

Tool development based on FAST for performing design optimization of offshore wind turbines: FASTLognoter

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ABSTRACT

The new engineering FASTLognoter software is presented. This code is essentially the result of the integration of two tools, along with some additional features. The first basis tool is FAST (developed by NREL), a comprehensive aeroelastic simulator code for wind turbines. The second basis tool is Lognoter (developed by *CompassIS*), a general-purpose commercial software for managing and creating engineering forms. The integration of FAST and Lognoter gives a useful, comprehensive and versatile toolkit, which is verified in this work by means of bibliographic documented cases. An important advantage of the tool presented is the parametric design capability, allowing the user of *FAST/AeroDyn/HydroDyn* codes to analyze a massive group of cases; therefore, optimal design can be carried out.

1. Introduction

Recently, several governments, including USA, Norway, France and United Kingdom among others, have undertaken ambitious offshore wind projects. Different review works can be found on this topic (Breton and Moe [1], Wang et al. [2], Joselin Herbert et al. [3], among others). For instance, Breton and Moe [1] have discussed briefly the advantages of offshore wind energy, including a summary of the status, plans and technologies for offshore wind turbines in Europe and North America, and Wang et al. [2] have carried out a literature survey on floating wind turbines research. Some authors focused their efforts in offshore wind turbine optimization on finding the best installations and overcoming the disadvantages of this technology (Jonkman [4], Agarwal and Manuel [5], Karimirad et al. [6], among others).

1.1. Simulation tools for onshore/offshore wind turbines

FAST (Jonkman and Buhl [7], *National Renewable Laboratory Energy*, NREL) is a reference code for the study and design of wind turbines. Other codes that allow beneficial interactions with FAST have appeared, such as HydroDyn (Jonkman [4]), for the calculation of the wave loads in offshore structures, and AeroDyn (Laino and

Hansen [8], Moriarty and Hansen [9]). AeroDyn, developed by *Windward Engineering*, is an aerodynamics software library for use in horizontal-axis wind turbine design. Besides, it is possible to find research related to the aerodynamics of wind turbines in order to validate and obtain tools that are more accurate. MEXICO and UAE experiments are two application examples of this research (Hand et al. [10], Schreck et al. [11], among others).

The most recent tools for designing wind turbines are expensive, although others, like FAST/AeroDyn, are freely available. Different commercial codes can be found, such as Bladed (GL Garrad-Hassan, www.gl-garradhassan.com), which is intended for making a complete calculation of wind turbine systems, SamCEF (Samtech, www.samtech.com), ADAMS (MSC Software Corporation, www.mscsoftware.com, NREL, www.nrel.gov, Laino and Hansen [12]) or FLEX5 (Technical University of Denmark, www.dtu.dk). Alternatively, free software for rotor aerodynamics or aeroelastic calculations of wind turbines can be found, such as QBlade (University of Berlin, www.qblade.de.to) and FAST/AeroDyn (NREL, Jonkman and Buhl [7], Laino and Hansen [8]), respectively.

1.2. The aim of this work

The main objective of this work is to provide a rapid prototyping software tool for studying the performance of offshore wind turbines; it means providing a new toolkit for operating with *FAST/AeroDyn/HydroDyn*. This goal is achieved through the implementation of a complete form based on Lognoter (www.lognoter).

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com), a commercial software developed by CompassIS (www.compassis.com), which allows for the efficient management of information in technology. The main advantage of this tool is its capability for easily creating new Graphical User Interfaces (GUI). For this reason, *Lognoter forms* collection of features has been chosen to develop a new utility for integration with FAST/AeroDyn/HydroDyn. This GUI allows the user to easily generate input files for the routines developed by NREL.

Summarizing, the new tool is called FASTLognoter, and is developed with the aim of generating and providing an interface to help the user in the normal operation with FAST/AeroDyn/HydroDyn, as well as to facilitate the design optimization of wind turbines, focused mainly on offshore wind turbines.

2. An overview of NREL codes: FAST/AeroDyn/HydroDyn

2.1. Background

The FAST code simulates the non-linear dynamic performance of both onshore and offshore *Horizontal-Axis Wind Turbines* (HAWTs). The aerodynamic calculations of HAWTs are carried out with the AeroDyn code (Laino and Hansen [8], Moriarty and Hansen [9]). For offshore floating structures, the hydrodynamics loads are determined with HydroDyn code (Jonkman [13]), recently added to FAST. This code permits the user to model the dynamic response of conventional horizontal-axis wind turbines with both two and three blades. Additional features have been added to the FAST code in recent years, which makes FAST an attractive code for calculating HAWT both onshore and offshore. As a significant capability, FAST can interact with other codes such as WAMIT [14] (a powerful software for analyzing and calculating the wave load in offshore structures), and other utilities such as DLL (Dynamic Link Library) interface for Bladed (Jonkman and Buhl [7]).

In this work, the integration of FAST with Lognoter is proposed, in order to achieve easier handling of the tools mentioned, obtaining FASTLognoter. Several functionalities have been added and automated in FASTLognoter, permitting the user a more complex modeling and design optimization for wind turbines. The tool presented has new capabilities, which makes FAST/AeroDyn/HydroDyn a more powerful simulation software.

2.2. Brief summary of FAST/AeroDyn/HydroDyn theory

Five relevant aspects can be highlighted in the basic theory used in the modeling with FAST/AeroDyn/HydroDyn. They are described in a summary way, and several new capabilities of FASTLognoter are described.

- A) *Deflection calculation.* The FAST routines employ both rigid and flexible elements to model different parts of the wind turbine. For instance, the tower and the blades are considered as flexible elements. In each flexible element two mode shapes are defined, which are expressed by a sixth degree polynomial. FASTLognoter can determine the coefficients of mode shapes, through computing the outputs given by BModes, a pre-processor developed by NREL (Bir [15]), which has been added and integrated into the FASTLognoter tool, assembling in a unique software some new capacities. The structural model employed considers the flexible parts of the wind turbine as cantilever beams (Wilson [16]), with continuous mass and stiffness distributions.
- B) *Kinematics calculation.* FAST code employs the *adding angular velocity theorem* to determine the angular velocity of the rotational parts of the wind turbines.

C) *Kinetics calculation.* The equations of motion are derived in FAST using Kane's equations [17] (which in turn are derived from Newton's Second Law).

D) *Aerodynamic modeling.* FAST integrates the AeroDyn routines in order to compute the wind loads on the wind turbine. When the user runs the FAST/AeroDyn codes, several parameters for computing the wind loads are required, such as aerodynamic lift, drag, and pitching moments along the wind turbine blade. AeroDyn needs data related to wind conditions, turbine geometry, and blade elements. A new pre-processor has been developed in this work, the AirFoil form (explained later), and it has been added to FASTLognoter in order to calculate the airfoil data necessary to carry out aerodynamic calculations.

The AeroDyn code allows the user to calculate the wind loads acting on the wind turbine. The code can simulate uniform or turbulent wind flow, and it uses two alternative aerodynamic models to simulate the aerodynamics of horizontal-axis wind turbines: the *Blade Element Momentum* theory (BEM) or the *Generalized Dynamic Wake* theory (GDW); in addition, it can include the static or the dynamic stall in the modeling.

E) *Hydrodynamic load calculation.* FAST incorporates HydroDyn for the calculation of the hydrodynamic loads acting on support platforms in offshore wind turbines. HydroDyn can simulate time-domain hydrodynamic effects from multiple parameters such as linear hydrostatic restoring, damping, non-linear viscous drag or sea currents. This code takes into account added mass contribution, which is calculated through WAMIT (Lee [14]), and it also includes free-surface memory effects, linear diffraction from wave excitation and quasi-static mooring line calculation (Jonkman [4]).

3. FASTLognoter: tool integration

The primary idea of the tool integration is shown in Fig. 1, from a new project to the results, including the interaction between FAST and FASTLognoter. To get an operative and efficient toolkit it is necessary to take into account that to operate with FAST/AeroDyn/HydroDyn, several pre-processors are required to achieve an accurate calculation, as is shown in this work.

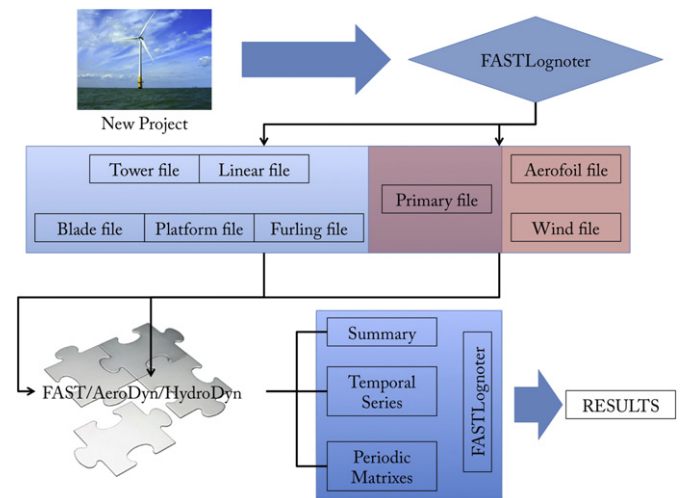


Fig. 1. Primitive idea of the tool integration proposed in this work, including the interaction between FAST and FASTLognoter.

3.1. An overview of Lognoter

Lognoter can be classified as a computer tool used for the *knowledge and information management* of processes of different nature (in engineering or in other fields). Because Lognoter is a free programmable platform, its capabilities and resources are inexhaustible, so it can be employed for innumerable uses.

Lognoter can be used for the development and commercialization of powerful forms and user interfaces by means of the project *Lognoter forms* (available on the Website www.compassis.com). Furthermore, it allows the Website management, the economic management of projects and the automated creation of reports. Because the FASTLognoter tool has been developed by means of *Lognoter forms*, the latter capacity will be discussed later in a more detailed manner. Summarizing, Lognoter has the following important capacities: insertion of tables and pictures; database storage (SQLite) and encrustation of links; adapted sight; back-up copy; database and page encryption; design and graphics creation tools; importation/exportation; mathematical utilities; translation tools; synchronization; ease of organization and page navigation, and creation of own user interface. Advanced capacities, such as XML (Extensible Markup Language) code editing and Tcl/Tk (Tool command language/Toolkit) programming, are also included.

The code gives a clear and fast audit of the form being able to visualize operations completely. It incorporates the possibility of interactive aid; the user acquires more quickly the understanding of the interface/form. The forms of Lognoter are also placed into project *Lognoter forms*. This is a Website based on the Wiki concept, whose main objective is the development of a site where developers and users can exchange forms, add tools, experiences, procedures, help, etcetera.

3.2. The development of FASTLognoter: software programming

FASTLognoter is a toolkit created to give FAST a consistent interface and to facilitate their use by beginner engineers and researchers. The framework of FASTLognoter is made up of *pages*. Each page is related to a different part of the wind turbine and given input files of FAST/AeroDyn/HydroDyn codes, which are necessary to perform the hydro-aeroelastic calculation with these codes. The new user of FAST/AeroDyn/HydroDyn codes finds it difficult to generate the files required to perform aerodynamic calculation with FAST/AeroDyn. Therefore, FASTLognoter establishes a gateway to facilitate and improve the management of these NREL codes, because it has new tools to carry out aeroelastic calculations, facilitate the file creation and the code execution, analyze the results obtained and manage and store all the information related to a new wind turbine project. The pre-processors added to FASTLognoter are related to tower structural properties (TowerProp), blade structural properties (BladeProp), calculations of the coupled shape modes (BModes), and airfoil definition (AirFoil). These tools check the values given by the users for errors. This capability facilitates the management of NREL codes, such as FAST/AeroDyn, as will be explained later.

A powerful Graphical User Interface (GUI) is developed, employing features of Lognoter like XML and Tcl/Tk programming capabilities. In addition, FASTLognoter employs an *Application Programming Interface* (API) of SQLite to get the input stored in the database. This toolkit gives the routines with the appropriate windows and tables in order to provide the input data for making the calculations. Furthermore, it can be difficult when using only FAST to give and obtain the appropriate parameters in order to obtain accurate computing (there are more than 600 parameters). Pre-processors are required to obtain these parameters, which model the behavior of wind turbines. For example, one needs the

coupled mode shapes of the tower and blades to find the blade-tip and tower-top deflection; it is also indispensable to obtain the aerodynamic parameters of the airfoil located in the blade nodes of the wind turbine.

Lastly, FASTLognoter facilitates the creation of input files, adding into this tool-predefined cases based on NREL certificate test, which are attached together with FAST/AeroDyn codes. It also adds new features and routines to improve these codes and creates a complete toolkit for the study, design and investigation of both onshore and offshore wind turbines.

3.3. Distinctive features of FASTLognoter

On the one hand, FASTLognoter can classify different types of projects, organizing the information and parametric calculations of wind turbines (onshore and offshore HAWTs) depending on the input file. The page distribution of FASTLognoter allows the user to classify the parameters in the following groups: configuration, tower, blade, platform, furling, linear, aerodynamics and output parameters (see Fig. 2). To give the user more information about the software management, several bibliographic resources are included, as well as dynamic help and adapted view.

On the other hand, the projects are stored in a SQLite database and the new tool handles these projects easily (Fig. 2). This toolkit allows the user to easily add innumerable projects into a SQLite database to analyze in an individual or in a collective calculation option. Therefore, the SQLite database has a great advantage over other software, because all the projects stored can be handled easily, and optimization calculations with FAST/AeroDyn can be achieved. Through FASTLognoter, the user may vary the specific parameters of the wind turbines and study their influence on the wind turbines behavior, using special features added for this purpose. For each ongoing case, the tool creates a specific folder where the input files and results are stored.

Finally, another distinctive feature of FASTLognoter is the addition of predefined cases, these based on the files attached together with FAST/AeroDyn code and NREL 5-MW wind turbine (Jonkman [18]). Therefore, a beginner can create a new project based on these predefined cases (this capability is not included in other codes).

3.4. Pre-processors added

In order to help the user of NREL codes to study a wind turbine easily, several pre-processors have been added into FASTLognoter, as previously mentioned. Focusing on the tower and the blades, TowerProp and BladeProp forms are attached to FASTLognoter.

The TowerProp form allows the user to create and edit files with distributed tower properties. The files can be easily incorporated into the FASTLognoter tool, facilitating the previous calculation of the wind turbine tower. It is possible to choose several types of tower material: concrete, steel, PRGF (Polyester Reinforced with Glass Fibre) and aluminum (see Fig. 3). This form divides the tower into multiple parts and assigns the properties of each part. A linear distribution is employed to calculate the mass per unit length and other properties of the tower.

The BladeProp form makes the generation of the CSV (Comma-Separated Values) format file with distributed blade properties easier, and it can easily modify the blade properties. The files can be imported into FASTLognoter, and the blade properties can be modified by simply adding the given parameters available for that purpose (see Fig. 4). These parameters are related to flap-wise, edge-wise or torsion stiffness of the blade (Jonkman and Buhl [7]).

With regard to the modal analysis of the flexible parts of the wind turbine, FASTLognoter incorporates a pre-processor, which allows the user to obtain the coupled mode shapes of these flexible

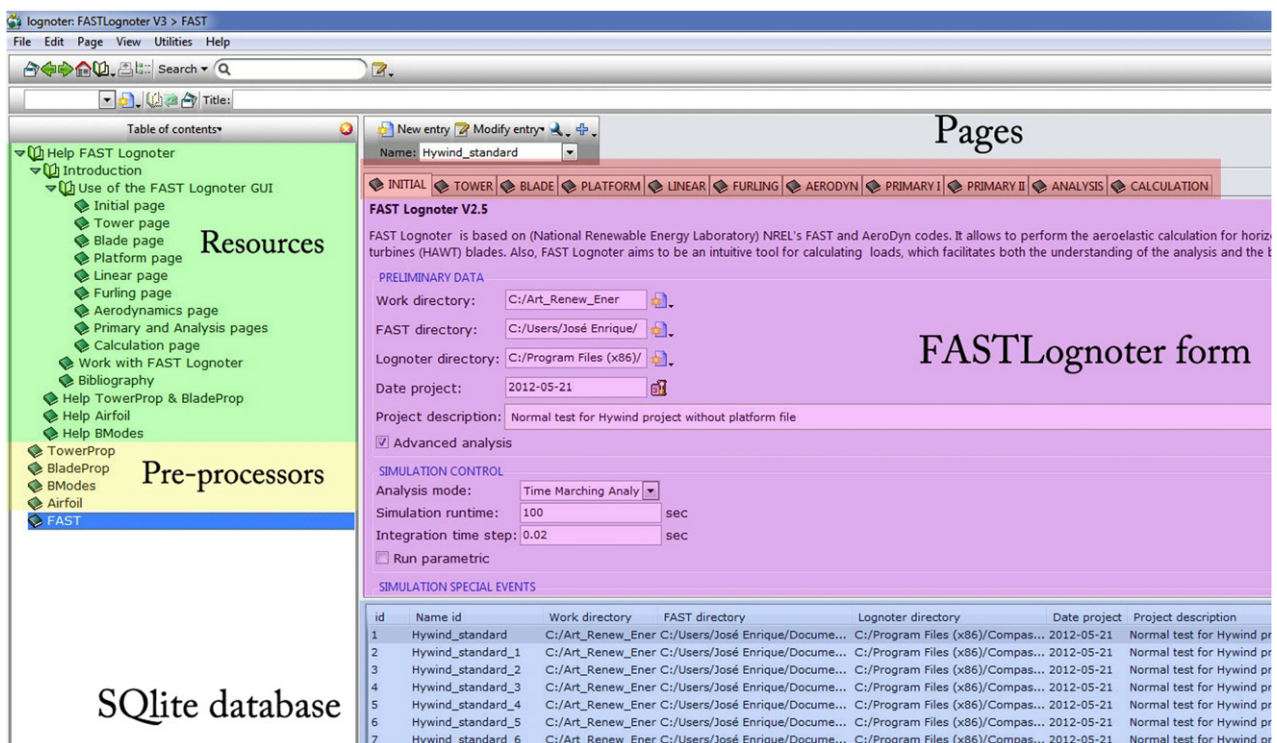


Fig. 2. Screenshot with several distinctive features of FASTLognoter.

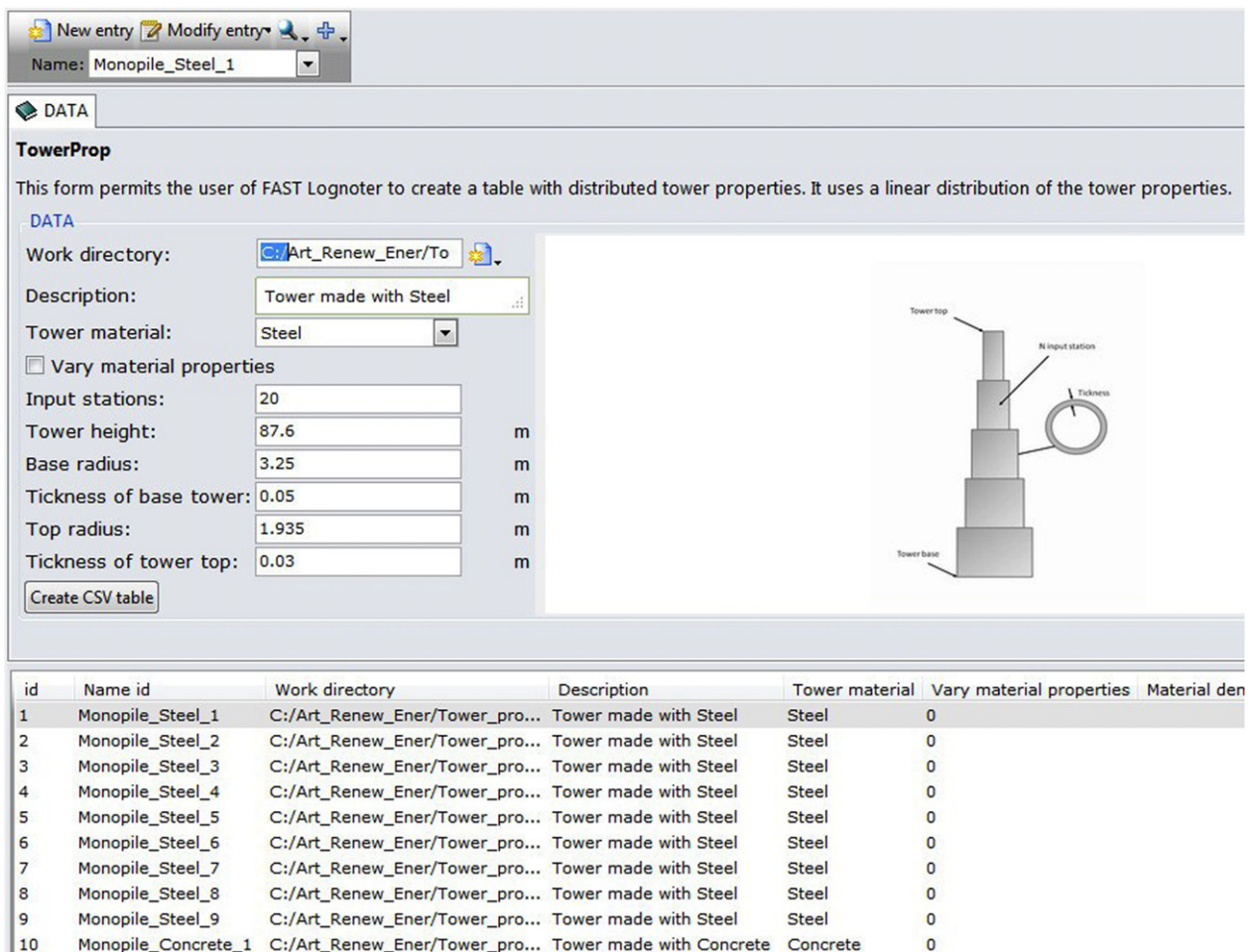


Fig. 3. Pre-processors added to FASTLognoter: TowerProp (tower properties).

New entry
Modify entry

Name: Blade Hywind

Initial data

BladeProp

This form permits the user of FASTLognoter to manage and create the tables with distributed blade properties

Initial data

Work directory: C:/WorkDirectory

Description: Set here a description

☒ **Modify properties**

Mass factor: 1.023

Thickness factor: 1.000

Flap-wise factor: 1.000

Edge-wise factor: 1.000

Torsion factor: 1.000

Properties

BlFract	AeroCe...	StrcTwst	BMassD...	FlpStff	EdgStff	GjStff	EASStff	Alpha	FlpIner	EdgeIner	Prec
0.00000	0.25000	13.308	848.669	22637.50...	22642.00...	6955.50E...	12161.85...	0.0	1216.08	1216.30	0.0
0.00325	0.25000	13.308	848.669	22637.50...	22642.00...	6955.50E...	12161.85...	0.0	1216.08	1216.30	0.0
0.01951	0.24951	13.308	966.704	24281.13...	24448.25...	6789.49E...	13486.88...	0.0	1364.40	1332.98	0.0
0.03577	0.24510	13.308	925.688	21819.88...	24372.25...	6242.48E...	12584.04...	0.0	1207.61	1309.20	0.0

Create CSV table

id	Name id	Work directory	Description	Modify properties	Mass factor	Thickness factor	Flap-wise factor	Edg
2	Blade Hywind	C:/WorkDirectory	Set here a description	1	1.023	1	1	
3	Blade Carbon	C:/WorkDirectory	Set here a description	1	1.023	1	1	
4	Blade Aramide	C:/WorkDirectory	Set here a description	1	1.023	1	1	
5	Blade Hywind Mod	C:/WorkDirectory	Set here a description	1	1.023	1	1	

Fig. 4. Pre-processors added to FASTLognoter: BladeProp (blade properties).

parts of the wind turbine; that is to say, the tower and blades. This pre-processor is called by the same name as NREL pre-processor available for this purpose, BModes. BModes uses a finite element discretization of the flexible part of the wind turbine to carry out the modal analysis. This form obtains coupled modes for wind turbine tower and blade (see Fig. 5). A coupled mode implies the presence of coupled flexural, axial, and torsion motions in a natural mode of vibration; so, because FAST assumes a predefined mode shape approach, BModes is used. This code allows the user to set the tip-attachment. To properly set the operation with BModes, the rotor speed, blade geometry, precone, pitch control setting, tip-attachment inertia properties, and distribution of structural properties the blade are needed.

Focusing on the aerodynamic parameters of airfoils, which are placed on the blades nodes, another pre-processor required by FAST/AeroDyn is AirfoilPrep (Hansen [19]). This leads to a form integrated with FASTLognoter, which allows the user to obtain the airfoil in the same way as AirfoilPrep. The pre-processor added is called AirFoil form (see Fig. 6). To obtain the aerodynamic performance of airfoils, this form uses the Viterna equations (Moriarty and Hansen [9]) for deep stall to expand aerodynamic parameters of the airfoil data for all angles from a limited set of measurements, which are required by AeroDyn. It also calculates the dynamic stall parameters needed by the Beddoes and Leishman semi-empirical

model [20], which is based on airfoil indicial response. AirFoil form can interpolate the aerodynamic coefficients for other span locations, with the Du's method to augment the lift and Egger's method to modify the drag (Du and Selig [21]). In short, all the features of AirfoilPrep are included in AirFoil.

The last pre-processor added to FASTLognoter is an algorithm that makes it easier to get the coefficients of coupled mode shapes given by BModes output. These algorithms replace the excel file attached with FAST/AeroDyn codes. The coefficients of mode shapes are obtained by multiple linear regressions, usually employed to model the linear relationship between a dependent variable and one or more independent variables,

$$\bar{Y} \approx \bar{X} \cdot \bar{\beta}, \quad (1)$$

where \bar{Y} is the matrix column with the displacement of the cantilever beam along undeflected tower or blade, \bar{X} the matrix design and $\bar{\beta}$ the wanted matrix column with the coefficients mode shapes.

Finally, it can be stated that FASTLognoter has sizeable advantages, because it links FAST with the user, allowing the automatic creation of the input files necessary to run FAST/AeroDyn/HydroDyn codes, calculating the previous data required, classifying the files, plotting, and analyzing the results. The last advantage facilitates the interpretation of the results obtained and the study of wind turbine

New entry Modify entry

Name: Hywind

Initial Data Table with structural properties

This form permits the user to calculate the mode shapes of flexible parts of wind turbine, using BModes

Initial Data

Work directory: C:/Users

BModes directory: C:/BModes

General

☒ Blade beam type

☐ Tower beam type

Rotor speed: 12.1 rpm

Rotor speed factor: 1.0

Rotor radius: 63.0

Hub radius: 1.5 m

Cone angle: 0.0 deg

Pitch angle: 0.0 deg

Number of modes: 20

Mass structural properties

Tip mass: 72.0 Kg

Tip mas c.m. offset: 0.05 m

Ixx: 18.0 Kg·m²

Iyy: 3.15 Kg·m²

Izz: 4.50 Kg·m²

Ixy: 0.0 Kg·m²

Iyz: 0.0 Kg·m²

Ixz: 0.0 Kg·m²

id	Name id	Work directory	BModes directory	Blade beam type	Tower beam type	Rotor speed	Rotor speed factor	Rotor radius
1	Hywind	C:/Users	C:/BModes	1	0	12.1	1	63

Fig. 5. Pre-processors added to FASTLognoter: BModes (mode shapes of flexible parts).

behavior, for both onshore and offshore types. The graphical tool added to FASTLognoter allows the user to understand and analyze the results obtained with FAST/AeroDyn codes, plotting the results into an individual or multiple adaptive graphs (see Fig. 7).

4. Discussion of results

4.1. FASTLognoter verification

It can be considered that the world's first operational deep-water wind turbine of high power (2.3 MW) is the Hywind Project Turbine (owned by the Norwegian company StatoilHydro, constructed by Siemens Wind Power), in the North Sea off Norway. In the current section, FASTLognoter is verified by comparing with other codes usually employed in the wind industry. The tests are based on the aforementioned wind turbine, with an offshore spar buoy wind turbine of power 5-MW.

Fig. 8 shows a representative comparison between the results obtained by using several codes and interfaces, following the IEA Wind Annex XXIII-Subtask 2, a benchmark test under the coordination of NREL. In addition to the results obtained in this work for the tower-top fore-aft shear force with FASTLognoter, Fig. 8 shows the results obtained by NREL, CENER (National Renewable Energies

Center, Spain), CWMT (Fraunhofer Center for Wind Energy and Maritime Engineering, Germany), Risø DTU (National Laboratory for Sustainable Energy, Denmark) and Siemens AG (Germany), with different codes: Bladed (based on modal analysis), ADCoS (based on finite element method), BHAWC (based on non-linear finite element method) ADAMS, HAWC and FAST (based on multibody dynamics formulation). The results are achieved with 6.9 rpm rotor velocity and 8 m/s steady inflow wind velocity. The GDW model for computing the loads on the turbine is employed, as well as the Beddoes–Leishman dynamic stall model; in addition, the aerodynamic pitching moments of the blades and the velocity deficit in the wake of the tower have been taken into account. It can be seen that the results obtained in this work follow a similar trend to those reported by NREL; the slight discrepancy may be due to differences in the input data.

4.2. Application case: a design investigation of blades based on NREL 5-MW offshore wind turbine

This application case, a design optimization study, is proposed to find better blade behavior in a given offshore wind turbine. In order to achieve this aim, NREL 5-MW offshore wind turbine (Jonkman et al. [22]) is proposed as a basis for the design

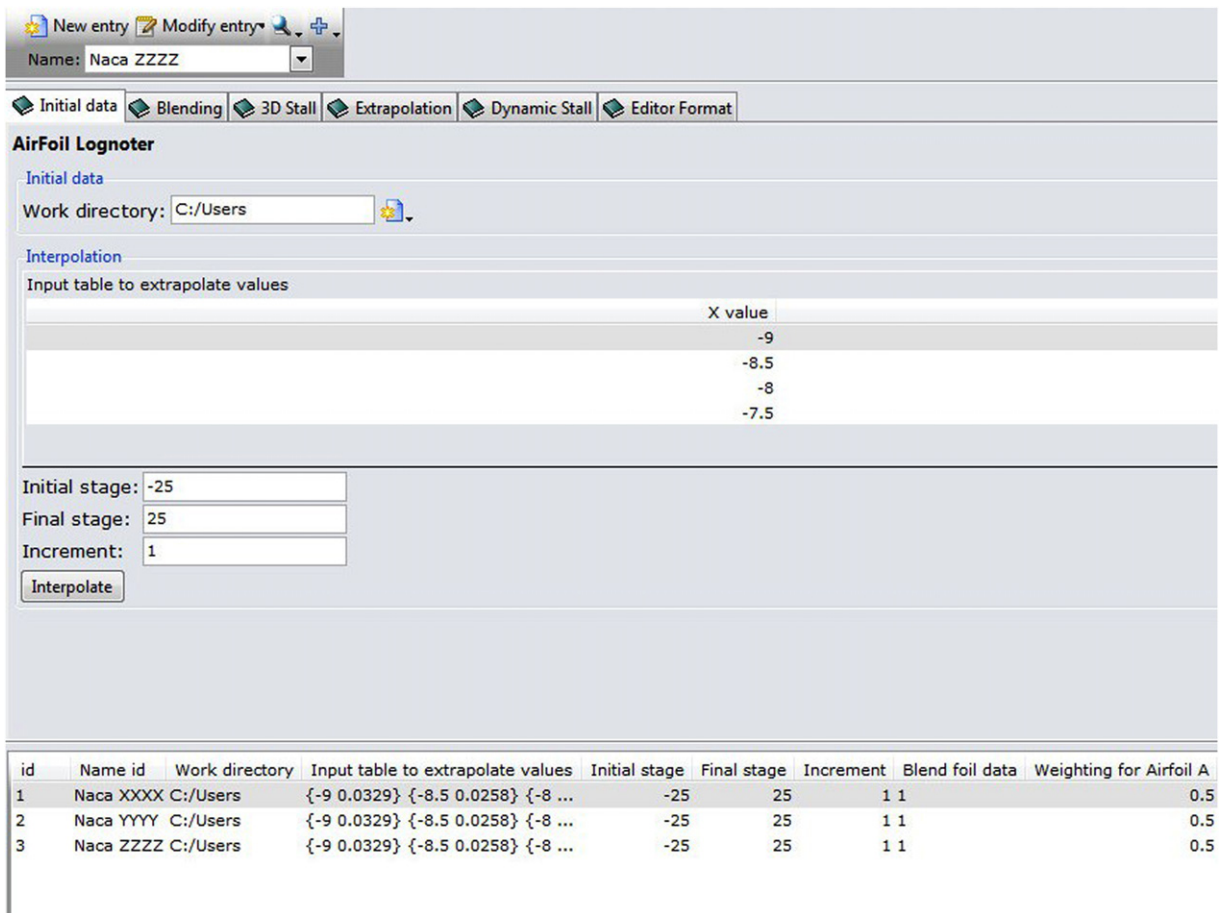


Fig. 6. Pre-processors added to FASTLognoter: AirFoil (profile aerodynamic parameters).

investigation; four types of blade with identical aerodynamic performance (but different mechanical characteristics) are examined.

The design optimization process with FASTLognoter is described schematically in Fig. 9. Although final design decisions should be stated taking into account additional considerations such as cost, visual impact or noise reduction, this new tool can perform

a systematic analysis of the different possibilities that the user wants to achieve. To establish a representative design problem, different types of blade are considered:

- *Blade Type 1.* This is the basis blade, based on the NREL 5-MW Baseline wind turbine, made of PRGF.

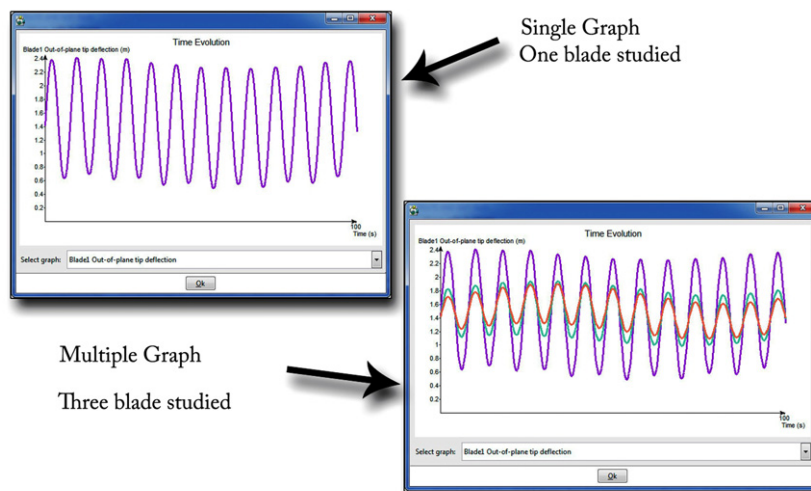


Fig. 7. Typical graphs obtained in FASTLognoter.

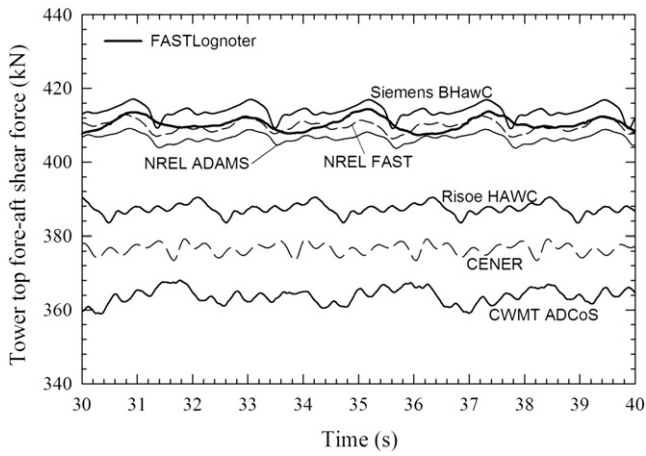


Fig. 8. Comparison between the results with FASTLognoter and those obtained with different companies and researchers, using several codes (IEA Wind Annex XXIII-Subtask 2, OC3-Hywind Turbine 5-MW).

- *Blade Type 2.* As Blade 1, but made of carbon fibre.
- *Blade Type 3.* As Blade 1, but made of aramide.
- *Blade Type 4.* As Blade 1, but with 25% increased thickness.

The blade mass and stiffness distribution of Blades 1–4 are shown in Fig. 10a–c. As expected, Blade Type 4 is the heaviest blade, whereas Blade Type 2 offers the best mechanical properties. Note that Blade Types 2–4 have higher values of edge-wise bending and flap-wise bending stiffness than Blade Type 1, and that Blade Types

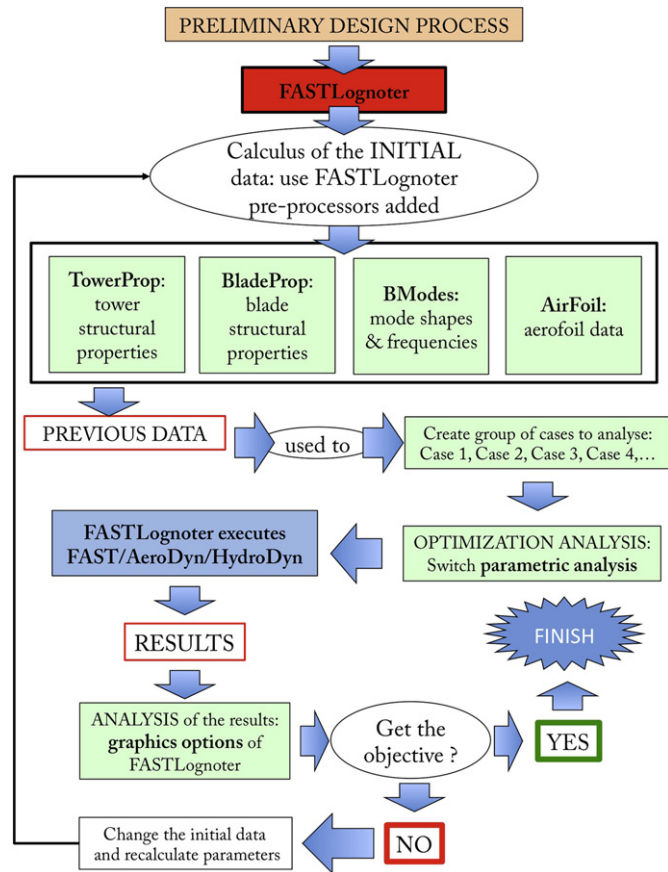


Fig. 9. Scheme of the design optimization process with FASTLognoter.

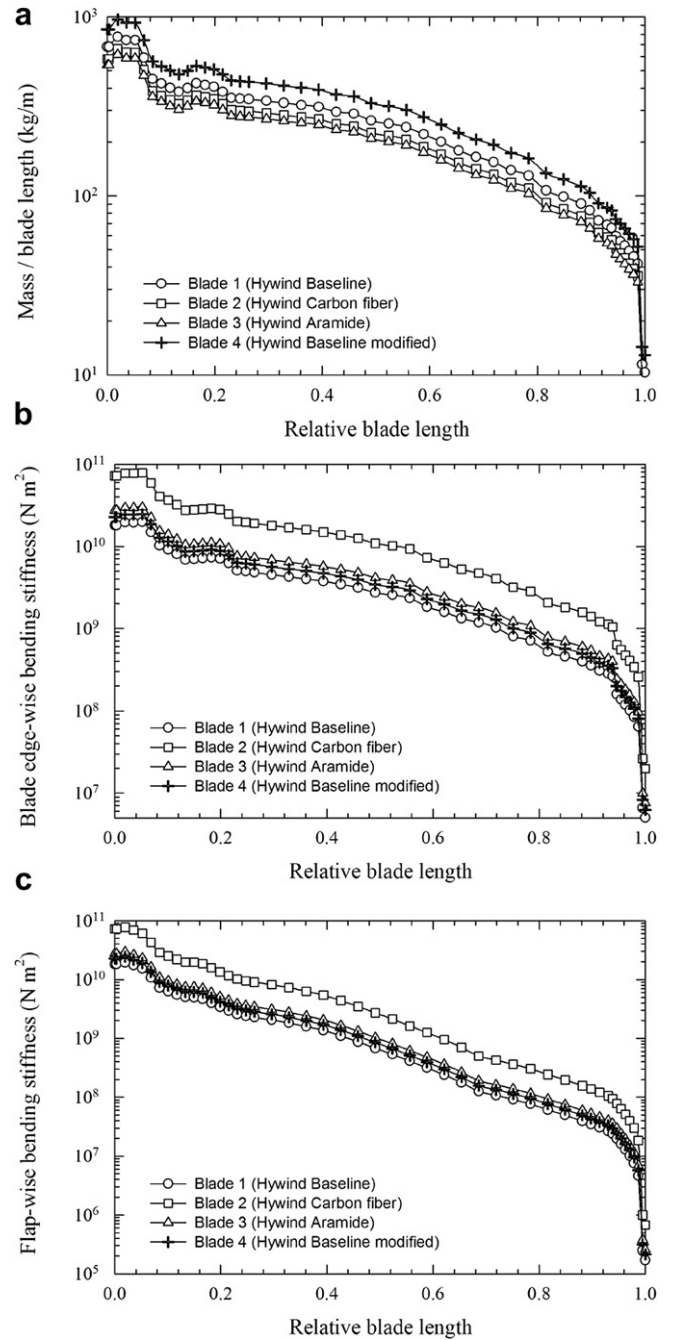


Fig. 10. Mass and stiffness properties of the proposed Blade Types 1–4. a) Mass per unit of blade length. b) Edge-wise bending stiffness. c) Flap-wise bending stiffness.

2 and 3 achieve a mass reduction compared to the reference Blade 1.

The behavior of the blades has been studied under the same axial wind flow, with values of 1–20 m/s. Several relevant parameters calculated through FASTLognoter are presented: blade edge-wise tip deflection, blade flap-wise tip deflection, tip to tower clearance and axial tip deflection. Each blade is divided into 17 nodes and the mechanical characteristics are presented per unit length. To carry out the proposed investigation, it is necessary to get data using pre-processors added into FASTLognoter toolkit (TowerProp, BladeProp, BModes and AirFoil).

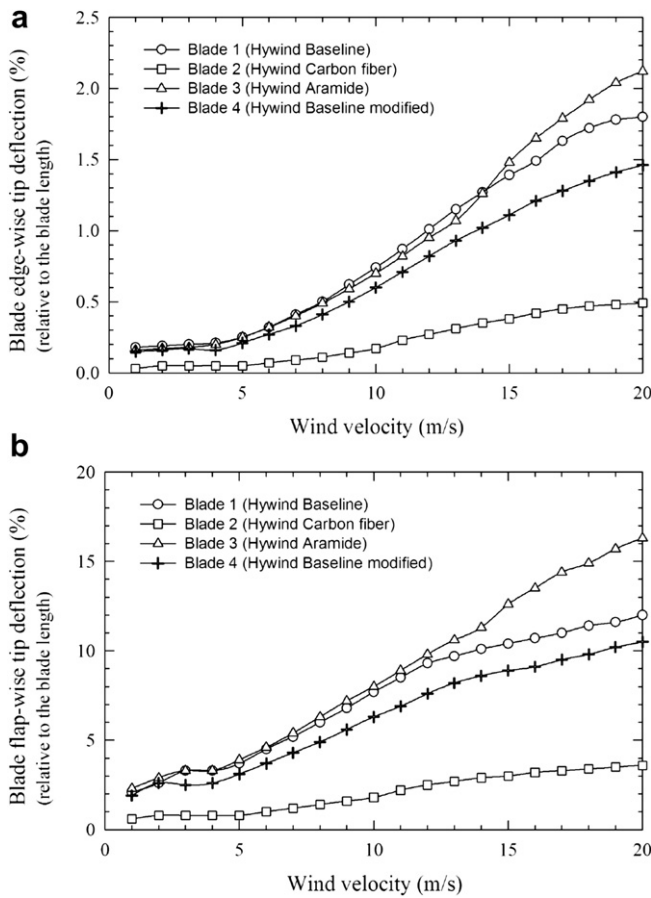


Fig. 11. Representative results obtained for the proposed Blade Types 1–4. a) Relative edge-wise tip deflection. b) Relative flap-wise tip deflection.

The first step to achieve the proposed study is to set up the mechanical characteristics, in order to make a modal analysis of the coupled mode shapes. This allows the user to obtain the first and second flap-wise bending mode and first edge-wise bending mode of each blade analyzed. For this purpose, BModes is used. Then, these data are used in FASTLognoter to create a blade file appropriate to run FAST/AeroDyn. For each case analyzed, it is necessary to establish a new entry in SQLite database of FASTLognoter, and then a new case is stored. When all the cases are prepared, the option *parametric analysis* is selected to carry out the complete calculation of all the cases given to FASTLognoter. With respect to the timing, a simulation time has been established following the rules given by the International Electrotechnical Commission procedure (61400-1, Wind turbine generator systems) on the normal operation of a wind turbine. A time increment given as $dt = d\theta/\omega$ (being θ the azimuth step and ω the rotor speed) has been assigned. Thus, the results presented belong to the last minute of the simulation in each case.

The results obtained can be observed in Figs. 11 and 12. The evolution of blade deflection versus wind velocity can be seen. The influence of the stiffness on the blades behavior is clear. To a great extent, the increase of the parameters related to type of material or airfoil thickness reduces the tip deflections. The relationship between the mass and the best mechanical behavior is optimized in carbon fibre. Indeed, Blade Type 2 has better performance than the original blade based on NREL 5-MW wind turbine (Blade Type 1), achieving the desired goal, i.e., to improve the tip deflection of wind turbine blade along with a relevant mass reduction. In this case, the carbon fibre blade obtains a sizeable 23.5% in mass reduction.

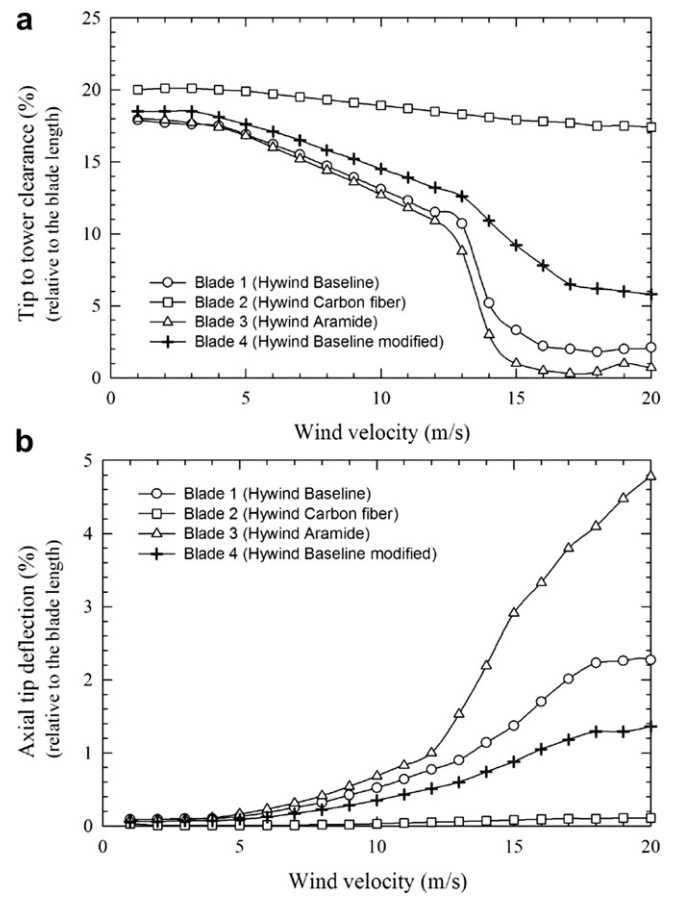


Fig. 12. Representative results obtained for the proposed Blade Types 1–4. a) Relative tip to tower clearance. b) Axial tip deflection.

5. Concluding remarks

- The present work gives response and solution to an existing need in wind energy engineering; the tool presented, FASTLognoter, provides a graphical user interface for FAST, for carrying out a complete study on wind turbines (both onshore and offshore).
- This software helps the beginner engineer and the inexperienced developer to work in the field of renewable energy.
- Several pre-processors have been added to make FASTLognoter a competitive toolkit, permitting the user to calculate the required data and carry out a complete analysis of a wind turbine: TowerProp, BladeProp, BModes and Airfoil.
- A key feature of the new toolkit presented is the capability to achieve parameterized studies and design optimization.
- It can be concluded that several useful features of FAST have been significantly enhanced through FASTLognoter.

References

- [1] Breton SP, Moe H. Status, plans and technologies for offshore wind turbines in Europe and North America. *Renew Energy* 2009;34:646–54.
- [2] Wang CM, Utsunomiya T, Wee SC, Choo YS. Research on floating wind turbines: a literature survey. *IES J Part A Civil Struct Eng* 2010;3(4):267–77.
- [3] Joselin Herbert GM, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. *Renew Sustain Energy Rev* 2007;11:1117–45.
- [4] Jonkman JM. Dynamics modeling and loads analysis of an offshore floating wind turbine. Technical Report NREL/TP-500-41958. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2007.
- [5] Agarwal P, Manuel L. Simulation of offshore wind turbine response for long-term extreme load prediction. *Eng Struct* 2009;31(10):2236–46.

- [6] Karimirad M, Meissonnier Q, Gao Z, Moan T. Hydroelastic code-to-code comparison for a tension leg spar-type floating wind turbine. *Marine Struct* 2011;24:412–35.
- [7] Jonkman JM, Buhl Jr ML. FAST user's guide. Technical Report NREL/EL-500-38230. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2005.
- [8] Laino DJ, Hansen AC. Users guide to the wind turbine aerodynamics computer software AeroDyn. Spanish Fork, USA: Windward Engineering LC, www.windwardengineering.com; 2002.
- [9] Moriarty PJ, Hansen AC. AeroDyn theory manual. Technical Report NREL/TP-500-36881. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2005.
- [10] Hand MM, Simms DA, Fingersh LJ, Jager DW, Cotrell JR, Schreck S, et al. Unsteady aerodynamics experiment phase VI: wind tunnel test configurations and available data campaigns. Technical Report NREL/TP-500-29955. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2001.
- [11] Schreck S, Sant T, Micallef D. Rotational augmentation disparities in the MEXICO and UAE phase VI experiments. Conference Paper NREL/CP-500-47759. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2010.
- [12] Laino DJ, Hansen AC. User's guide to the computer software routines AeroDyn interface for ADAMS. Colorado, USA: Winward Engineering, National Renewable Energy Laboratory, www.nrel.gov; 2001.
- [13] Jonkman JM. Modeling of the UAE wind turbine for refinement of FAST-AD. Technical Report NREL/TP-500-34755. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2003.
- [14] Lee CH. WAMIT theory manual. Report No. 95-2. Cambridge (Mass.), USA: Department of Ocean Engineering, Massachusetts Institute of Technology; 1995.
- [15] Bir GS. User's guide to BModes (software for computing rotating beam coupled modes). Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2007. <http://wind.nrel.gov/designcodes/preprocessors/precomp/PreComp.pdf>; 2007 [accessed 16.07.2012].
- [16] Wilson RE, Walker SN, Heh P. Technical and user's manual for the FAST-AD advanced dynamics code. NREL Report 99-01. USA: Oregon State University; 1999.
- [17] Kane RT, Levinson DA. Dynamics: theory and applications. New York: McGraw-Hill; 1985.
- [18] Jonkman JM. Definition of the floating system for phase IV of OC3. Technical Report NREL/TP-500-47535. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2010.
- [19] Hansen AC. NWTC design codes (AirfoilPrep). <http://wind.nrel.gov/designcodes/preprocessors/airfoilprep/>. [accessed 16.07.2012].
- [20] Leishman JG, Beddoes TS. A semi-empirical model for dynamic stall. *J Am Helicopter Soc* 1989;34:3–17.
- [21] Du Z, Selig MS. A 3-D stall-delay model for horizontal axis wind turbine performance prediction. In: ASME wind energy symposium, and 36th AIAA-1998-21 aerospace sciences meeting and exhibit, Reno (Nevada), USA; 1998. p. 12–5.
- [22] Jonkman JM, Butterfield S, Musial W, Scott G. Definition of a 5-MW reference wind turbine for offshore system development. Technical Report NREL/TP-500-38060. Colorado, USA: National Renewable Energy Laboratory, www.nrel.gov; 2009.