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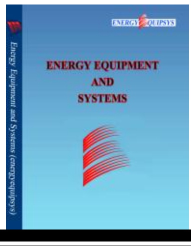

A robust engineering approach for wind turbine blade profile aeroelastic computation

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ABSTRACT

Wind turbines are important devices that extract clean energy from wind flow. The efficiency of wind turbines should be examined under various working conditions in order to estimate off-design performance. Numerous aerodynamic and structural research works have been carried out to compute aeroelastic effects on wind turbines. Most of them suffer from either the simplicity of the modelling approach or from the difficulty of the computing technique, which limits the practical applicability of the results. In this research, a robust approach is proposed to compute the aeroelastic behaviour of a horizontal axis wind turbine blade profile for conceptual design purposes. The simplicity and applicability of the approach are the significant points of the research work. Aerodynamic and elastic computations made using XFOIL and MATLAB PDE toolbox. Those tools are linked through an algorithm to interactively compute aeroelastic effects. A real measured time history of wind velocity is used as an input flow condition to simulate a real angle of attack for aeroelastic computation. Investigation of numerical output shows lift and drag coefficient values are lower compared to the corresponding values of the rigid profile. The study of modulus of elasticity value on the separation point location is also conducted, and the delayed stall is observed by decreasing the airfoil rigidity.

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1. Introduction

In recent decades, increasing industrial activities in the world have increased energy needs considerably, while sources of oil, coal and other fossil fuels have remained limited. On the other hand, environmental concerns have intensified efforts to use clean energy that is renewable and relatively cheap. Among the clean sources of energy, wind has attracted attention such that in the United States the annual capacity of power production from wind, by the end of 2012, was more than 6 GW. This value is estimated to be over 16 GW by 2020 [1]. Hence, numerous research studies have been carried out in order to use wind turbines more efficiently, especially related to the blades including blade material, structural analysis, aerodynamic analysis or other interdisciplinary subjects such as aeroelasticity. Aeroelastic analysis is an interdisciplinary field that is concerned with the interaction between the deformation of an elastic structure in airflow and the resulting aerodynamic forces [2]. The use of large wind turbines is becoming more common due to the demand for renewable energy in the 21st century. Aeroelastic effects are quite noticeable in large wind turbine blades, leading to considerable blade deflection resulting in performance degradation.

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Many approaches regarding the aeroelastic analysis of wind turbines blades can be found in the literature.

Chaviaropoulos has performed a linear analysis to study the aeroelastic stability of wind turbine blade sections. The effect of various parameters such as density and structural damping on instability has also been studied [3]. Zhao and Hu have studied aeroelastic analysis of a non-linear airfoil using a vortex lattice model. The goal of that study was to detect complex non-linear aeroelastic behaviour [4]. Maheri et al. have proposed a combined analytical/FEA-based coupled aero-structure simulation of a wind turbine with bend-twist adaptive blades. This method employs induced twist distribution and flap bending at the hub of the blade; predicted through an FEA-based simulation for a reference wind turbine run condition to determine wind turbine performance at other wind turbine run conditions [5]. Baxevanou et al. have introduced a new aeroelastic numerical model, which combines a Navier-Stokes CFD solver with an elastic model and two coupling schemes for the study of the aeroelastic behaviour of wind turbine blades undergoing classical flutter [6]. Ahlstorm showed that large blade deflections have a considerable effect on structural loads and generated power, and therefore must be considered in designing of slender turbines [7]. Streiner et al. implemented 3D CFD simulation results for aeroelastic stability computation of wind turbines. [8]. Deilmann proposed a design procedure for passively adaptive rotor blades containing aerodynamic simulation and optimization (based on BEM & FEM) and a correction loop for fluid-solid interaction [9]. Zhang and Huang [10] reviewed aeroelastic models and codes for wind turbines including the development of such codes for future applications. In the conceptual design of wind turbine blades, aeroelastic effects are often neglected despite their importance on large-scale turbines. The blade element method is normally used for initial design of wind turbine blades. In the BEM approach, airfoil aerodynamic characteristics are used to estimate blade aerodynamic performance. Therefore, it is important to have a quick and reasonable estimation of the aerodynamic characteristics of a blade profile, including aeroelastic effects. In most of the wind turbine aerodynamic computations either the aeroelastic effects are neglected or they suffer from technical difficulties and computing costs limiting the practical applicability of such computations.

In this research, an engineering robust approach is proposed to compute the aeroelastic behaviour of a horizontal axis wind turbine blade profile for conceptual design purposes. The simplicity and applicability of the approach taken are the significant points of the research work. In the present study, each iteration is divided into two steps. First, aerodynamic computations are conducted using XFOIL software. Computed viscous and normal stresses are then given to MATLAB PDE Toolbox. In the next step, elastic computations are performed using MATLAB PDE Toolbox to find the deformed shape of the airfoil due to aerodynamic forces, and finally, for the deformed airfoil, this cycle is repeated to obtain the desired parameters. The independent programs for the fluid and solid domains are coupled through an iterative approach; therefore, this is a weakly coupled approach.

XFOIL software has many advantages to be employed in this study. This freely available software, which is very popular in aeronautical applications, uses a combination of boundary layer equations and panel method for aerodynamic computations, making it very fast in comparison with CFD methods. XFOIL may also be used for inverse design of airfoils [11].

Nomenclature

Elasticity Modulus	E
Shear Modulus	G
Normal Stress, Source Strength	σ
Vortex Strength	γ
Shear Stress	τ
Poisson's ratio	ν
Body Force Matrix	$\underline{k}$
Displacement Vector	$\mathbf{u}$
Free Stream Velocity in x direction	u_∞
Free Stream Velocity in y direction	v_∞
Stream Function	ψ
Mechanical Properties Tensor	c

2. Governing equations

2.1 Aerodynamic computation

In aerodynamic computations, the domain is divided into a boundary layer region in which viscous effects are present, and an outer layer region, in which the viscous effects are neglected and potential flow and is solved using the panel method.

The panel method simulates geometry and flow around the airfoil using superposition of free stream, source elements with strength σ, and vortex elements with strength γ, as illustrated in Fig.1. N nodes on the airfoil surface and N_w nodes on the wake direction are set.

Source elements with constant strength are used on the airfoil surface and its end. Vortex elements with a linear distribution of strength are set on the airfoil surface [11]. It should be noted here that linear distribution of strength is more stable than constant distribution, and its results have less dependency on the panel setting [12].

The streamline of flow around the airfoil could therefore be determined using [11]:

$$\psi(x,y) = u_\infty y - v_\infty x + \frac{1}{2\pi}\int \gamma(s)\ln r(s;x,y)ds + \frac{1}{2\pi}\int \sigma(s)\theta(s;x,y)ds \quad (1)$$

where s is the component in the direction of element's planes, for a vector between a point on s and another point in (x,y) out of s, the magnitude and direction are denoted by r and θ respectively.

Equation 1 could be discretized such as Fig.1.

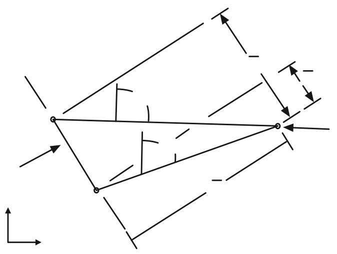


Fig.1 Source and vortex distribution on the airfoil and its end [11]

$$\psi(x,y) = u_\infty y - v_\infty x + \frac{1}{4\pi}\Sigma_{j=1}^{N+N_w-1}\psi_j^\sigma(x,y)2\sigma_j + \frac{1}{4\pi}\Sigma_{j=1}^{N-1}[\psi_j^{\gamma+}(x,y)(\gamma_{j+1}+\gamma_j) + \psi_j^{\gamma-}(x,y)(\gamma_{j+1}-\gamma_j)] + \frac{1}{4\pi}[\psi_N^\sigma(x,y)|\hat{s}\times\hat{t}| + \psi_N^{\gamma+}(x,y)|\hat{s}.\hat{t}|](\gamma_1-\gamma_N) \quad (2)$$

where

$$\psi_j^{\gamma+}(x,y) = \bar{x}_1\ln r_1 - \bar{x}_2\ln r_2 + \bar{x}_2 - \bar{x}_1 + \bar{y}(\theta_1-\theta_2) \quad (3)$$

$$\psi_j^\sigma(x,y) = \bar{x}_2\theta_2 - \bar{x}_1\theta_1 + \bar{y}\ln\frac{r_1}{r_2} \quad (4)$$

$$\psi_j^{\gamma-}(x,y) = \frac{1}{\bar{x}_1-\bar{x}_2}[(\bar{x}_1+\bar{x}_2)\psi_j^{\gamma+} + r_2^2\ln r_2 - r_1^2\ln r_1 + \frac{(\bar{x}_1^2-\bar{x}_2^2)}{2}] \quad (5)$$

Corresponding variables are defined in Fig. 2.

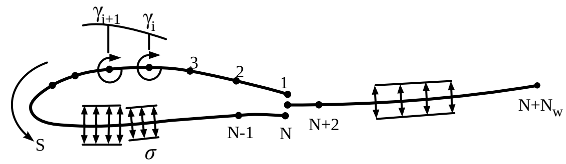


Fig. 2. Local coordinates of panel [11]

The flow field analysis is performed employing XFOIL [11]. For the viscous layer, standard momentum and shape factor equations are implemented as well as the e^n power method for transition point prediction [13].

2.2 Elastic computation

The span of the airfoil is long compared to its chord, so in elastic computation the spanwise strain is negligible. As a result, the plane strain condition is assumed as the governing equation. Hook's law for plane strain condition and strain-displacement relations are combined with the following force balance equations.

$$-\frac{\partial\sigma_x}{\partial x} - \frac{\partial\tau_{xy}}{\partial y} = K_x$$
$$-\frac{\partial\tau_{xy}}{\partial x} - \frac{\partial\sigma_y}{\partial y} = K_y \quad (6)$$

This combination yields an elliptic partial differential equation:

$$-\nabla.(\underline{\mathbf{c}}\otimes\nabla\underline{\mathbf{u}}) = \underline{\mathbf{k}} \quad (7)$$

where **u** is displacement vector, **k** is body force matrix and **c** is mechanical properties tensor, which could be represented by:

$$\underline{\mathbf{c}} = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix},$$
$$c_{11} = \begin{pmatrix} 0 & \mu \\ 0 & 0 \end{pmatrix}, c_{11} = \begin{pmatrix} 2G+\mu & 0 \\ 0 & G \end{pmatrix}$$
$$c_{21} = \begin{pmatrix} 0 & G \\ \mu & 0 \end{pmatrix}, c_{22} = \begin{pmatrix} G & 0 \\ 0 & 2G+\mu \end{pmatrix} \quad (8)$$

In the above relationship, G is the shear modulus, ν is Poisson's ratio and ν is given as

$$\mu = \frac{2G\nu}{1-2\nu}, \underline{\mathbf{k}} = \begin{pmatrix} K_x \\ K_y \end{pmatrix}.$$

In this step, **u** is computed with the finite element method using MATLAB PDE Toolbox.

3. Analysis procedure

In the present study the FFA-W3 airfoil, which is a typical blade section for horizontal axis wind turbines, is considered. The set-up of the planes on the airfoil for aerodynamic analysis is shown in Fig. 3. Two hundred panels are used, which are denser on the leading and trailing edges of the airfoil.

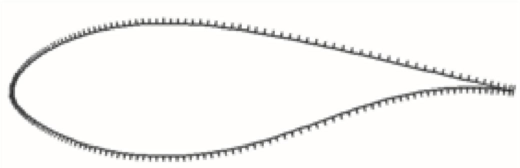


Fig. 3. Setting up the panels on the airfoil

A typical generated triangular mesh, which is implemented for the elasticity analysis of the blade section, is shown in Fig.4.
To set the boundary conditions, the spar position based on a real wind turbine blade profile is set to be fixed. This is a Dirichlet B.C., in which deflections are set to zero. Two Neumann B.C.s are also applied. One is set on the outer surface, which is exposed to airstream, and upon which shear stress and pressure distribution are applied, and the other Neumann B.C. is set on the remaining surfaces, which are free and not subjected to any surface tractions. Boundary conditions are shown in Fig.5.

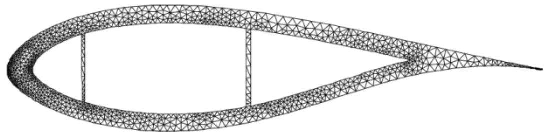


Fig. 4. Generated mesh inside the blade section

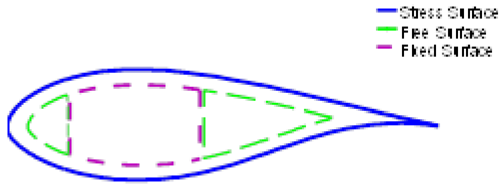


Fig. 5. Boundary conditions

Boundary conditions for fixed surfaces are **u** = 0, and for stress and free surfaces are $\mathbf{n}\otimes(\underline{\mathbf{c}}\otimes\nabla\mathbf{u})=\sigma$ and $\mathbf{n}\otimes(\underline{\mathbf{c}}\otimes\nabla\mathbf{u})=0$ respectively, in which **n** is outward normal vector of surface and σ is stress tensor. To begin the analysis, first XFOIL reads the airfoil coordinate from a file. After setting stream characteristics and panel generation, XFOIL computes pressure and shear stress distribution on the airfoil using the panel method and boundary layer equations. Geometry of the airfoil and stress distribution are then written in a file that is used by PDE toolbox as input to solve a plane strain problem using FEM. Elastic computations are carried out and the resulting shape is written in a file as input data for XFOIL again. This cycle is continued until displacement of the airfoil is converged to a specified range. XFOIL and PDE toolbox are linked through an algorithm written in MATLAB. The procedure described is shown in Fig.6.

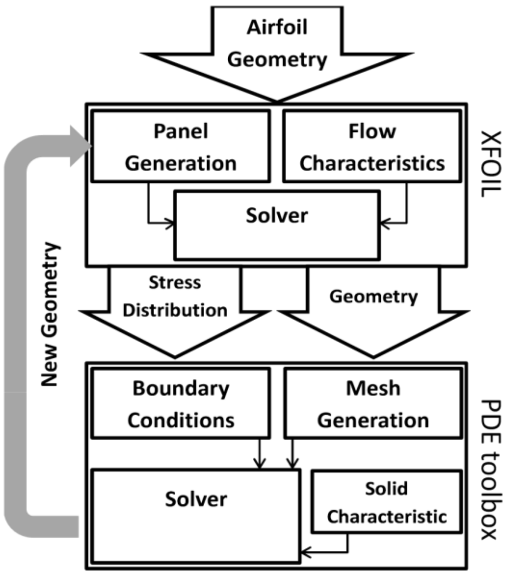


Fig. 6. The coupling algorithm diagram

4.Validation

To validate the numerical procedure, the work by Hoogedoorn et al. [14] has been repeated and a comparison has been conducted. A fully elastic NACA 0012, which is completely solid (with no hollow part), has been investigated. The airfoil's leading edge is set to have no displacement (Dirichlet B.C.) and the rest of the airfoil is exposed to surface traction (Neumann B.C.).

Lift and drag coefficient curves are plotted for rigid and flexible airfoil with E=1.2×105 Pa and Re=100,000. Figures 7 and 8 show good agreement for lift and drag coefficient curves between the current numerical procedure and the work done by Hoogedoorn et al. [14]. The change in lift curve slope is due to a transition of the flow regime predicted by XFOIL in Re = 100000. For the FFA-W3 airfoil studied in this paper, flow is assumed to be fully turbulent along the airfoil.

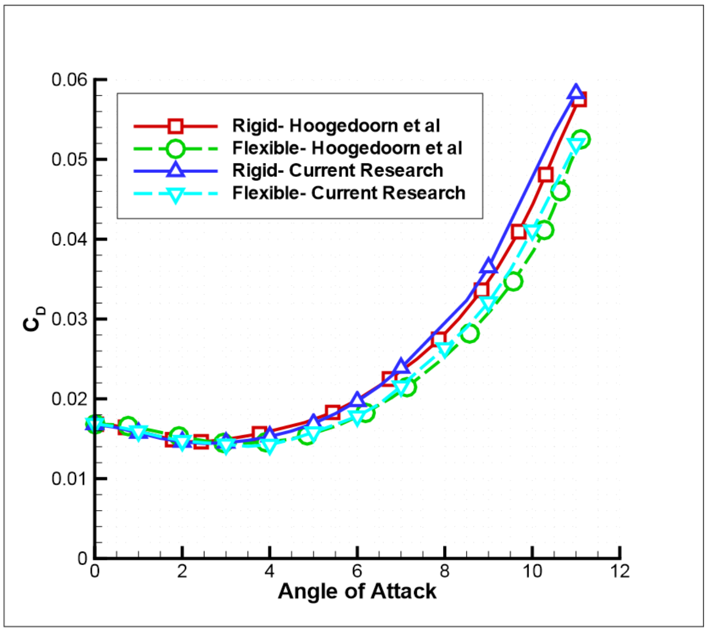


Fig. 7. Validation result for coefficient of drag

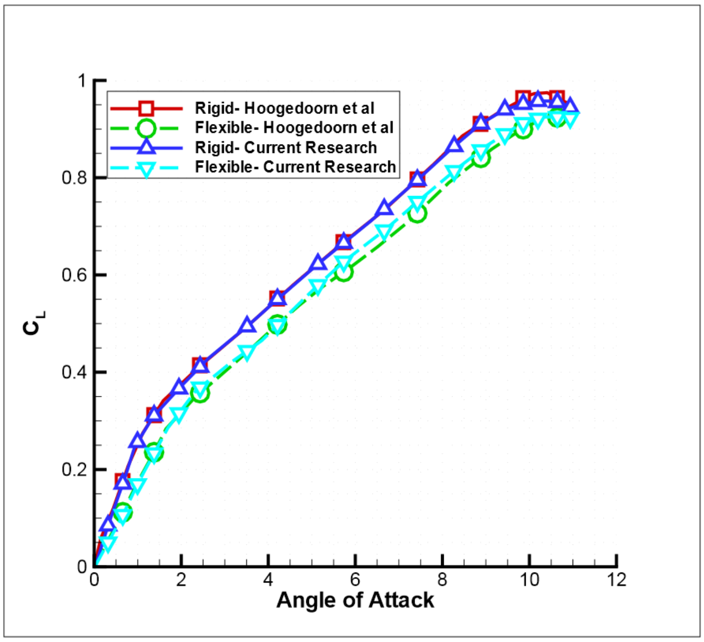


Fig. 8. Validation result for coefficient of lift

5. Results

The results shown here are for FFA-W3-241 airfoil with no body force and a Reynolds number of one million. The problem setup and boundary conditions were mentioned in detail in the analysis procedure section.

Airfoil aeroelastic computations are performed for various elasticity. Variation of the coefficients of lift and drag versus attack angle are sketched in Figs.9 and 10. Since the acting negative aerodynamic pitching moment noses down the airfoil, the angle of attack of the elastic airfoil decreases, resulting in lift and drag reduction. This effect is larger when a blade with a lower elastic modulus is used. Therefore, it is obvious that C_L (coefficient of lift) and C_D (coefficient of drag) in the flexible blade sections are lower than the rigid ones.

Figure 11 indicates the effect of rigidity on the location of the flow separation point. As is shown, changing the modulus of elasticity does not considerably change the separation point and consequently its wake width remains constant. Fig.12a shows typical wind velocity fluctuations measured experimentally using a turbine hub probe. As is shown in Fig. 12b, the fluctuations of the lift coefficient in rigid airfoil are much smaller than the elastic ones, since a smaller change in the angle of attack occurs.

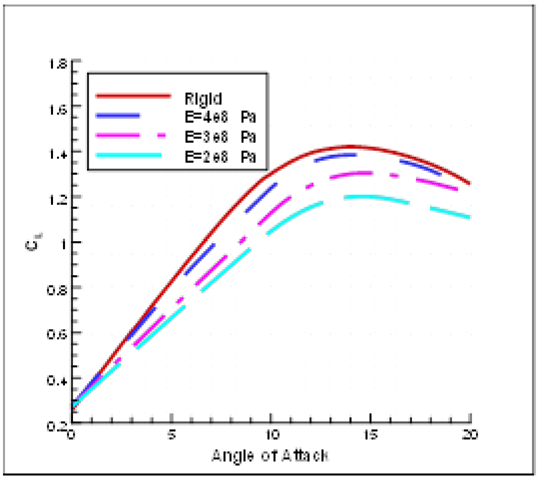


Fig. 9. Variation of coefficient of lift vs. attack angle

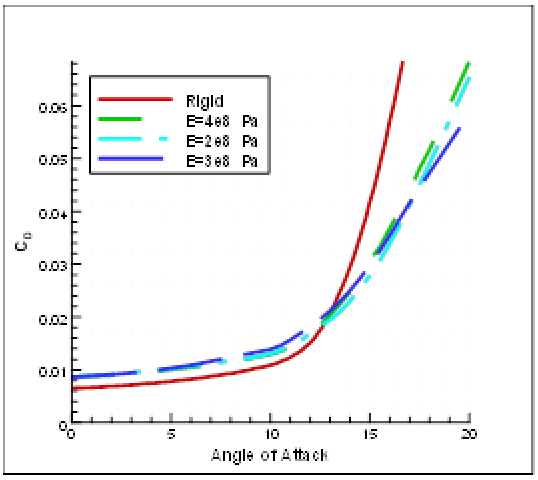


Fig. 10. Variation of coefficient of drag vs. attack angle

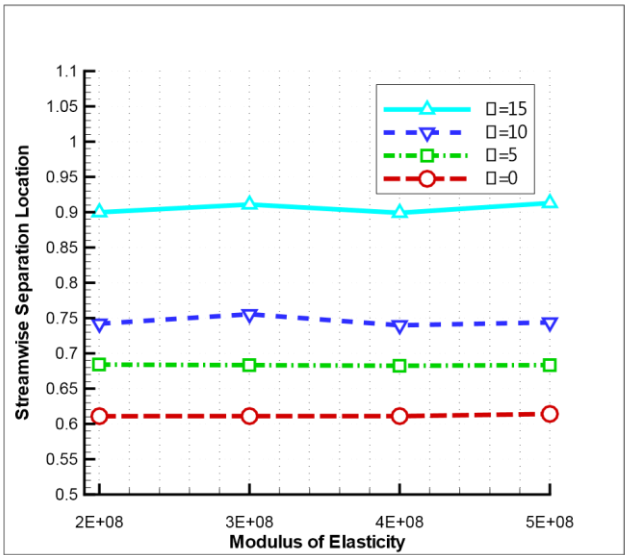
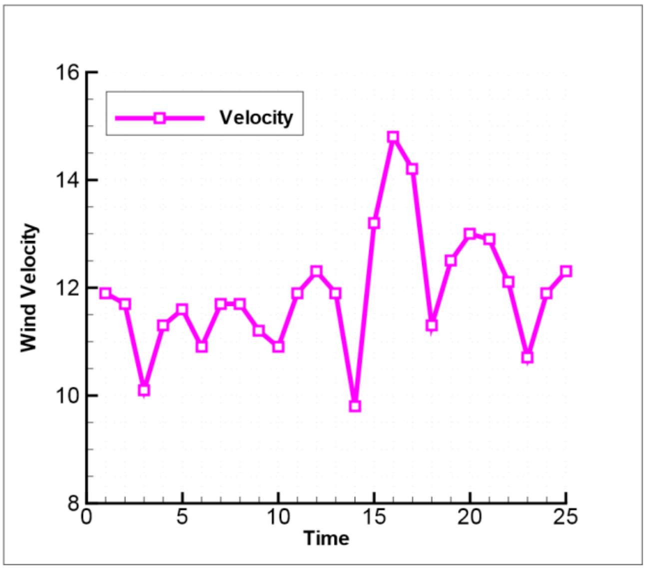


Fig. 11. Flow separation point location vs. modulus of elasticity



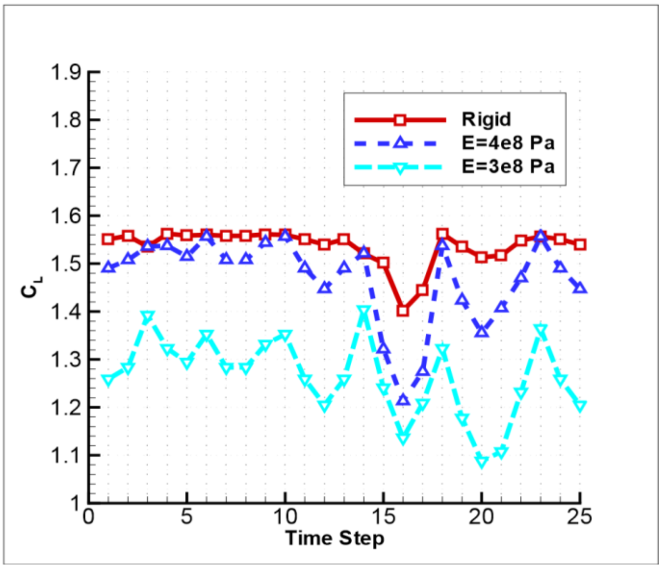


Fig. 12. Time history of velocity (a) and lift coefficient (b)

For a real wind turbine, incoming wind velocity is recorded every ten seconds. These data are used by wind turbine controllers to perform appropriate actions, such as the pitching of the blades. Considering those values and the rotational speed of wind turbines, the attack angle for the present blade section is determined, and consequently the history of the lift coefficient is computed for both rigid and elastic blades, and is sketched in Fig. 12. In the operation of a wind turbine, or when redesigning it, the controller must be updated with the aforementioned information.

There are wind turbines equipped with memory-based controllers, which use the wind turbine history data for better performance [15]. This is particularly important when flow conditions, such as air density, are changing due to a considerable temperature gradient or humidity of the flow in addition to wind velocity.

In redesigning such controllers for wind turbines with elastic blades, the study of the time history of wind velocity, and setting the appropriate, pitch angle are crucial in power output. Our presented study may be used to provide input data for such memory-based controllers.

6. Conclusion

In this study the aeroelastic behaviour of the FFA-W3, a typical blade section for HAWT was investigated. Computations were performed using XFOIL and MATLAB PDE Toolbox in an iterative procedure. According to the results, lift and drag coefficients for a flexible airfoil are lower than those of a rigid one. This is because, in situations of positive lift, the airfoil noses down and the local attack angle is thus decreased. Less fluctuation in power output is also expected for a rigid airfoil when there are oscillations in wind velocity. The variation of the separation point versus the modulus of the elasticity of the blade was studied briefly. Changing the modulus of elasticity does not have a noticeable influence on flow separation point location, and probably also on the resultant wake width.

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