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Preliminary validation of ATOM: an aero-servo-elastic design tool for next generation wind turbines

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Abstract. Upscaling wind turbines has resulted in levelised cost of energy (LCoE) reductions. However, larger turbine diameters pose significant design challenges, often with conflicting requirements. For example, non-linear dynamics of aeroelastic tailored blades must be accurately predicted whilst, for the sake of efficient gradient-based design, it is also desirable to simplify the numerical definition of such blades—keeping design variables (DVs) to a minimum. This work presents and validates two features of the ATOM code (**A**eroelastic **T**urbine **O**ptimisation **M**ethods), developed at the University of Bristol, that enable accurate and efficient modelling of large-scale wind turbine blades. Both an efficient parameterisation method and high-order beam elements illustrate the capacity for increasing the speed of gradient evaluations whilst accurately predicting blade dynamics—either by reducing DVs or simulation time. As a preliminary validation, aero-servo-elastic simulations from ATOM and an industry-standard software—DNV GL Bladed—are compared against field measurements gathered from an existing 7 MW turbine.

1. Introduction

Wind energy offers an economically competitive source of renewable energy, with the average levelised cost of energy (LCoE) for onshore wind being 60 USD/MWh [1]—this being at the lower end of the spectrum for fossil fuels. Further decreases in cost of energy are desirable as they will encourage further investment in wind power generation, decreasing global reliance on fossil fuel and aiding governments in reaching climate change targets.

Upscaling wind turbines has been a reliable means to reduce the LCoE, and turbine sizes are, consequently, predicted to grow further (20 MW+) [2]. It is, therefore, imperative that industry can effectively design such machines and accurately predict their feasibility—whether from an economic, structural, or operational perspective. A key research field that is gaining much interest for wind turbine design is that of multi-disciplinary optimisation (MDO) and, in particular, gradient-based methods [2, 3, 4]. Wind turbines have a large design space with many, and often conflicting, design choices to be made. MDO techniques allow these design spaces to be algorithmically searched, minimising the cost-function (usually LCoE) with novel solutions that may not always be obvious to human designers during an iterative process.

The success of MDO in finding novel design solutions relies heavily on accurate analysis modules. Modelling aero-servo-elastic phenomenon for next-gen wind turbines becomes more challenging for a number of reasons:

- Longer, more slender blades are often more compliant, therefore, non-linear structural models are required to accurately predict large deflections, strains and other metrics required to assess structural feasibility.
- Blades with aeroelastic tailoring [5, 6] require accurate prediction of torsional dynamics as the aerodynamic loads are very sensitive to small variations in sectional angles of attack [7]. Torsional dynamics also require accurate prediction of cross-sectional properties.
- Large deflections, prebend, sweep, cone tilt and other re-orientation of blade sections require that the aerodynamic models are able to dynamically resolve wind and loading vectors in three-dimensions. Higher-order aerodynamic models such as lifting line/free-vortex wake or computational fluid dynamics offer this capability, however, are currently still too costly from a computational point of view for MDO.

MDO tools must also be computationally efficient to ensure that convergence is achievable within practical time and hardware limitations. Wind turbine standards [8] require a vast number of randomly seeded turbulent simulations to ensure statistical likelihood of capturing the full load envelope/spectrum experienced by wind turbines over their lifetime. Whilst this set of standardised load cases can be condensed for design purposes, performing a single gradient evaluation of a wind turbine design remains, to date, computationally demanding. Given these computational demands, MDOs can be made more efficient in two ways, either by reducing the time required to evaluate the fitness of a given design solution, or reducing the number of fitness evaluations. Literature offers many ways in which speed of fitness evaluations can be improved for wind turbine MDO—for example, fast and reliable BEM convergence methods [9], higher-order beam modelling to maintain accuracy of stiffness variations with fewer beam nodes [10], or reducing the number of simulations required for load evaluation [11]. Alternatively, the number of fitness evaluations can be reduced by using fewer design variables (DVs), or by using a more efficient (or better-suited) optimisation algorithm. For gradient-based algorithms, the number of fitness evaluations for one gradient evaluation through finite difference is proportional to the number of DVs. Therefore, by clever parameterisation of the turbine definition into a concise set of numerical DVs, the number of DVs can be kept to a minimum without sacrificing model accuracy or causing excessive bias in the final solution. A biased, and possibly sub-optimal, solution may be found if the parameterisation scheme favoured certain types of solutions over others that may have equal, or even better, fitness.

Given the conflicting requirements for computational efficiency and model accuracy during optimisation, this work presents a software tool developed to tackle these issues. The ATOM code (**A**eroelastic **T**urbine **O**ptimisation **M**ethods), part of ongoing development at the University of Bristol [7], is a multi-disciplinary optimisation and analysis (MDAO) tool capable of performing design studies for the next generation of wind turbines. This work presents two features of ATOM that specifically target the aforementioned issues: efficient blade parameterisation, and high-order beam modelling. The blade parameterisation highlights the potential for reducing the number of DVs whilst accurately representing blade dynamics, whereas high-order beam modelling allows more efficient structural modelling, thus, reducing simulation times. To illustrate the applicability of these methods for modern wind turbines, they are employed in a preliminary validation study of ATOM, using an existing 7 MW turbine. Simulations are run using empirical wind data taken from met-mast and anemometer recordings, field measurements from the turbine are then compared against results from ATOM and an industry standard aeroelastic software, DNV GL Bladed [12].

Section 2 begins by introducing ATOM, and the 7 MW baseline turbine used in this work.

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Section 3 presents the efficient blade parameterisation, followed by high-order beam modelling in Section 4. Lastly, results from the preliminary validation are displayed in Section 5.

2. Modelling details

This section begins by giving details of the modelling capabilities within ATOM that are relevant to this work. Next, a brief introduction of the baseline 7 MW turbine is given.

*2.1. ATOM (**A**eroelastic **T**urbine **O**ptimisation **M**ethods)*

ATOM is an analysis and optimisation tool specifically aimed at the optimisation of aeroelastic tailored, horizontal-axis wind turbines—whereby turbine topology remains fixed during the optimisation. From an analysis point of view, a set of numerical DVs that define each aspect of a turbine can be input by the user, ATOM then performs every step from meshing of the blade and tower beams, right through to running a full set of aero-servo-elastic design load cases (DLC) and post-processing results for statistics on power, loads, cross-sectional strains and failure indices. This analysis capability is smoothly integrated within an optimisation framework with a choice of algorithms. ATOM also interfaces with the DNV GL Bladed API so as to allow equivalent Bladed models to be created from an ATOM model and then validation simulations to be performed.

A key feature of ATOM's design capabilities is the use of spline surfaces and lamination parameters [7]. These features allow completely free, un-biased design of a wind turbine rotor, with the goal of realising the full potential of composite laminates for aeroelastic tailored structures. During optimisation, DVs control a number of spline surfaces that define variations in lamination parameters and laminate thickness across the blade. This framework allows for the optimisation process to be unconstrained by conventional structural configurations and stacking sequences.

ATOM utilises a range of analysis modules, in which full detail will be given in a future publication. However, a brief summary is given here:

- The aerodynamic model utilises a modified blade element momentum (BEM) theory with corrections for dynamic wake and dynamic stall. A key feature is the 3D resolution of wind vectors, aerofoil section vectors and loading vectors to ensure that geometric deviations such as deflections, sweep, prebend, cone and tilt are all accounted for. A similar 3D formulation of BEM can be found in work by Ponta *et al.* [13].
- The structural models of the blade and tower utilise beam finite-elements (FE), with linear damping. The beam elements allow for anisotropic composite laminates with fully populated stiffness and mass matrices. A cross-sectional modeller uses 2D bar elements to generate properties from the laminate spline surfaces. ATOM allows for high-order beam modelling whereby three, four or five node beam elements can be used [10]. Application of these high-order beam elements is presented in Section 4. ATOM also allows solving for displacements of the beam models using modal decomposition, or the non-linear co-rotational framework. Lastly, beam strains can be used to extract cross-sectional laminate strains and failure indices, which can then be aggregated using Poon *et al.*'s adaptive method [14].
- The non-linear aero-servo-elastic model combines aerodynamic and structural models with a simple controller and multiple options for time-varying wind fields. The controller is embedded into the code and employs PI pitch control above rated and a simple optimal mode gain to control torque below rated. At any time step, the solver iterates through each aero-servo-elastic analysis module using a combination of explicit first- (Euler) and second-order (Heun) schemes.

Parameter	**Value**
Wind class	I_A/S_B
Rotor diameter	171.2m
Hub height	110.6m
Blade length	83.5m
Capacity	7MW
Generator	Medium (3.3kV) PMG
Convertor	Full power conversion
Drivetrain	400 rpm
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

Table 1. Levenmouth 7 MW turbine parameters [15].

2.2. The Levenmouth 7 MW turbine

To illustrate the efficacy of this work for modelling of modern turbines i.e. large, multi-megawatt, offshore turbines with aeroelastic tailored blades, the baseline model used in this work is derived from an existing 7 MW turbine. Further, the turbine offers a starting point for future gradient-based optimisation studies that is known to be commercially-endorsed technology and thus can make the outcomes of those studies more relevant for industry applications.

The wind turbine is located off the coast of Levenmouth, Scotland, it was built by Samsung Heavy Industries and is now owned and managed by ORE Catapult for research purposes. The turbine is instrumented with a basic supervisory control and data acquisition (SCADA) system and a nearby met-mast offers meteorological data. Details of the turbine are given in Table 1 [15].

3. Structural blade parameterisation

This section presents the structural blade parameterisation method available in the ATOM code and applies it to the Levenmouth 7 MW turbine. Given this blade, the potential for minimising the number of DVs whilst accurately representing global blade dynamics is highlighted.

Large blades that have undergone detailed design phases (i.e. the Levenmouth 7 MW) have a considerable amount of information describing the geometric and structural layout. There are usually a number of spline curves that describe external geometric properties such as chord, twist, thickness, sweep and prebend, in addition to the many sets of aerofoil coordinates. Internally, the blade structure is composed of composite laminates that may include glass/carbon fibres, foam/balsa, gelcoat, lightning protection, paint and resins such as epoxy. Glass/carbon fibre layers are often used in the form of thick uni-directional (UD), biaxial or tri-axial mats. There are laminate schedules for each structural component (i.e. spar cap, web) describing the layer order, material, orientation, and spanwise start/termination locations of each ply. Then there is also definition of the component locations (i.e. distance from leading-edge (LE) to web) that often vary along the blade span. In addition to these main structural components, the detailed design may also include smaller hand lay-up patches or interfacing layers, however, these are of less importance to a MDO which, in general, is more concerned with the preliminary design phase.

Given the vast structural description generated by a detailed design phase, it is not feasible, or necessary, that all of this be accounted for during MDO. Therefore, the blade parameterisation should represent enough structural detail so as to accurately capture global blade dynamics (i.e.

stiffness/mass variations), as well as in-plane strains. Accurate global blade dynamics allow the analysis modules and optimiser to consider realistic aero-elastic effects, and in-plane strains allow for a preliminary assessment of ultimate and fatigue failure criteria.

The blade parameterisation capability in ATOM is fully detailed by Macquart *et al.* [7], however, it will be briefly described here for the sake of completeness. ATOM allows for the blade to be split into a number of regions (or components) i.e. spar cap, trailing edge reinforcement, webs etc. The location of these regions is defined by a set of key-points (KPs) that vary along the blade span and are normalised as a percentage of chord length. Each region is comprised of a number of material layers. Some layers may span a number of regions (i.e. glass TRIAX in skin) and some may be present only in a single region (i.e. UD carbon in spar). Each material layer has a set of material properties, in addition to a set of spline surfaces that define the variations in lamination parameters and laminate thickness. Additionally, there is an option to independently specify suction and pressure sides of the aerofoil, or to apply a symmetry constraint.

The 7 MW turbine blade is parameterised according to ATOM's framework. The blade structural description can be categorised into a number of conventional structural regions (see Table 2). There are a small number of laminates that don't fit exactly into a single region, such as web flanges, however, these layers can easily be absorbed into nearby regions, such as the spar cap, without significant deviation from the description. As well as region definitions, Table 2 describes the material layers present in each region and whether or not they are to be considered as DVs for optimisation. The choice for including a layer as a DV is dictated by whether the modelling fidelity allows the optimiser to effectively observe the primary purpose of that layer. For example, the optimiser will observe a relatively strong sensitivity to tip deflection constraint with respect to the thickness of a UD layer in the spar cap, thus a DV is used. However, the BIAX in the spar cap, whilst it has some contribution to global properties, is primarily used to avoid crack propagation when too many plies of the same orientation are stacked together. The structural fidelity of the model is not able to predict such phenomenon, therefore, such layers are not DVs.

After splitting of the structure into regions and material layers, thickness distributions of the layers (spline surfaces) need to be specified. An initial heuristic method was used to ensure that all material thickness distributions were matched perfectly with the minimal number of control points (CPs) along the span. This heuristic method resulted in 24 CPs. As evidence of this close match in thickness distributions, the damped modal frequencies (assumed 0.5% linear damping) of the resulting beam model match to within 2% of experimentally derived modes (see Table 3), other than the torsional mode. The blade modal testing was conducted with a hammer excitation, and strain gauge data was collected and processed using a fast Fourier transform. Therefore, the procedure was not particularly appropriate for accurately measuring a torsional mode, for which LE and TE accelerometers would be required for accurate measurement of torsional dynamics. In addition, the torsional dynamics are relatively coupled to the flapwise and edgewise dynamics of this blade, thus further complicating the successful isolation of modes. Hence, the authors deem it appropriate to discount the experimentally-derived torsional frequency. It is noted that mode shapes or damping ratios were not experimentally determined.

The potential problem with this distribution of 24 CPs is that there would be an unnecessarily large number of DVs if the design were to be used in an optimisation study. Given the 11 regions selected to be DVs, and 24 CPs, there could be up to $(24 \times 11 \times 2 =)$ 528 DVs if top and bottom skins were allowed to vary asymmetrically. As already discussed, it is desirable to reduce the number of DVs so as to reduce the computational effort of gradient evaluations. In this work, the number of DVs are reduced by removing CPs and simplifying the laminate thickness distributions. Therefore, this study aims to determine how many CPs can be removed whilst still providing a good match to the experimentally derived modal frequencies.

In order to provide a number of reduced CP distributions, a cosine spacing is used to

Table 2. Material layers present in each blade region.

Region name	**Layer name**	**Material**	**DV**
All regions	Skin TRIAX	Glass	**Yes**
	Gelcoat/paint	-	No
	Root UD	Glass	**Yes**
	Root BIAX	Carbon	**Yes**
	Root connection	Steel	No
LE reinforcement	LE UD	Glass	**Yes**
	LE TRIAX	Glass	No
	Adhesive	-	No
LE shell	LE core	PVC	**Yes**
Spar cap	Spar cap UD	Glass	**Yes**
	Spar cap UD	Carbon	**Yes**
	Spar cap BIAX	Carbon	No
TE shell	TE core	PVC	**Yes**
TE reinforcement	TE UD	Glass	**Yes**
	TE TRIAX	Glass	No
	Adhesive	-	No
Webs	Web BIAX	Glass	**Yes**
	Web core	PVC	**Yes**

Table 3. Percentage differences in modal frequencies and mass between experimental values and blade model with full laminate detail. Absolute values are omitted due to an NDA. 'F' = Flapwise, 'E' = Edgewise, 'T' = Torsional.

Percentage difference in metric (%)							
Mass	**F1**	**E1**	**F2**	**E2**	**F3**	**E3**	**T1**
0.11	0.53	0.41	1.86	0.33	1.66	0.63	12.39

automatically generate sets of points. The original detailed laminate thickness distributions are then interpolated over these reduced meshes. The cosine spacing results in closer spacing toward the root and tip which, at least for this particular blade, is appropriate for some of the more structurally-dominant laminates (i.e. spar cap) as they exhibit more thickness variations in these regions. It is noted that other spacings (i.e. linear spacing) may be more appropriate for other blades, and each spacing will offer its own bias on the optimised designs. However, the cosine spacing is deemed appropriate for the purpose of this example and similar results could be obtained with other similar spacings.

Results from this study are displayed in Table 4, containing percentage differences between the ATOM blade model and experimentally derived metrics, for differing numbers of CPs. The key result from this is that the number of control points, and thus the match of laminate thickness distributions, can be significantly reduced without compromising the accuracy of global blade dynamics. The mass and modal frequencies only start to deviate significantly from the experimental for 12 and fewer CPs. This result highlights that, for the purpose of wind turbine MDO, the number of DVs can be significantly reduced compared to that required for a full detailed structural representation of a blade. This reduction in information specifying the blade laminates does not diminish the global blade dynamics which are crucial for observing aero-

Table 4. Percentage differences between model and experimental modal and mass metrics.

		No of control points (CPs)										
		6	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**24***
Percentage difference in comparison metric (%)	**Mass**	2.3	5.6	8.2	0.3	1.2	1.6	1.2	0.3	1.4	0.4	0.1
	F1	23.9	4.6	3.9	1.9	1.3	0.1	0.4	0.1	0.2	0.3	0.5
	E1	16.2	6.9	11.4	3.2	1.3	1.0	0.6	0.4	1.7	1.6	0.4
	F2	17.7	4.8	1.0	0.2	0.9	0.8	2.1	0.3	0.9	1.5	1.9
	E2	12.1	3.1	2.6	1.0	0.3	1.8	0.3	1.1	0.9	0.2	0.3
	F3	15.5	0.6	0.3	0.5	0.6	0.2	0.7	0.2	0.9	1.6	1.7
	E3	5.0	2.8	2.8	0.8	0.5	1.7	0.4	1.8	0.9	0.3	0.6
	T1	26.3	16.2	26.3	14.1	13.9	14.0	13.3	13.5	14.9	13.8	12.4

elastic phenomenon, blade displacements, and cross-sectional strains.

4. High-order beam modelling

This section presents the benefits of high-order beam elements, available in the ATOM code, for the efficient and accurate structural modelling of modern wind turbine blades. Again, the 7 MW turbine is used as an example to highlight the efficacy of such elements.

High-order beam elements refer to formulations of the conventional FE beam element with three, four or five nodes per element, compared to the conventional two node element [10]. Such elements allow for variations in structural properties along the element length, and thus a converged beam mesh can be achieved with fewer nodes than with conventional elements.

ATOM's beam mesh, and thus cross-section distribution, is independent of the CP mesh. Therefore, varying beam meshes can be chosen by the user and the material properties described in the spline surfaces are interpolated over the beam mesh. Given this functionality, a mesh convergence study is performed to highlight the effects of the higher-order elements. Specifically, the number of beam elements (and thus nodes) is varied, using two- and three-node elements, and certain structural metrics are compared. Two example convergence diagrams of flapwise tip displacement and the 2nd flapwise modal frequency are given in Figure 1. It can be seen that for both metrics, the three-node beam converges with far fewer nodes than the conventional two-node beam.

The comparison metrics in this convergence study are modal characteristics and deflections under a representative flapwise ultimate load case. It is noted that convergence here is not assessed against experimentally derived values, but against the asymptotically convergent values obtained numerically. The modal assurance criterion (MAC) [16] is used for comparing mode shapes, in addition to a comparison of modal frequencies. Deflection comparisons are given for both the linear (fixed linear stiffness matrix) and co-rotational non-linear (changing stiffness with geometry) beam models. The results are condensed into a table format, whereby the number of nodes for convergence is given for each metric. Here, convergence is defined as being within 1% of the final converged value. The results for convergence of modal characteristics are displayed in Table 5, where it is noted that a large number of nodes are required to model this blade due to the complexity of the internal structure. It can be seen that almost all mode shapes and mode frequencies require the same or fewer nodes for convergence when using three-node beam elements. The only exception to this is the second torsional mode shape for which the difference in number of nodes is near-negligible. Another result to note is that the mode shapes, in particular the edgewise and torsional, do not benefit as much from the higher-order elements

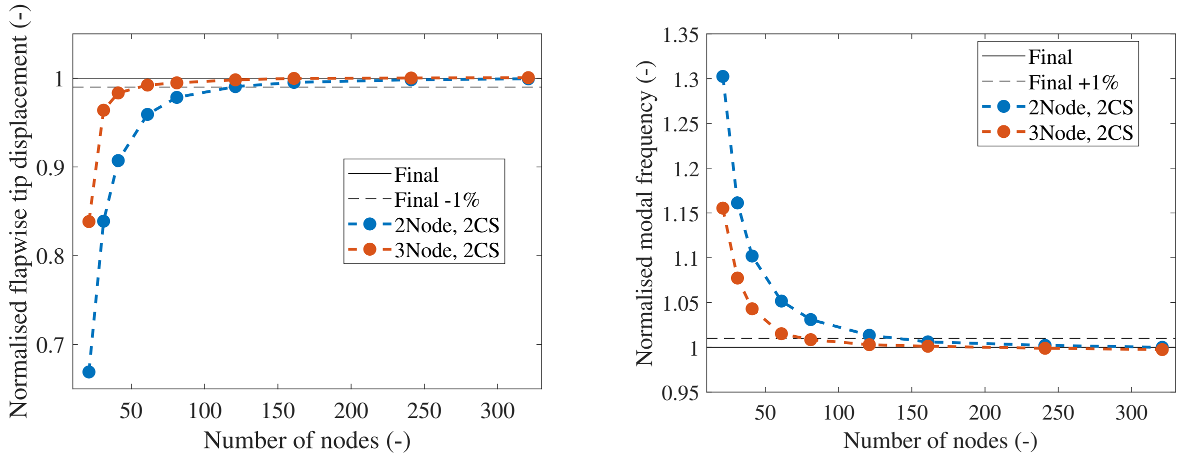

Figure 1. Convergence of blade flapwise tip deflection and 2nd flapwise modal frequency, for two and three-node elements. Values are normalised due to a NDA.

Table 5. The number of nodes required for convergence of mode shapes and modal frequencies.

Mode Type	**No of nodes for convergence 2-node**	**3-node**
F1	21	21
E1	21	21
F2	51	41
E2	41	31
F3	81	51
F4	111	61
E3	81	81
T1	31	31
E4	81	81
T2	41	51

Mode shapes (MAC)

Mode Type	**No of nodes for convergence 2-node**	**3-node**
F1	81	61
E1	71	61
F2	141	91
E2	121	71
F3	171	111
F4	181	101
E3	141	81
T1	71	61
E4	141	91
T2	221	81

Modal frequencies

as do the modal frequencies. This discrepancy further points toward high-order elements being particularly beneficial for dynamic, as opposed to steady, aero-elastic simulations.

Tip displacement results are displayed in Table 6. It can be seen that three-node elements aid convergence of displacements consistently for the non-linear beam model. However, the torsional predictions from the linear beam model do not benefit from the high-order elements—indicating that the variations in structural properties relevant to overall torsional response are represented well enough by conventional elements for this blade, and at low numbers of nodes may be misrepresented by higher-order elements.

5. Preliminary aero-servo-elastic validation

This forms the first in a series of validation exercises using the ATOM code—highlighting its applicability as a tool for optimisation and design purposes (Section 2.2). This validation exercise focuses on aero-servo-elastic simulation of the 7 MW turbine. Results from ATOM, DNV GL Bladed [12], and recorded field data are compared so as to provide code-to-code validation as

Table 6. The number of nodes required for convergence of blade tip displacements.

	Linear beam		**Non-linear beam**	
Displacement	**2 node**	**3 node**	**2 node**	**3 node**
Flapwise	121	61	121	51
Edgewise	81	61	81	61
Axial	131	61	211	101
Torsional	31	81	91	71

well as experimental validation.

Dynamic simulations are run with turbulent wind fields, generated by TurbSim [17]. Empirical met-mast wind data and temporally-matched SCADA data were recorded from the 7 MW turbine between April and September 2017 and have been made available for this validation study by ORE Catapult. Thousands of data samples were recorded, however, 84 samples have been used for this work as they show minimal yaw misalignment ($< 1°$) and minimal error between wind measurements from the nacelle and met mast ($< 5\%$). The blade model in ATOM has material spline surfaces specified at 14 control points along the span, and the beam model uses 50 3-node elements (101 nodes). Whilst the bladed model uses 80 element as a compromise between accurate beam modelling and computational efficiency, being that high-order beam elements are unavailable. Both modal and non-linear (ATOM: co-rotational framework, Bladed: multi-part beam) structural analysis modules are employed in both codes for comparison. Bladed uses a compiled dynamic link library (dll) controller designed for the turbine, however, there is a discrepancy in that the real turbine exhibits a speed exclusion zone below rated whilst the Bladed controller does not. Being that ATOM is unable to interface with Bladed-style dll controllers, a simplified version of the real controller is implemented whereby the gains are an exact match, however, the switching strategy around rated is a simplification. Both mechanical and electrical loss tables are included in ATOM and Bladed.

Validation results for key aero-servo-elastic parameters are displayed in Figure 2. It can be seen that both codes slightly over-predict power and generator torque in below-rated operation, and in a similar vein, pitch angles are also over-predicted by the codes when above-rated. This points toward the modelled rotors having a higher power coefficient than the real version in both above and below rated regimes. A possible source of this uncertainty could come from the idealised aerodynamic polars used by the BEM module, as opposed to reality where the blades may suffer from geometric defects due to manufacturing or degradation, and the aerodynamic polars may vary significantly due to 3D effects not captured by the low fidelity models. Another source may be uncertainty in the wind inputs, as only limited information was available from the met mast for generating wind field inputs.

One operational feature that is unfortunately omitted in the aero-servo-elastic simulations is a speed exclusion zone below-rated. This can be seen in the flat section of rotor speeds for the SCADA data, where a range of rotor speeds are not operated in, likely for vibrational reasons. This is another possible source of the more aerodynamically efficient operation modelled by the codes in the below-rated region.

As a preliminary validation of load predictions, flapwise and edgewise bending moments are displayed in Figure 3. Due to uncertainties in the load signals coming from the turbine, only code-to-code validation is currently available, however, reasonably good agreement can be seen.

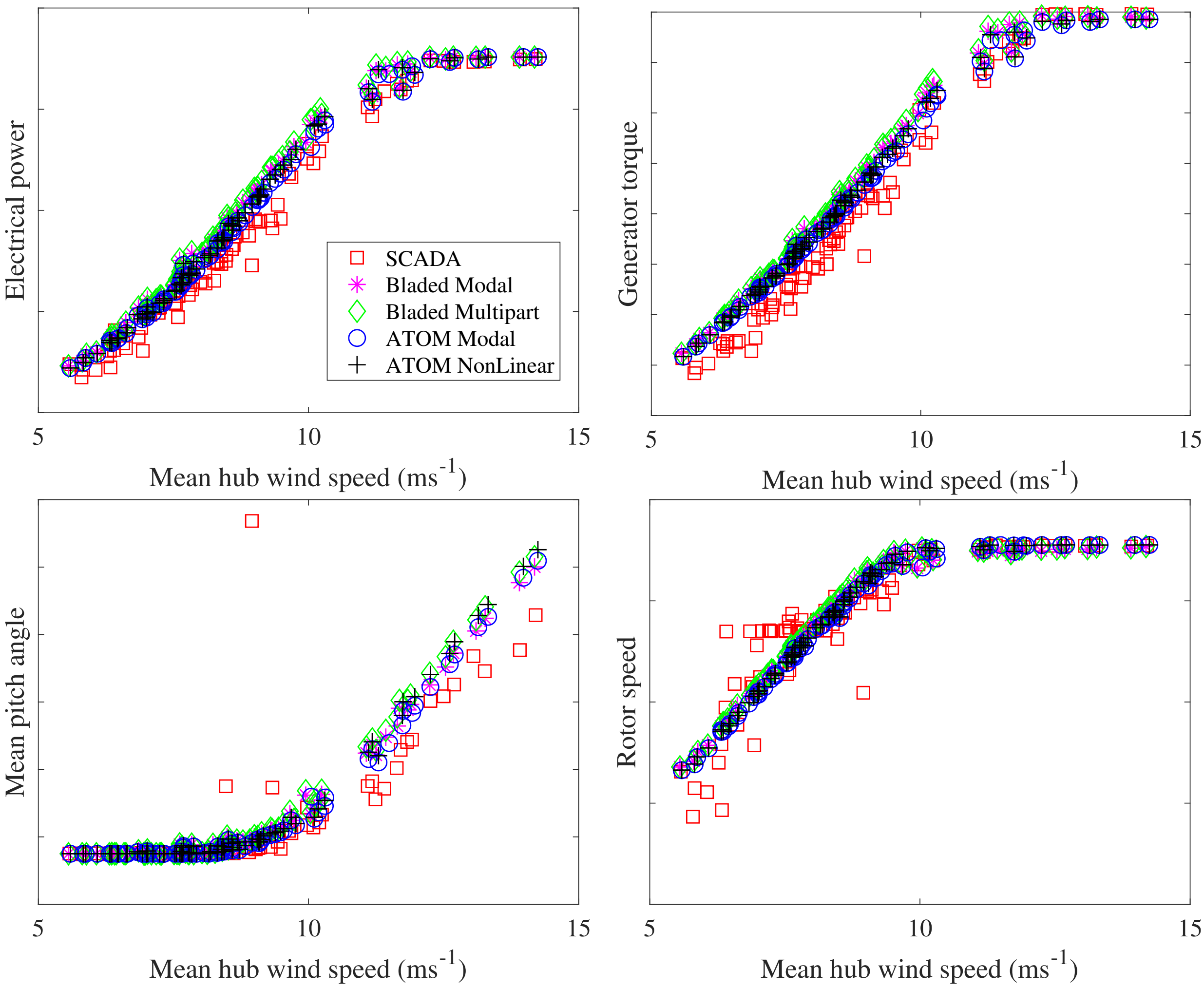

Figure 2. 10-minute averages of electrical power, generator torque, mean pitch angle and rotor speed.

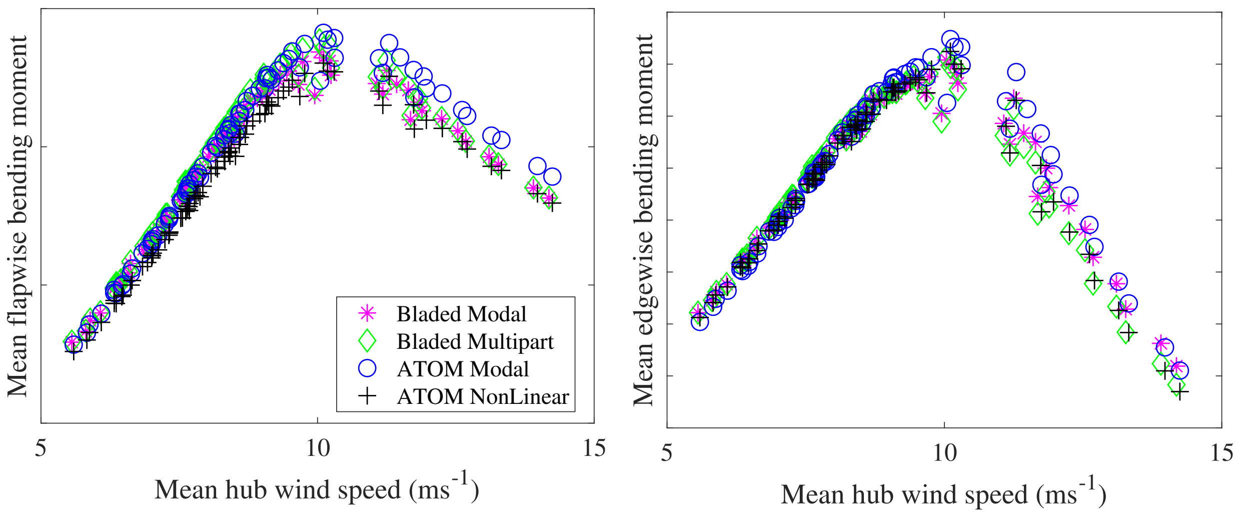

Figure 3. 10-minute averages of flapwise and edgewise blade root bending moments.

6. Conclusions

This work presents and validates two features of the ATOM code for accurate and efficient design and modelling of next-generation wind turbines. An existing 7 MW turbine is used as a baseline model for modelling and aero-servo-elastic validation. The following conclusions are drawn:

- Considering the vast structural detail in a real turbine blade, it would require many DVs to accurately represent the laminate thickness distributions. Given the desire for minimising the number of DVs for MDO, Section 3 highlights the potential for approximating true thickness distributions with fewer DVs. It is shown that the number of DVs can be reduced without any loss in accurate representation of blade dynamics—modal frequencies are within 2% of those experimentally derived.
- The ATOM code allows the use of high-order beam elements [10], with three-, four- or five-node elements. Section 4 highlights the efficacy of these elements for structural modelling of the 7 MW turbine. A mesh convergence displays that the high-order beam model converges in modal frequencies, shapes, and tip displacements with far fewer nodes than conventional two-node elements.
- The ATOM code, using aforementioned blade model with reduced DVs and high-order elements, is validated for its aero-servo-elastic capabilities. A set of 10-minute simulations are run using ATOM, and DNV GL Bladed, and results are compared against field measurements. Both codes show good agreement in power, generator torque, pitch angle and rotor speed predictions, whilst both slightly over predict power and torque below-rated, and over predict pitch above-rated. Root bending moments from ATOM and Bladed agree well, however, experimental load measurements are unavailable.

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