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Aeroelastic investigation of a composite wind turbine blade

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Abstract. Static aeroelastic is investigated in a wind turbine blade. Imposed to different loadings, the very long and flexible structures of blades experience some changes in its preliminary geometry. This results in variations of aerodynamic loadings. An iterative approach is developed to study the interactions between structure and aerodynamics evaluating variations in induced stresses in presence of aeroelasticity phenomenon for a specific wind turbine blade. A 3D finite element model of the blade is constructed. Aerodynamic loading is applied to the model and deflected shape is extracted. Then, aerodynamic loadings are updated in accordance with the new geometry of the deflected blade. This process is repeated till the convergence is met. Different operational conditions consisting of stand-by, start-up, power production and normal shut-down events are investigated. It is revealed that stress components vary significantly in the event of power production at the rated wind speed; while it is less pronounced for the events of normal shut-down and stand-by.

Keywords: composites; aeroelasticity; wind turbine blade; simulation

1. Introduction

Pollution free electricity generation has been received huge interests during the last decades. This has led to the considerable growth in the worldwide demand for renewable energies and among them; wind energy is of growing importance. Wind turbines are designed using innovative technological solutions to improve efficiency and reliability of its performance for converting kinematic energy of wind flow to electricity. Capturing wind energy, the blade is the key element in horizontal axis wind turbines.

Economical power generation necessitates employment of light and long structures for the blades. As a consequent of the former, they can start rotating at low wind speeds; while due to the low density of air, the later will increase the swept area to capture as much wind energy as possible.

Wind turbine blades are made of composite materials to present not only strong and light structures but also appropriate lifetime against fatigue phenomenon (Harrison *et al.* 2000). They need to sustain its mission for at least 20 years while exposed to severe conditions.

Ranging from 15 meter up to 54 meter, wind turbine blades are very flexible structure (See Fig. 1). The blade level of flexibility becomes more pronounced for larger wind turbine blades. The

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design problem of wind turbine blades was previously limited to static and fatigue investigations (Shokrieh and Rafiee 2006, Kong *et al.* 2005, Kong *et al.* 2006, Marin *et al.* 2009, Noda and Flay 1999, Ronold *et al.* 1999, Sutherland 1999).

Fig. 1 23 meter blades belonging to 660 kW wind turbine (Courtesy of Sabaniroo Co., Iran)

Emergence of longer wind turbine blades dictates aeroelastic considerations in design process of wind turbines. A comprehensive review of wind turbine aeroelasticity has been done by Hansen *et al.* (2006). Aero elasticity studies interaction between structure and aerodynamics. When a wind turbine blade is exposed to wind flow, it is subjected to different loadings. Those loadings will induce some changes to the geometry of blade structure because of the flexible structure of blades.

It will result in variations of aero dynamical forces. When deflection of the blade increases, elastic and aerodynamic forces will increase. This will change the imposed level of stress in the most critical regions on the blades from static and fatigue viewpoints. This implies on the importance of aeroelastic simulation for wind turbine blades.

The main goal of this context is to study the influence of aeroelastic phenomenon on the loadings of a wind turbine blade in different operational conditions. The degrees to which that static aeroelasticity will increase loadings are evaluated for a specific wind turbine blade.

2. Case study

In this paper, a 23-meter blade of a V47-660 wind turbine was selected. Detailed specifications of the selected wind turbine and its blades are inserted in Table 1.

The investigated blade consists of three different parts as shell, spar and root joint. While, the shell is responsible to provide the required pressure distribution on the blade from aerodynamic point of view, the spar has to accommodate loads on the blade from structural point of view. The root joint is the only metallic part in the current blade connecting whole blade structure to the hub by screws. This metallic joint is covered by composite laminates internally and externally.

The cross sections of the shell are different airfoils categorized under different class of NACA, FFA-W3 or mix one dictated by aerodynamic refined theories to improve the efficiency in

capturing wind energy. The cross sections of the spar are box shaped types.
Due to aerodynamical and structural considerations (Burton *et al.* 2001, Manwell *et al.* 2001), this wind turbine blade not only has a tapered shape but also twists from root to tip about 15°.

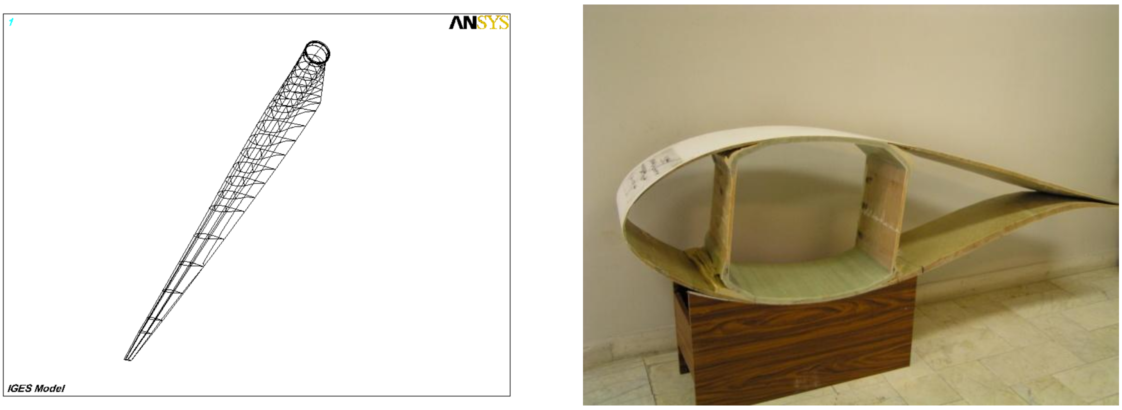
Table 1 Technical specification of investigated wind turbine and its blades

General Specification of the wind turbine		Specification of the blade	
Nominal power	660 kW	Length	22,900 mm
Rotor diameter	47 m	Minimum chord	282.5 mm
Swept area	1735 m^2	Maximum chord	2087 mm
Cut-in wind speed	4 m/s	Station of max. chord	R4500
Cut-out wind speed	25 m/s	Twist	15.17°
Rated power wind speed	15 m/s	Station of CG	R1800
Revolving speed of rotor	28.5 rpm	Wight of the blade	1250 kg
Elapsed time to reach 28.5 rpm from stationary status	30 sec	Airfoil cross section types	FFA-W3, NACA-63,MIX
Yaw movement speed	0.5°/sec	Surface area	28 m2
Temperature range	-20°~+40°	Tip to tower distance	4.5 m

3. Modelling

A geometrical frame model of the blade is constructed using the airfoil cross sections in different stations from the root to the tip of the blade. Loft method is used to draw surface in the space between the cross sections. The wireframe of investigated blade is shown in Fig. 2.

After constructing geometrical model of the blade two finite element models for structural and aerodynamic analyses have to be built.



(a) Wireframe model (b) Cut section of blade including shell and spar

Fig. 2 Investigated wind turbine blade

3.1 Structural finite element model

Finite element model is built using second order shell element to increase the accuracy of modeling in ANSYS commercial software. Shell99 is selected from element database of software. Convergence analysis is carried out and sufficient mesh density is obtained, accordingly. The constructed finite element model consists of 8505 elements.

For this specific blade, pre-impregnated materials are used to increase the efficiency of production process from both quantity and quality aspects. Tri-axial and bi-axial fabrics are used in the shell structure and unidirectional (U-D) and bi-axial are used in the spar structure. The configuration of the bi-axial lamina is [±45] and the configuration of the tri-axial laminate is [0/+45/-45]. In order to construct the sandwich panel, two kinds of foam, polyvinyl chloride (PVC) and polymethacrylimide (PMI) are used at the spar and shell locations, respectively. Each tri-axial and bi-axial laminates are replaced with an equivalent U-D ply in accordance with inserted data in Table 2. Lay-up configurations of the blade including both lay-up sequence and lay-up orientation are fed into the software carefully.

Table 2 Mechanical properties of the materials used for the investigated blade

Material	E_x [GPa]	E_y [GPa]	ν_{xy}	E_s [GPa]
U-D ply	43	9.77	0.32	3.31
Bi-axial laminate	16.7	16.7	0.06	2.01
Tri-axial laminate	17.6	7.01	0.53	5.075
PVC foam	0.05	0.05	0.32	0.02
PMI foam	0.066	0.066	0.32	0.025

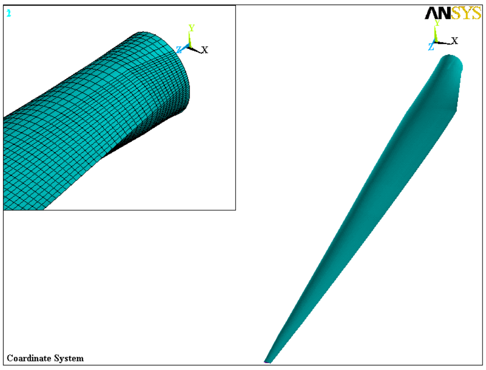


Fig. 3 Blade coordinate system

3.2 Aerodynamical finite element model

The appropriate finite element model for aerodynamic analysis is constructed on the same geometry platform previously used for structural model. Free mesh is used for fluid environment. Using Flotrant142, the same pattern of blade outer elements is followed by the fluid elements which are in direct contact with blade surface. Considering coordinate system depicted in Fig. 3, wind speed along x- and y-directions on side planes are constantly taken as wind flow speed. The linear velocity of blade in each location is obtained by multiplying angular velocity by corresponding radius of rotation. Wind speed along z-direction on side plane is assumed to be zero. Pressure is also taken zero on the trailing edge of the blade. Wind speeds along all directions on the blade are taken as zero, as well.

4. Loading analysis

A wind turbine blade is subjected to different load cases arising from wide variety of resources. Germanschier Lloyd (1993) rules have provided a clear insight to classification of different loading conditions associated with experiencing events. Specific combinations of different load cases are selected for different strength, statics, dynamics and fatigue analyses.

Normal operating conditions and normal external conditions are considered in this research due to the rare occurrence and insignificant influence of other conditions. Normal operating conditions are divided into four events: stand-by, start-up, power production and normal shut-down events. Stand-by condition is defined as the situation that there is neither a fault/shut-down condition nor wind speed is outside the range of power production interval. Start-up event takes place when the turbine is experiencing transient event either from stand-by to power production situation or from lower wind speed to higher value during power production. In power production condition, a turbine generates power within cut-in and cut-out wind speeds. Normal shut down implies on transient situation from power production to stand-by conditions or from a higher wind speed to a lower one. The associated wind speeds with mentioned normal operating conditions are presented in Table 3 for the investigated wind turbine.

Table 3 Classifications of normal operation conditions for studied wind turbine

	Stand-by	Start-up	Power production	Normal shut-down
Wind speed [m/s]	< 4	4	> 4 and < 25	25

Normal external conditions describe the interactions between a wind turbine and its surrounding environment. They can be categorized as normal gust, changes in wind directions and temperature ranges. The acceleration of normal gust is assumed as 5 m/s^2 and as a subsequent the normal gust factor is selected as 5/3. It is necessary to consider the suddenly unpredictable changes in wind direction up to ±30 degree relative to the dominant direction of wind flow (GL rules and regulations 1999). A variation of ambient temperature can cause additional internal stresses on different layers of composite structure of a blade due to different thermal expansion coefficients and should be taken into account.

Specific combination of load cases addressing normal operating conditions and normal external conditions are taken into account according to below pattern for investigated wind turbine blade:

- Stand-by: Aerodynamic loads, weight, annual gust and changes in wind directions
- Start-up: Aerodynamic loads, weight, annual gust and angular acceleration effect
- Power production: Aerodynamic loads, weight, centrifugal forces arising from angular velocity of a blade, gyroscopic effect arising from Yaw movement of wind turbine, annual gust and changes in wind direction

- Normal shut down: Aerodynamic loads, weight, activation of mechanical brake, effect of angular acceleration of a blade and annual gust

Among all load cases, aerodynamic loading is the most important one from aeroelasticity point of view. Several researches have been devoted to develop appropriate methods of load extraction using advanced aerodynamic theories and simulation (Stewart 1976, Lupo 1982, Riziotis and Voutsinas 2000, Snel 2003, Hasegawa *et al.* 2004). The simple routine presented by GL rules and regulation (1999) is employed here to calculate mentioned load cases except aerodynamic loading which is obtained using aero dynamical finite element model (section 3.2). The details of calculation for each load case can be found in GL rules and regulations (1999). The most critical load cases are considered for each case and applied to the finite element model to study the response of the structure.

5. Wind flow characterization

The probability distribution function of the governing wind pattern in the wind farm is obtained using metrological data as below in the form of Weibull function (Shokrieh and Rafiee 2006)

$$h(v) = \left(\frac{1.425}{9.3206}\right)\left(\frac{v}{9.3206}\right)^{(0.425)} e^{-\left(\frac{v}{9.3206}\right)^{1.425}} \tag{1}$$

Where, V is a wind speed and $h(V)$ is the corresponding probability of occurrence.

From the mentioned wind speed interval in Table 3 for the power production event, both mode wind speed value (obtained from Weibull distribution) and rated power wind speed (inserted in Table 1) which are 5 and 15 m/s are selected, respectively.

For stand-by, start-up and normal shut-down, wind speeds of 3, 4 and 25 m/s are chosen, respectively.

The investigated blade is equipped with a pitch control system regulating produced power by rotating wind turbine blade along its length up to 89° in accordance with wind speed. Subsequently, the global status/position of blade with respect to general coordinate system is taken into account according to corresponding wind speed.

6. Aeroelastic study

In this research, static aeroelasticity is studied, i.e., interaction between aerodynamic forces and elastic forces is investigated (Hodges and Pierce 2002). In other word, the coupling between fluid and structural behavior is denoted as aeroelasticity phenomenon wherein the study of interaction between the deformation of an elastic structure in an airstream and resulting aerodynamic force is considered.

For aeroelastic simulation of investigated blade experiencing nonlinearity and large deformations, semi-coupled method is used (Hodges and Pierce 2002). Semi-coupled method is an iterative method wherein fluid and structural spaces are solved sequentially and data exchange is accomplished for deflections and pressure distributions. The flowchart of aeroelastic simulation is depicted in Fig. 4.

The modeling procedure consists of four different steps as model preparation, aerodynamic analysis, structural analysis and convergence study. Involved procedures for aeroelastic simulation are briefly outlined as below.

At the very first step of modeling, the preliminary geometry of investigated blade is used for aerodynamic analysis and deformed shape which will be obtained after structural analysis will be employed in the next steps.

Aerodynamic analysis is carried out using fluid solver of ANSYS for constructed aerodynamical finite element model. The pressure distribution on the nodes of finite element model is obtained as the output of this step. The obtained pressure on the nodes is converted to the structural loading which is required for the next step.

Obtained loadings from the preceding section are applied to the structural finite element model. For the structural boundary conditions, the root of the blade is fully restricted from any movements and rotations. Non-linear static analysis is performed to obtain deformed shape of blade at this stage.

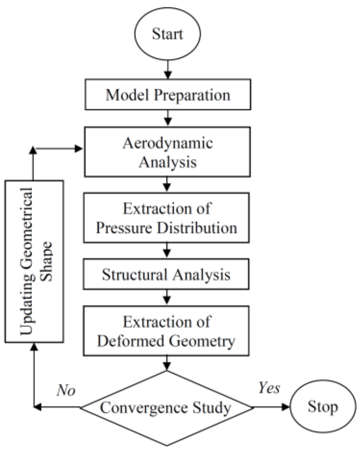


Fig. 4 Flowchart of aeroelastic simulation

The solution is converged whenever both deflection and applied pressure approach certain values and associated error is less than predefined values. If the convergence is not experienced, newly deflected geometry of the blade is considered for aerodynamic analysis. Namely, aerodynamical finite element model is constructed again relying on the deformed geometry and the whole explained process repeats till the convergence is met.

7. Results and discussion

Prior to aeroelastic simulation, a free vibration analysis is carried out to obtain natural frequencies of both flap-wise and edge-wise mode shapes. The obtained results are inserted in Table 4 in comparison with experimental data.

Table 4 Results of free vibrations analysis

	Flap-wise frequency (Hz)	Edge-wise frequency (Hz)
Finite element analysis	1.089	1.953
Experimental data	1.09	1.97
Error estimation	0.09%	0.8%

A very good agreement can be seen between obtained results and experimental data. This established our confidence toward the proper construction of finite element model. The variation in aerodynamic loading arisen from aeroelasticity phenomenon is reported in Fig. 5 for different events.

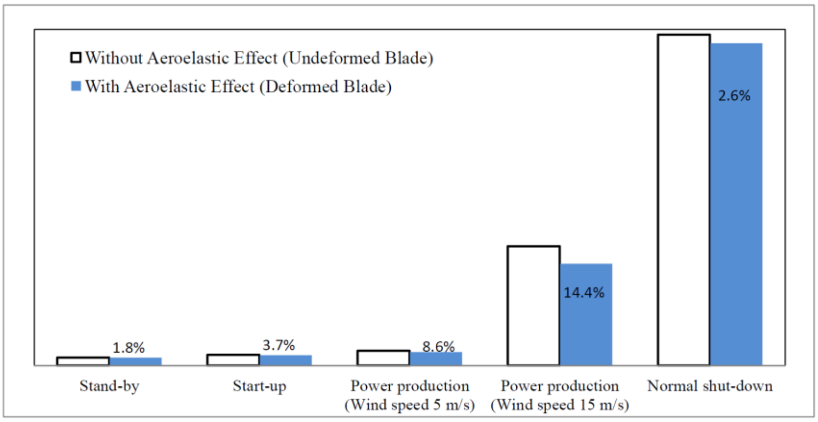


Fig. 5 Aerodynamic loading reduction due to static aeroelasticity

As it can be seen from Fig. 5, the maximum variation of aerodynamic load is associated with the power production event at the rated wind speed which will have a significant influence on the power production efficiency. Although the maximum wind speed is considered for the event of normal shut-down, the variation is less pronounced comparing to power production and start-up. This is originated from this fact that in this event the blade is rotated using pitch mechanism, thus total deflection of the blade will be reduced.

Considering all load cases introduced in preceding sections, the results of structural analyses of investigated blades are inserted in Table 5. It is worth mentioning that due to the pitch control system, the location of critical regions wherein maximum stress components are experienced varies for each event in accordance with global status of the blade.

Comparing obtained results in Table 5 with the results of blade static analysis without aeroelastic consideration (Shokrieh and Rafiee 2010) (i.e., rigid blade), it is revealed that static aeroelastic has a considerable influence not only on the tip deflection of the blade but also on the level of induced stress components in composite layers. Despite the reduction in global loadings, the level of induced stresses in some cases has been increased which is originated from the influence of blade deformed shape on unsymmetrical lay-up sequence of composite layers. The growth in induced stresses is pronounced when fatigue phenomenon is studied.

Comparing the tip deflections of the blade reflected in Table 5 with the results without aeroelastic coupling (Shokrieh and Rafiee 2010), it can be seen that the reduction of the blade tip deflection is between 0.8% and 3.3% with respect to the static analysis without considering aeroelastic phenomenon. The results show that blade deformation leads to a considerable change in the level of aerodynamic forces. This variation is related to the induced changes in the angle of attack.

Table 5 Maximum stresses and tip deflection of blade with and without aeroelastic coupling

Event	Tip Deflection [m]		Maximum Longitudinal Stress [MPa]		Maximum Transverse Stress [MPa]		Maximum In-plane Shear Stress [MPa]	
	A*	B**	A	B	A	B	A	B
Standby	1.22	1.23	503.2	520.1	12.2	13.6	19.7	21.3
Start-up	1.64	1.67	602.4	650.3	9.3	12.9	30.1	32.5
Power Production	2.88	2.94	693.2	705.3	14.6	15.8	28.1	29.2
Power Production	4.07	4.21	762.6	725.0	17.3	15.5	20.4	18.1
Shut-down	4.28	4.33	747.6	764.0	27.41	19.0	17.6	21.3

*A: results with aeroelastic coupling

**B: results without aeroelastic coupling (Shokrieh and Rafiee 2010)

8. Conclusions

A wind turbine blade is subjected to different loadings during its mission inducing some considerable changes to the preliminary geometry of the blade due to its very long and flexible structure. These variations will change the elastic and aerodynamic forces followed by variations in the imposed stress levels. In this study, static aeroelasticity on a composite wind turbine blade is investigated. A 3D finite element model of the blade is constructed. Loadings of the wind turbine blade are analyzed and applied to the finite element model. The deflected shape of the blade is obtained and applied loadings are updated in accordance with updated geometry of the blade. This procedure repeats until the convergence is met and final loadings are extracted accordingly. Four different normal operating conditions comprising of stand-by, start-up, power production and normal shut-down events are evaluated. It is revealed that for the event of power production at the rated wind speed, the static aeroelasticity will increase the applied loadings, significantly; while this effect is not considerable for normal shut-down and stand-by events. Due to the pitch mechanism employed in the power regulating system of the investigated wind turbine, the wind turbine blade is rotated along its length by changes of wind speed. This will reduce the total deflection of the wind turbine blades at very high wind speed from structural point of view. It results in less pronounced variations in aerodynamic and elastic loading attributed to static aeroelastic consideration. Since the level of induced stresses in the composite laminates of the blade increases due to static aeroelastic phenomenon, this should be taken into account during the design procedure of a wind turbine blade and especially when fatigue simulation is implemented.

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