A New Computational Model for Fluid-Structure Interaction Phenomena in Wind-Turbine Blades

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ABSTRACT

In this paper, we shall introduce a new approach aimed to create a *Virtual Test Environment* where the aeroelastic dynamics of innovative prototype blades may be tested at realistic full-scale conditions, with a reasonable computational cost. It combines two advanced numerical models implemented in a parallel HPC supercomputer platform: A model of the dynamics of unsteady separated flows using Vorticity–Velocity Adaptive algorithms; and a model of the structural response of heterogeneous composite blades using Variational–Asymptotic Beam Sectional techniques.

Keywords: fluid-structure interaction, wind-turbine blades, vorticity-velocity methods, adaptive algorithms

INTRODUCTION

During the last two decades, there has been a spontaneous tendency in the wind-turbine industry to increase the size of the state-of-the-art machine. This tendency is driven by economies-of-scale factors that substantially reduce the cost of wind energy. Today, commercial models in the range from 3.6 to 6 MW, with rotor diameters up to 127 meters, are available from several manufacturers. The new technological challenge in wind power is to develop a next generation of feasible upscaled turbines of cheaper construction that may further reduce generation costs.

But limitations in the current blade technology constitute a technological barrier that needs to be broken in order to continue the improvement in wind-energy cost. Blade manufacturing is mostly based on composite laminates, which is labor-intensive and requires highly-qualified manpower. It constitutes a bottleneck to turbine upscaling that reflects into the increasing share of the cost of the rotor, within the total cost of the turbine, as turbine size increases. Moreover, while the rest of the wind turbine subsystems are highly developed technological products, the blades are unique; there is no other technological application that uses such a device. Thus, practical experience in blade manufacturing is relatively new, and changes in structural response due to the development of new designs, construction techniques, and/or the use of new materials represent a major factor to take into account if the development of a new prototype blade is considered.

Blades also operate under a complex combination of fluctuating loads, and huge size differences complicate extrapolation of experimental data from the wind-tunnel to the prototype scale. Hence, computer models of fluid-structure interaction phenomena are particularly relevant to the design and optimization of wind-turbines. The wind-turbine industry is increasingly using computer models for blade structural design and for the optimization of its aerodynamics. Nevertheless, many features of the complex interaction of physical processes that characterize the coupled aeroelastic problem still exceed the capacities of existing commercial simulation codes. The result is a very understandable tendency of the industry to be cautious in introducing changes in blade design and manufacturing technology, in order to ensure reliability.

Hence, a key factor for a breakthrough in wind turbine technology is to reduce the uncertainties related to blade dynamics, by the improvement of the quality of numerical simulations of the fluid-structure interaction process, and by a better understanding of the underlying physics. The goal is to provide the industry with a tool that helps them to introduce new technological solutions to improve the economics of blade design, manufacturing and transport logistics, without compromising reliability. In this paper, we shall introduce a new approach aimed to create a *Virtual Test Environment* where the aeroelastic dynamics of innovative prototype blades may be tested at realistic full-scale conditions, with a reasonable computational cost. It combines two advanced numerical models implemented in a parallel HPC supercomputer platform: A model of the dynamics of unsteady separated flows using Vorticity–Velocity Adaptive algorithms; and a model of the structural response of heterogeneous composite blades using Variational–Asymptotic Beam Sectional techniques.

1 THE KLE METHOD

The vorticity-velocity methods present several advantages compared with the classical velocity-pressure

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formulation (see [1]–[3], among others). We may single out the elimination of the pressure variable (which simplifies the study of incompressible flows on the inviscid limit and the treatment of boundary conditions at infinity in external flows) [2]; and also their intrinsic invariance against acceleration of the frame of reference [3]. The latter gives them flexibility to deal with complex body motions with translational and rotational components, making them particularly attractive to the analysis of rotor blades.

In reference [1], a novel procedure belonging to the $(\boldsymbol{\omega}, \boldsymbol{v})$ family was introduced. This procedure, called the KLE method, is characterized by a complete decoupling of the two variables in a vorticity-in-time/velocity-in-space split approach, thus reducing to three the number of unknowns to solve in the time integration process. This time-space splitting also favors the use of adaptive variable-stepsize/variable-order ODE algorithms, which enhances the efficiency and robustness of the time integration process. The KLE method solves the time evolution of the vorticity as an ordinary differential equation on each node of the spatial discretization. The input to evaluate the vorticity transport equation at each time-step is computed from the instantaneous velocity field. The latter is obtained by solving a linear PDE expression in weak form called the *Kinematic Laplacian Equation* (i.e. , the KLE), which is based on a modified version of the Poisson equation for the velocity. The input to solve the KLE is provided by the time integration of the vorticity at each time step. Thus, an evolving scheme is created in which the KLE provides the input for the ODE solver and vice-versa.

A detailed description of the numerical implementation of the KLE method for two-dimensional incompressible flows can be found in [1], including validation tests performed against analytical solutions and experimental data. Here, we shall see a brief outline of its mathematical basis. Starting from the well-known vector identity

$$\nabla^2 \boldsymbol{v} = \boldsymbol{\nabla} \cdot \boldsymbol{\nabla} \boldsymbol{v} = \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{v}) - \boldsymbol{\nabla} \times (\boldsymbol{\nabla} \times \boldsymbol{v}), \tag{1}$$

we found that a variational form of this "Laplacian" expression could be advantageously used as the spatial counterpart of the vorticity transport equation in a new type of vorticity-velocity method.

Let us consider the full three-dimensional incompressible Navier–Stokes equation in vorticity form for a flow domain Ω, with solid boundary $\partial\Omega$ and *external* boundary $\partial\Omega_\infty$ in the far field, in a moving frame of reference fixed to the solid,

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = -\boldsymbol{v} \cdot \boldsymbol{\nabla} \boldsymbol{\omega} + \nu \nabla^2 \boldsymbol{\omega} + \boldsymbol{\omega} \cdot \boldsymbol{\nabla} \boldsymbol{v}. \tag{2}$$

If we know the velocity field $\boldsymbol{v}$ in Ω at a certain instant of time, we can rewrite (2) as

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = -\boldsymbol{v} \cdot \boldsymbol{\nabla}(\boldsymbol{\nabla} \times \boldsymbol{v}) + \nu \nabla^2 (\boldsymbol{\nabla} \times \boldsymbol{v}) + (\boldsymbol{\nabla} \times \boldsymbol{v}) \cdot \boldsymbol{\nabla} \boldsymbol{v}, \tag{3}$$

and solve for $\boldsymbol{\omega}$ at each point of the discretization of Ω by integration of (3) using an ODE solver.

Now, let us revisit (1) but this time imposing a given distribution for the vorticity field and the rate of expansion:

$$\nabla^2 \boldsymbol{v} = \boldsymbol{\nabla} \mathcal{D} - \boldsymbol{\nabla} \times \boldsymbol{\omega}, \tag{4}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{v} = \mathcal{D}, \tag{5}$$

$$\boldsymbol{\nabla} \times \boldsymbol{v} = \boldsymbol{\omega}. \tag{6}$$

Here $\boldsymbol{\omega}$ is the vorticity field in Ω given by (3) and $\mathcal{D}$ is the corresponding rate of expansion (i.e. the divergence field). The KLE is essentially defined as a solution of (4) in its weak form under the simultaneous constraints (5) and (6).

For incompressible-flow cases, such as discussed here, $\mathcal{D}$ is simply set to zero. For compressible cases, $\mathcal{D}$ can be a general distribution given by a solution analogous to (3) but for the divergence transport equation (i.e. the momentum equation in divergence form), together with a solution of the mass transport equation.

Now, imposing the no-normal-flow condition and the no-slip condition on the solid boundary $\partial\Omega$, in a way compatible with the vorticity distribution at a certain time, we obtain a compatible solution for the instantaneous velocity field. From this velocity field we produce the right-hand side of (3) required to advance the time-integration process to the next step. This algorithmic sequence is repeatedly performed inside the time-iteration process commanded by an adaptive variable-stepsize ODE solver. The solution is checked by the adaptive stepsize control by monitoring of the local truncation error, which ensures the stability of the time-marching solution. We use a multistep variable-order Adams-Bashforth-Moulton predictor corrector (ABM-PC) solver with adaptive stepsize control. A big advantage of the ABM-PC and other multistep algorithms is that we can get a high order of accuracy with just a few evaluations of the right-hand side of the ODE system. This is achieved by reusing previously computed solution values, so they are also called "methods with memory" [4].

This higher efficiency of the adaptive-ODE time integration, plus the linearity of the KLE's spatial solution, result in an economy of computational effort compared to more classical velocity-pressure approaches. Additionally, the symmetric and positive-definite variational form associated to the KLE shows a substantial tolerance to discretization by unstructured meshes, which allows a more suitable meshing of complex geometries than structured-mesh approaches would permit. The generality of the KLE method allows for the use of different techniques for discretization in space and time. The first implementation of the KLE method made use of classical finite-element techniques for spatial discretization of the domain, which showed a very satisfactory agreement with the experimental measurements. Further refinement of the method would include a high-order implementation by spectral-element techniques

The KLE method was applied successfully to the study of the Strouhal-Reynolds number relationship for vortex streets [5], [6], to the analysis of vortex structures in the wake of oscillating cylinders [7], and as a basis of a vortex-identification technique [8]. An earlier version of the method was applied, in combination with vortex-lattice techniques, to the aerodynamic study of vertical-axis Darrieus wind turbines [9], and to the analysis of airfoils for Darrieus wind-turbine applications [10].

2 THE VABS TECHNIQUE

Even though blades are slender structures that may be studied as beams, they are usually not simple to model due to the inhomogeneous distribution of material properties and the complexity of their cross section. The *ad hoc* kinematic assumptions made in classical theories (like the Bernoulli or the standard Timoshenko approaches) may introduce significant errors, especially when the blade is vibrating with a wavelength shorter than its length. Complex blade geometry due to reasons of aerodynamic/mechanical design, new techniques of blade construction, and the use of new materials combine themselves to give a new dimension to the problem.

To make our fluid-structure interaction model capable of dealing with the complex features of new generation blades, we developed a code based on a somewhat modified implementation of the Variational-Asymptotic Beam Sectional (VABS) model. Proposed and developed by Prof. Hodges and his collaborators [11], [12], VABS is a model for curved and twisted composite beams that uses the same variables as classical Timoshenko beam theory, but the hypothesis of beam sections remaining planar after deformation is abandoned. Instead, the real warping of the deformed section is interpolated by a 2-D finite-element mesh and the strain energy is rewritten in terms of the classical 1-D Timoshenko's variables. The geometrical complexity of the blade section and/or its material inhomogeneousness are reduced into a stiffness matrix for the 1-D beam. The reduced 1-D strain energy is equivalent to the actual 3-D strain energy in an asymptotic sense. Elimination of the *ad hoc* kinematic assumptions produces a fully populated 6x6 symmetric matrix for the 1-D beam, with as many as 21 stiffnesses, instead of the six fundamental stiffnesses of the original Timoshenko theory [12]. That is why VABS is referred to as a *generalized Timoshenko theory*. Even for the case of large displacements and rotations of the beam sections, VABS allows for accurate modeling of the bending and transverse shear in two directions, extension and torsion of the blade structure as a 1-D finite-element problem. Thus, through VABS we are able to decouple a general 3-D nonlinear anisotropic elasticity problem into a linear, 2-D, cross-sectional analysis (that may be solved *a priori*), and a nonlinear, 1-D, beam analysis that is what we solve at each time step of the fluid-structure interaction analysis. The cross-sectional 2-D analysis (that may be performed in parallel for the many cross sections along the blade) calculates the 3-D warping functions asymptotically and finds the constitutive model for the 1-D nonlinear beam analysis of the blade. After one obtains the global deformation from the 1-D beam analysis, the original 3-D fields (displacements, stresses, and strains) at each time step can be recovered *a posteriori* using the already-calculated 3-D warping functions.

Detailed descriptions of the development of VABS can be found in [12]–[15], including validation tests for different cases of complex beams, and applications to helicopter and wind-turbine blades. Here, we shall see some recent results we have obtained applying our code to composite laminate wind-turbine blades [16].

To test our code, we designed a 50-meter long test blade using airfoil sections of the DU series. The DU airfoils were specially developed for wind turbine applications by researchers at Delft University, Netherlands [17], and are widely used by the wind-turbine industry. Constructive characteristics as thickness, and number and orientation of fiberglass layers for the different structural components of the blade section were selected following the examples included in [18], [19] for blades of similar size. The aerodynamic loads for these tests were computed using the modified Glauert model described in [20], Chapter 3, which was also used for the basic aerodynamic design of the blade geometry.

As an example, Fig. 1(a) shows one of the 2-D unstructured meshes used to discretize the blade sections: a blade section with DU-93-W-210 profile located at 60% of the span from the blade root. Figure 1(b) shows the Z_{11} component of the stress tensor, where index 1 indicates the radial direction along the span.

In order to couple KLE and VABS, we shall add the VABS equations for the 1-D finite-element dynamic structural problem to the general ODE system that solves the time evolution of the flow problem through the KLE approach. Then, the blade would be *cut* in *slices*, each one corresponding to a node on the 1-D structural mesh. Next, a *master* 2-D mesh for the flow around a generic airfoil section is mapped to the actual airfoil geometry on each slice along the span using conformal-mapping techniques, which preserve topological correspondence

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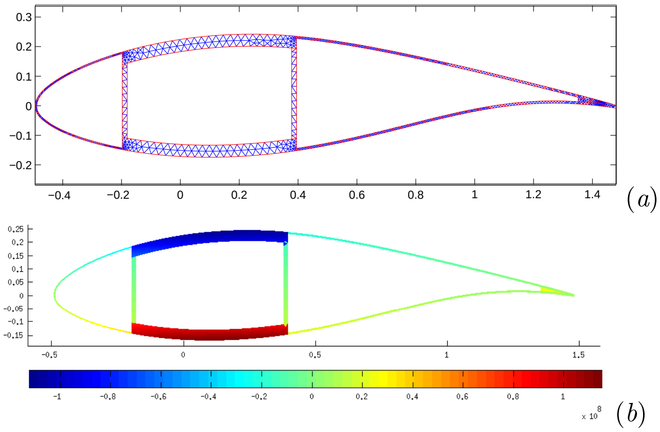

Figure 1: A blade section of DU-93-W-210 profile located at 60% of the span . Panel (a): 2-D finite-element unstructured mesh. Panel (b): component Z_{11} of the stress tensor.

on all the mapped meshes. Finally, the 3-D flow domain is constructed as an isoparametric-element mesh obtained by connecting the topologically-corresponding nodes on consecutive slices.

In an isoparametric-element mesh, the nodal coordinates are interpolated using the same functions than the variables to solve. This geometrical interpolation is used to compute the required Jacobians for each element. If each slice remains attached to a reference line drawn along the axis of the blade, and moves rigidly following the deformation computed by the VABS algorithm, the resulting displacement of the nodes due to twisting and bending of the blade provides the input for the automatic updating of the Jacobians in the isoparametric-element mesh for the flow problem. Thus, the KLE approach provides a natural way of integrating the structural dynamics into the general solving of the time-marching problem. This allows a simultaneous solution of both: the flow and the structural problem, in a process constantly controlled by the same self-adaptive ODE algorithm, improving the accuracy and efficiency of the time-integration.

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