of realistic multi-MW turbines are needed.

The NREL FAST model developed during this study is stable and demonstrates reliable results. Hence, this model is an appropriate first step towards the virtualisation of the Levenmouth wind turbine.

There is a concern regarding the tower base force in the Y direction and tower base moment in the X direction since the NREL FAST simulated values are very low compared to the commissioning results. The discrepancies between NREL FAST and GH Bladed results are related with the different approach used by the codes to calculate the loads, the different controllers used during the simulations, and differences regarding the definition of the systems, e.g. transition piece, substructure.

Because both codes show significant differences, these should be compared to SCADA data coming from the turbine to validate them.

Since the Levenmouth wind turbine has very flexible blades and NREL FAST ignores axial, and torsion Degrees of Freedom (DoFs), the use of BModes helps to overcome these limitations partially by implicitly accounting for these constraints [3].

Open-source coupled models like NREL FAST provide superior flexibility compared with commercial software, allowing the users to modify the code as appropriate. Since NREL FAST has been widely validated in the IEA Wind tasks 23 and 30 [16, 17], that makes it a suitable tool to virtualise wind turbines.

Offshore wind in deeper water will be an increasing source of renewable energy over the next few years and has some of the lowest global warming potentials per unit of electrical power generated. As the industry is moving further offshore, floating wind turbines will become the only possible solution. Therefore, understanding the behaviour of the Levenmouth wind turbine is the first step to design a floating substructure. From this perspective, the results obtained by the NREL FAST simulation are a suitable approximation for a subsequent structural and hydrodynamic design of the floating substructure.

9 RECOMMENDATIONS

To improve the NREL FAST simulation of the Levenmouth wind turbine, the following future enhancements have been identified:

- The implementation of the simulator BeamDyn instead of ElastoDyn has the potential to improve the accuracy of the results. BeamDyn uses a nonlinear geometrically exact beam spectral FE blade theory which improves the structural dynamics results compared to ElastoDyn when used to model beams made of composite materials, initially curved and twisted, and subject to large displacement and rotation deformations such as this of the Levenmouth turbine blades.

- A deeper understanding of the controller operation is needed to develop more accurate filters leading to more accurate and precise simulations. The development of a re-tuned 64-bit controller will help to provide more stability to the simulations until the IP issues that prevent the use of the original controller are resolved.
- The addition of a hydrodynamic model will make the simulation more useful since it will allow forecasting the coupled behaviour of the system with different offshore substructures.

ACKNOWLEDGMENTS

1. This work is funded in part by Floating Wind Turbines Limited (FWT Ltd), and the Energy Technologies Institute (ETI); Research Councils UK (RCUK); Energy Programme for the Industrial Doctorate Centre for Offshore Renewable Energy (IDCORE) [grant number EP/J500847/1].
2. This work is based on the data kindly provided by Offshore Renewable Energy (ORE) Catapult.
3. The content of this document is solely the responsibility of the authors and does not necessarily represent the official views of the IDCORE, FTW Ltd and ORE Catapult.

REFERENCES

[1] ORE Catapult. (2017). Catapult gives CLOWT to its Levenmouth turbine - Catapult. [online] Available at: https://ore.catapult.org.uk/press-release/catapult-gives-clowt-levenmouth-turbine/ [Accessed 14 Nov. 2017].

[2] Jonkman, J. and Buhl, M. (2005). FAST user's guide. 1st ed. Golden, Colo.: National Renewable Energy Laboratory.

[3] Bir, G. (2005). User's guide to BModes (software for computing rotating beam coupled modes). 1st ed. Golden, CO: National Renewable Energy Laboratory.

[4] NWTC Information Portal (IECWind). https://nwtc.nrel.gov/IECWind. Last modified 28-September-2014; Accessed 10-March-2017.

[5] Jonkman, B. and Buhl, M. (2006). TurbSim user's guide. 1st ed. Golden, CO: National Renewable Energy Laboratory.

[6] Wang, Q., Jonkman, J., Sprage, M. and Jonkman, B. (2016). BeamDyn. 1st ed. Golden, CO: National Renewable Energy Laboratory.

[7] Jonkman, J., Hayman, G., Jonkman, B. and Damiani, R. (2015). AeroDyn v15 User's Guide and Theory Manual. 1st ed. Golden, CO: National Renewable Energy Laboratory.

[8] Jonkman, J. (2013). Overview of the ServoDyn Control & Electrical-Drive Module.

[9] NWTC Information Portal (FAST-OrcaFlex Interface). https://nwtc.nrel.gov/OrcaFlexInterface. Last modified 25-July-2016; Accessed 10-March-2017

[10] NWTC Information Portal (SubDyn). https://nwtc.nrel.gov/SubDyn. Last modified 12-April-2016; Accessed 10-March-2017

[11] Offshore Renewable Energy Catapult, (2016). Levenmouth 7MW demonstration offshore wind turbine. [online] Fife, Scotland, UK: ORE Catapult. Available at: https://ore.catapult.org.uk/wp-content/uploads/2016/04/Levenmouth-7MW-demonstration-offshore-wind-turbine.pdf [Accessed 10 Mar. 2017].

[12] Wind turbines - Design requirements (2005). IEC 61400-1 1st ed. Geneva: International Electrotechnical Commission.

[13] Wind turbines - Design requirements for offshore wind turbines (2009). IEC 61400-3 1st ed. Geneva: International Electrotechnical Commission.

[14] Bush, E. (2008). ModeShapePolyFitting.

[15] Dtuwindenergy.github.io. (2015). Source Documentation — Basic DTU Wind Energy Controller. [online] Available at: http://dtuwindenergy.github.io/BasicDTUController/srcdocs.html#f/turbine_controller_mod/turbine_controller [Accessed 20 Mar. 2017].

[16] Jonkman, J. and Musial, W. (2010). Offshore Code Comparison Collaboration (OC3) for IEA Task 23 Offshore Wind Technology and Deployment. [online] Golden, Colorado. Available at: https://www.nrel.gov/docs/fy11osti/48191.pdf [Accessed 5 Feb. 2018].

[17] Vorpahl, F., Strobel, M., Jonkman, J., Larsen, T., Passon, P. and Nichols, J. (2013). Verification of aero-elastic offshore wind turbine design codes under IEA Wind Task XXIII. Wind Energy, 17(4), pp.519-547.

[18] Robertson, A., Jonkman, JM., Vorpahl, F., Popko, W., Qvist, J., Frøyd, L., Chen, X., Azcona, J., Uzunoglu, E., Guedes Soares, C., Luan, C., Yutong, H., Pengcheng, F., Yde, A., Larsen, T.J., Nichols, J., Buils, R., Lei, L., Nygaard, T.A., Manolas, D., Heege, A., Ringdalen Vatne, S., Duarte, T., Godreau, C., Hansen, H.F., Nielsen, A.W., Riber, H., Le Cunff, C., Beyer, F., Yamaguchi, A., Jung, K.J., Shin, H., Shi, W., Park, H. & Alves, M. (2014), Offshore code comparison collaboration continuation within IEA Wind Task 30: Phase II results regarding a floating semisubmersible wind system. in Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. vol. 9B, OMAE2014-24040, American Society of Mechanical Engineers.ss