

A COMPUTATIONALLY EFFICIENT AEROELASTIC MODEL OF WIND TURBINE BLADES INTEGRATED WITH A LATTICE BOLTZMANN METHOD SOLVER

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ABSTRACT

1. Introduction

The trend toward larger, more flexible wind turbines poses challenges for accurately and efficiently modeling their dynamic behavior. Full wind farm simulations require blade models that are both accurate and computationally inexpensive.

A key challenge lies in coupling structural dynamics with highly efficient fluid solvers, notably the Lattice Boltzmann Method (LBM) solver using an Actuator Line Method (ALM) [1]. The very efficiency of the LBM solver creates a new bottleneck, demanding an equally fast structural model to avoid negating its benefits.

This work addresses this challenge by developing a high-efficiency structural solver for wind turbine blades, purpose-built for integration into advanced aeroelastic frameworks. Unlike fully nonlinear beam solvers, the proposed approach prioritizes computational efficiency and is specifically tailored for tightly coupled aeroelastic simulations with massively parallel LBM-LES solvers. Based on the Rayleigh-Ritz method, it models the blade's dynamics, including non-uniform properties and rotational stiffening, using a minimal number of degrees of freedom while retaining the dominant blade dynamics, enabling efficient time-domain simulations. The primary objective of this work is to enable tightly coupled, time-domain aeroelastic simulations with a parallelized LBM-LES code by implementing a two-way iterative coupling with the low-cost structural solver.

2. Methodology

2.1. Structural Model

The structural model uses the Rayleigh-Ritz method, discretizing the continuous bending displacement $v(x, t)$ with a finite series of shape functions [2], with a set of n Bardell's polynomials [3] that satisfy the blade's clamped-free boundary conditions. The equations of motion are then derived from the resulting kinetic and potential energy expressions using Lagrange's equations [4].

$$v(x, t) \approx \sum_{i=1}^n N_i(x)q_i(t) = N(x)q(t)$$

The system's mass and stiffness matrices are derived from its kinetic and potential energies. Non-uniform blade properties are directly included through the spatially varying mass and stiffness distributions. Centrifugal stiffening effects due to rotation are incorporated via a linearized geometric stiffness matrix derived from the axial tension field [2]. Although the formulation is linear in the generalized coordinates, geometric nonlinear effects associated with centrifugal stiffening are therefore partially captured.

Modal decomposition is employed to compute the natural frequencies, mode shapes, and forced time-domain response efficiently.

$$(K - \omega^2 M)\Phi = 0$$

Solving this problem provides the natural frequencies (ω_j) and mode shapes (Φ_j).

This reduces the problem to solving the uncoupled SDOF equation for each modal coordinate $\eta_j(t)$:

$$\mu_{jj}\ddot{\eta}_j(t) + \beta_{jj}\dot{\eta}_j(t) + \kappa_{jj}\eta_j(t) = \phi_j(t)$$

where μ_{jj} , β_{jj} , and κ_{jj} are the modal mass, damping, and stiffness, respectively and ϕ_j is the modal force. This reduced-order formulation retains the dominant blade dynamics while minimizing the number of degrees of freedom, ensuring computational efficiency for tightly coupled aeroelastic simulations.

2.2. Aerodynamic Model

The structural model is developed with the goal to integrate with the Large Eddy Simulation framework based on the lattice Boltzmann method and the ALM presented in [1].

The LBM solves the Navier-Stokes equations by solving a transport equation for discrete velocity populations and can be implemented with extreme efficiency on massively parallel hardware.

Therefore it also requires an equally efficient structural solver.

3. Preliminary Results

The IEA 15-MW turbine model [5], implemented using six retained and six neglected Bardell shape functions, predicts the first flapwise and edgewise natural frequencies with low error relative to the reference values (Table 1). The first six mode shapes are shown in Figure 1.

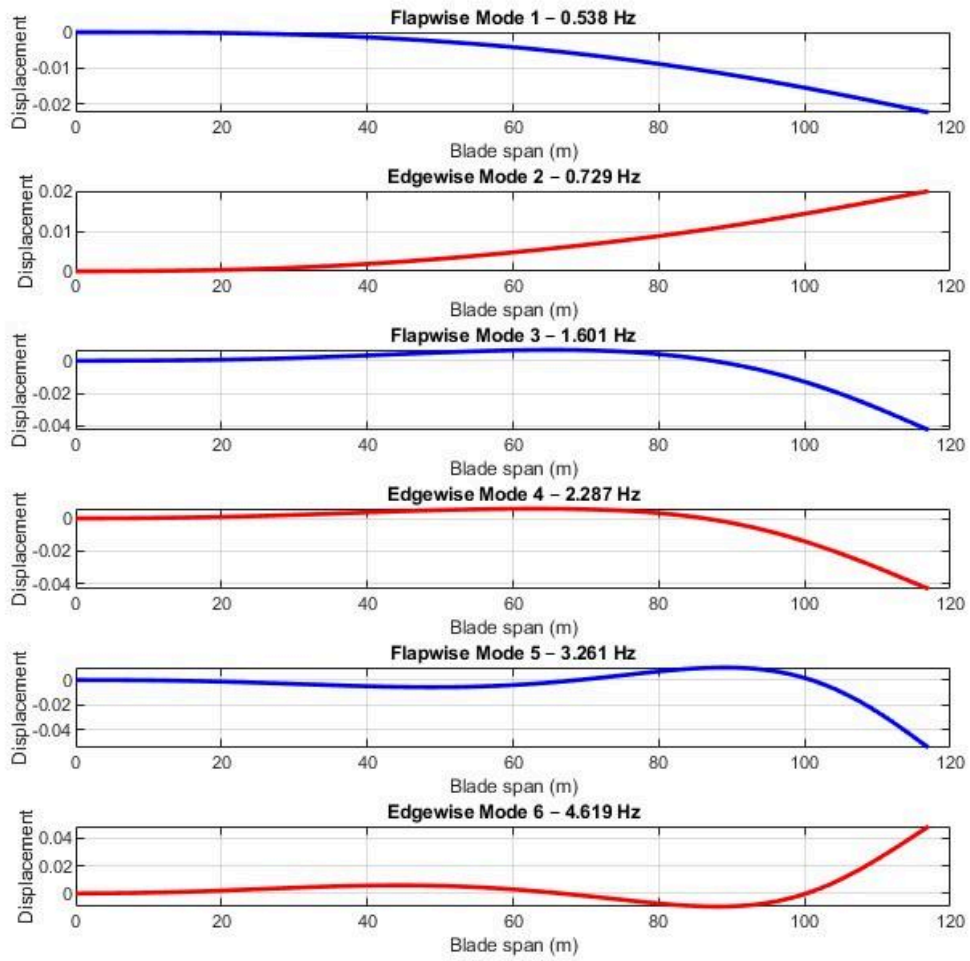


Figure 1: First 6 mode shapes.

Vibration Mode	Calculated	Reference	Relative Error
1st Flapwise	0.538	0.506	6.3%
1st Edgewise	0.729	0.693	5.2%

Table 1: Comparison of fundamental natural frequencies.

Finally, the model time-domain structural response was evaluated using externally generated aerodynamic forces obtained from large-eddy simulations of an IEA 15 MW wind farm reported by [6]. The blade tip deflection predicted by the proposed structural model was compared against OpenFAST results, and the corresponding time histories, shown in Figure 2, exhibit good agreement, confirming the consistency of the dynamic formulation and time integration.

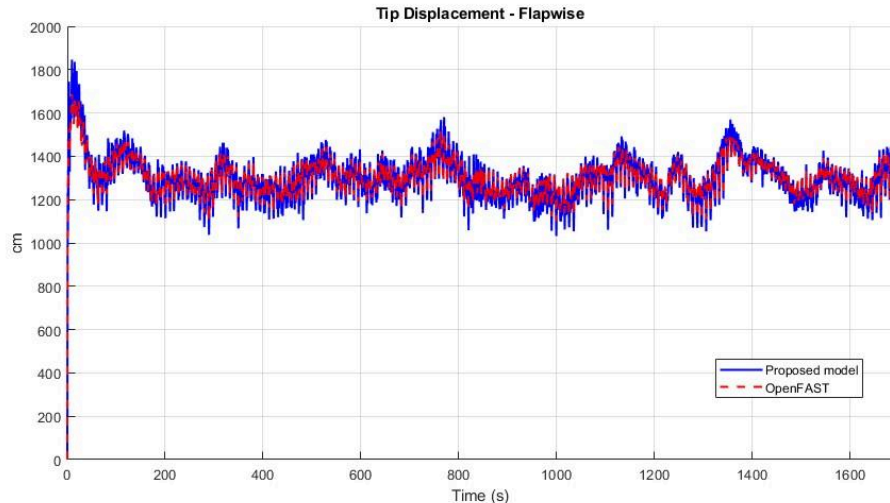


Figure 2: Comparison of blade tip deflection time histories: proposed model vs. OpenFAST.

4. Next Steps: Towards a Fully Coupled LBM-LES Aeroelastic Framework

The next phase of this research will focus on integrating the validated structural solver into the complete, two-way coupled LBM-ALM aeroelastic framework. This involves developing a lightweight two-way interface for aerodynamic load projection onto the modal basis and expanding the structural model to include torsional degrees of freedom for bend-twist coupling. The details of the method will be described in the final paper.

References

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