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Evaluation study of a Navier–Stokes CFD aeroelastic model of wind turbine airfoils in classical flutter

C.A. Baxevanou [a], P.K. Chaviaropoulos [b], S.G. Voutsinas [c], N.S. Vlachos [a,*]

[a] *Department of Mechanical & Industrial Engineering, University of Thessaly, Athens Avenue, 38334 Volos, Greece*
[b] *Centre for Renewable Energy Sources, Pikermi Attikis, Greece*
[c] *Department of Mechanical Engineering, National Technical University of Athens, Greece*

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ABSTRACT

This paper describes 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. The basic characteristics of the aerodynamic and elastic models are presented together with the coupling schemes. The present model is evaluated by comparing with previous numerical results and the corresponding linear analytical solutions. Consequently, a parametric study is carried out. Conclusions are drawn about the ability of the model to handle the aeroelastic behaviour of an airfoil and about the most appropriate coupling scheme in terms of predicting the modal damping and the flutter limiting point. The present study shows that the predictions are only slightly affected by the coupling or the space discretization scheme and mainly by the turbulence model used.

1. Introduction

The interest in the study of the aeroelastic stability of wind turbines has been recently renewed when cracks were observed on wind turbine blades (Moeller, 1997). Linear analysis performed on rotating typical blade sections undergoing a coupled flap–lag motion has shown that cracks would appear as a result of negative aerodynamic damping in stalled flow conditions when low temperatures or material aging may have degraded the inherent structural damping (Chaviaropoulos,

* Corresponding author. Tel.: +30 24210 74094; fax: +30 24210 74085.
E-mail address: vlachos@mie.uth.gr (N.S. Vlachos).

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Nomenclature

Symbols

$(\cdot)^*$	chord scaling: $(\cdot)^* = (\cdot)/c$
$(\cdot)'$	reduced time derivatives
$(\bar{\ })$	denotes time averaging
$(\bullet)$	time derivative

Latin letters

ang0	initial angle of attack
ang_{eff}	effective angle of attack
$\vec{b}$	body force
C_i	aerodynamic coefficient ($i = L$ for lift, M for moment, D for drag, u for the flap driving force and w for the edge driving force)
c	airfoil chord
D	damping ratio ($D = P_r/\omega_0$)
D_i	structural damping coefficient
$F_{u,w}$	aerodynamic load
I	inertia tensor
k	stiffness coefficient
k	turbulence kinetic energy
k_R	roughness height
M	pitching moment
MD	modal damping ratio ($\text{MD} = -D/2\pi$)
m	airfoil mass per unit length
P_r, P_i	the real and imaginary part of the eigenvalues
p	the fluid pressure
$\bar{p}$	fluid pressure mean value
p'	fluctuating pressure value
p_0	initial pitch angle
R	airfoil radial position
Re	Reynolds number
R_f	mass ratio $R_f = \rho_{air}c^2/m$
$\bar{r}$	mass scaling (r/m)
$\overline{r^2}$	inertia mass scaling (I_p/m)
S_i	static moment about elastic axis
U	wind velocity
$\bar{U}$	non-dimensional wind speed
$\bar{u}$	fluid velocity mean value
u'	fluctuating velocity value
$\vec{u}$	fluid velocity vector
$\vec{u}_I$	airfoil surface velocity at point (ξ,ζ)
$\dot{\vec{u}}_I$	airfoil surface acceleration at point (ξ,ζ)
u, w	flap and edge displacements, respectively
V_i	i-component of input air stream velocity
y^+	non-dimensional distance from the wall ($y^+ = yu_\tau/\nu$)
u^*	friction velocity
u_τ	friction velocity

Greek letters

a	displacement vector
α	torsion angle
ε	turbulence dissipation rate
κ	reduced frequency $\kappa = \Omega c/\overline{U}$
μ	fluid viscosity
μ_t	turbulent viscosity
ν	kinematic fluid viscosity
(ξ,ζ)	sectional principal elastic axes
ξ_{Di}	non-dimensional structural damping coefficient $2\xi_{Di}\omega_i = D_i/m$
τ	reduced time ($= \overline{U}t/c$)
$\overset{\leftrightarrow}{\tau}$	viscous stress tensor
Ω	rotational speed $\dot{\theta}$
ω	specific dissipation rate
$\bar{\omega}_i$	uncoupled harmonic oscillation frequency $\bar{\omega}_i (= \omega_i/\Omega)$
ω_0	natural frequency $\left(\omega_0 = \sqrt{P_r^2 + P_i^2}\right)$

1999). In order to overcome this problem industry introduced stall strips to avoid negative aerodynamic damping (in spite of the penalty on the produced energy) and by revising the structural design in order to increase structural damping (Chaviaropoulos et al., 2004). However, because the available margins for design modifications are narrow, it became necessary to reconsider the aeroelastic problem in more detail on the basis of more accurate non-linear models so as to gain better understanding. In this connection viscous aerodynamic models have been introduced, classical and stall flutter problems have been considered at the level of wind turbine blade sections and results have been compared to linear theory (Dowell et al., 1995). Following the analysis in Chaviaropoulos (1999) the 3D flow conditions are mapped on typical sections and the flexibility of the blades is introduced by means of concentrated stiffness. Although such an approach deals with a