Energy 90 (2015) 1055–1065

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Experimental and Fluid Structure Interaction analysis of a morphing wind turbine rotor

David W. MacPhee [a,*], Asfaw Beyene [b]

[a] Department of Mechanical Engineering, The University of Alabama, Tuscaloosa, AL 35487, USA
[b] Department of Mechanical Engineering, San Diego State University, San Diego, CA 92182, USA

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
22 July 2015
Accepted 8 August 2015
Available online 28 August 2015

Keywords:
FSI
Morphing
Wind turbine
Flexible

ABSTRACT

Active control of blade pitch for wind turbines is known to increase efficiency, especially for part and over-load operation. An unfortunate consequence of this practice is added upfront and maintenance costs, making these schemes economically viable only in large scale applications. This study investigates a novel concept for wind turbine design, in which the blade is purposefully built of a flexible material which can passively adapt its geometry according to local wind conditions. This design concept therefore acts as a low cost, simplistic passive pitch control mechanism. Using a finite-volume fluid–structure interaction solver, the aeroelastic response of such a turbine is analyzed and compared to experimental data collected from wind tunnel tests as part of this project. The results indicate that the flexible rotor is markedly superior to a geometrically identical rigid one in terms of the size of its operational envelope as well as average and maximal torque production. Using post-processing tools, the performance improvements are attributed to passive deflection of the airfoil, which act to delay blade stall and drastically change surface pressure distribution to improve turbine performance.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Engineering systems are designed to operate optimally at a set point, often called the design point. For WEC (Wind Energy Conversion) systems, efficiency can drop drastically away from this point. As a result, handling of part and over-load wind conditions is a major issue for wind turbine designers. To mitigate efficiency drops during off-design operation, many WEC systems utilize blade pitching techniques which act to increase efficiency especially during operation in varying wind conditions. These schemes are almost universally active in nature, in that they require a feedback loop, motors and sensors to achieve the desired blade pitch at the desired wind and shaft speeds. Consequently, blade pitching comes with a significant added upfront cost, requiring increased maintenance and drawing a parasitic load on shaft power. Due to these costs, active pitch control is utilized only in large-scale settings, where power output justifies the increase in capital investment.

While pitch control is quite common for large turbines and has received much attention as of late (e.g. [1], and [2]), a relatively sparse amount of effort has been spent investigating passive pitch control schemes, which do not require actuators or sensors. Such passive schemes could have a substantial impact on the economic feasibility of WEC systems, especially those expecting highly variable winds.

Recent efforts ([3,4], and [5]) involving flexible or morphing turbine blades have shown that such passively deforming designs have the ability to increase aerodynamic lift, reduce drag and increase the lift to drag ratio for a wide range of Reynolds numbers and attack angles. Needing no sensors, actuators or control systems, these blades effectively act as a passive pitch control mechanism [6], augmenting both the attack angle and cross sectional geometry to increase power production at off-design loadings without a marked increase in system complexity.

To investigate the performance of such a morphing turbine blade, simulation and/or experimental measures are required. Computational efforts which attempt to resolve and couple both fluid and structural physics are dubbed FSI (Fluid Structure Interaction) simulations. Until relatively recently, wind turbines were small enough to not warrant transient, comprehensive FSI simulations due to the rigid design of rotors. These studies made use of, for example, blade-element momentum [7] and/or panel methods in the fluid, combined with FE (Finite Element) methods using simplified beam elements [8] in the solid.

* Corresponding author.
E-mail address: dwmacphee@ua.edu (D.W. MacPhee).

http://dx.doi.org/10.1016/j.energy.2015.08.016
0360-5442/© 2015 Elsevier Ltd. All rights reserved.

With the recent increase in available computing power, combined with the increase in complexity of WEC systems, more complex models (e.g., [9,10]) are becoming commonplace. These strategies can better predict the aeroelastic response and flow field behavior of much larger wind turbines [11] which can experience larger deflections due to increased inertial effects and higher wind speeds. Such models typically make use of the FE framework in both the fluid and solid domain, mainly due to a relatively sparse amount of solid mechanics progress in the FV (Finite Volume) community. Recent advances in FV solid mechanics [12] have increased the viability of FV FSI simulations, which are especially efficient in the fluid domain, where a multitude of turbulence models and solution schemes have been available for some time.

In this study, the aeroelastic response of a morphing horizontal axis wind turbine is studied both numerically and experimentally. Experimental tests are conducted using a large diameter wind tunnel, in which both a flexible and a geometrically identical (at zero load) rigid rotor are tested at various operational conditions. FSI simulations are conducted utilizing the OpenFOAM [13] software package, a FV toolbox capable of coupling fluid and solid domains in a strong fashion. This study builds upon previous works by the authors (e.g. [4], and [6]) by extending the numerical analysis to a fully three-dimensional, transient simulation. Experimental data concerning both flexible and rigid-bladed rotor torque is first used to validate the solver, after which differences in performance are highlighted through post-processing of results.

2. FSI modeling

The boundary value problem is shown in Fig. 1. This simplified domain description mimics the experimental setup, to be explained shortly, and consists of two domains, the fluid D_F and the solid D_S. Both domains are surrounded by various boundaries, denoted by Γ, where numerical conditions are applied. The FSI interface contains coincident but not necessarily identical fluid and solid boundaries, which are denoted by Γ_{F1} and Γ_{S1}, respectively.

The solid boundary Γ_{S2} denotes the area in which the flexible turbine is anchored to a static member, while Γ_{F2}, Γ_{F3} and Γ_{F4} represent the fluid inlet, wind tunnel walls and fluid outlet, respectively.

As previously mentioned, the FSI algorithm used herein makes use of the FV framework in both the solid and fluid domains, thanks to recent developments in solid modeling [12]. The model incorporates finite or nonlinear strain analysis in the solid, generic turbulence modeling in the fluid, and implements a time step size based on the maximum Courant number in the domain, which varies as the solution progresses.

The computational algorithm is laid out for a single time step in Fig. 2. Classified as a segregated solver, fluid and solid domains are handled separately, with an interface displacement convergence requirement enforced before time can be incremented and the solution can be progressed.

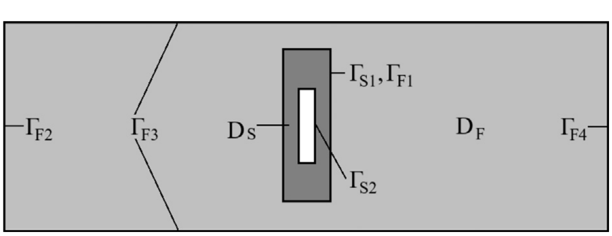

Fig. 1. Simplified description of the domains and boundaries, denoted by D and Γ, respectively, associated with the FSI problem.

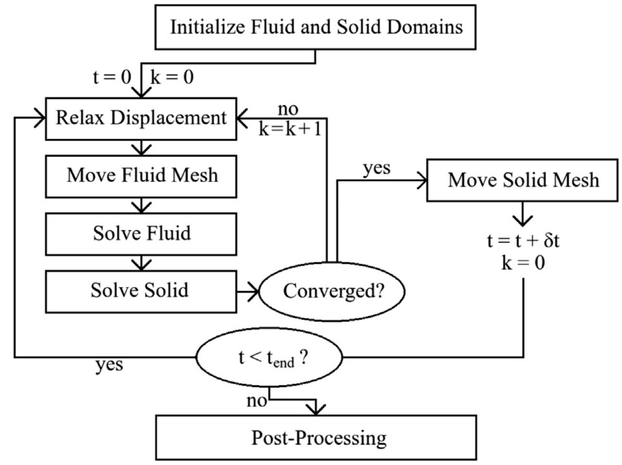

Fig. 2. Overview of FSI algorithm.

Due to the addition of the mesh motion solver, which handles interface deformation and allows for the fluid to be solved using the ALE (Arbitrary Lagrangian Eulerian) format [14], the algorithm essentially becomes a three solver system, requiring many iterations at each time step before convergence is reached. As such, the FSI algorithm is laid out in the following three sections, after which the interface convergence, displacement relaxation and solid mesh update procedures are discussed.

2.1. Fluid domain

Since the fluid/solid interface is free to move as the solution progresses, the fluid mesh must deform appropriately. To account for this mesh motion, fluid governing equations are cast in the ALE format, which describes continuum velocity u_i on a mesh moving at arbitrary velocity $\hat{u}_i$. This study makes use of Reynolds-averaged turbulence modeling, wherein the time-averaged continuum velocity $\overline{u}_i$ and pressure $\overline{p}$ are solved, in lieu of their instantaneous values. Assuming an incompressible, Newtonian fluid, the mass and momentum conservation equations can then be written as:

$$\frac{\partial}{\partial x_i}(\overline{u}_i - \hat{u}_i) = 0 \quad \text{in } D_F \tag{1}$$

$$\rho\left[\frac{d\overline{u}_j}{dt} + (\overline{u}_i - \hat{u}_i)\frac{\partial \overline{u}_j}{\partial x_i}\right] = -\frac{\partial \overline{p}}{\partial x_j} + \frac{\partial}{\partial x_i}\left[2\mu S_{ij} - \rho\overline{u_j' u_i'}\right] + \rho f_j \quad \text{in } D_F \tag{2}$$

where S_{ij} is the strain rate tensor. As is the typical for wind turbine analyses, simulations are conducted in a reference frame rotating at the turbine shaft speed, Ω, assumed constant. Then, the body force term in Eqn. (2) is written as:

$$f_i = 2\varepsilon_{ijk}\Omega_j u_k - \varepsilon_{ijk}\Omega_j \varepsilon_{klm}\Omega_l r_m \tag{3}$$

Here, the rightmost two terms represent the centrifugal and Coriolis forces and ε_{ijk} is the Levi-Civita symbol.

Using the Boussinesq assumption, the eddy viscosity μ_t and the turbulence kinetic energy k are introduced, which are linearly related to the Reynolds stress tensor $\rho\overline{u_j' u_i'}$:

$$\rho\overline{u_i' u_j'} = 2\mu_t\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{4}$$

The k-ω-SST ([15, 16]) is implemented in order to evaluate the Reynolds stress, through the introduction of another variable, the

Download English Version:

https://daneshyari.com/en/article/1731804

Download Persian Version:

https://daneshyari.com/article/1731804

Daneshyari.com