THREE-DIMENSIONAL LARGE DEFORMATION RECONSTRUCTION OF WIND TURBINE BLADES BASED ON STRAIN MEASUREMENT

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ABSTRACT

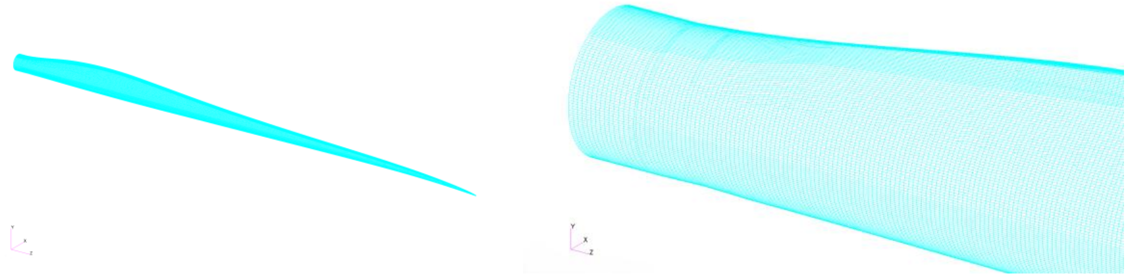
With the continuous increase in wind turbine capacity and blade size, wind turbine blades exhibit increasingly pronounced flexible responses under complex aerodynamic loading conditions. In recent years, several catastrophic accidents, including blade fracture and collapse events, have demonstrated that conventional deformation monitoring techniques—typically relying on sparse displacement measurements or linear assumptions—are no longer sufficient to meet the accuracy requirements of high-fidelity structural health monitoring. To address this challenge, this paper proposes a three-dimensional large-deformation reconstruction method for wind turbine blades based on strain measurement technology.

To overcome the constraints on sensor placement on blade surfaces, a sensor layout optimization method is developed by jointly considering reconstruction error and spatial distribution constraints. An improved genetic algorithm is employed to optimize sensor locations over the entire blade. By dynamically adjusting the crossover and mutation probabilities, the algorithm maintains a high crossover probability and low mutation probability at higher fitness levels, and a low crossover probability and high mutation probability at lower fitness levels, thereby achieving a better balance between global exploration and local convergence. The incorporation of elitist preservation and tournament selection strategies further enhances the convergence efficiency and robustness of the algorithm.

For deformation reconstruction, the blade geometry is mathematically represented using a central reference line and a series of beam-like cross sections, and a modal rotation method[1] is adopted to reconstruct the deformed configuration. Unlike conventional approaches based on modal displacements, the modal rotation method computes the spatial position of the reference line using modal rotation angles, enabling more effective treatment of geometric nonlinearities in complex structures. By introducing rotation matrices and piecewise interpolation strategies, the proposed method improves adaptability to large-deformation conditions while maintaining high computational efficiency.

Numerical simulation results demonstrate that the proposed sensor layout optimization method enhances measurement sensitivity while ensuring adequate spatial coverage of response information, effectively reducing deformation reconstruction errors. Under limited sensor conditions, the deformation reconstruction method accurately recovers the three-dimensional blade shapes under different operating conditions and exhibits strong robustness.

The proposed approach provides a theoretical basis for aeroelastic analysis and structural health monitoring of wind turbine blades, and has significant engineering value for ensuring the safe operation and lifetime prediction of large-scale wind turbines.



(a) Full blade model (b) Blade root detail

Fig 1 Finite element model of wind turbine blades

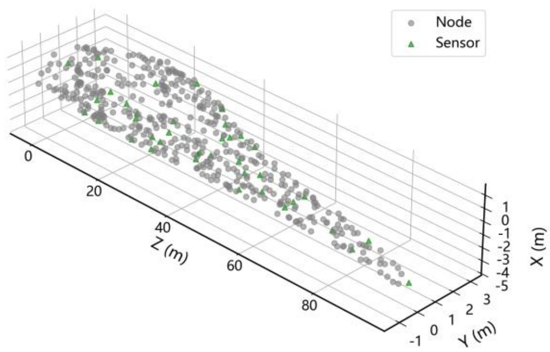


Fig 2 Optimal sensor network layout

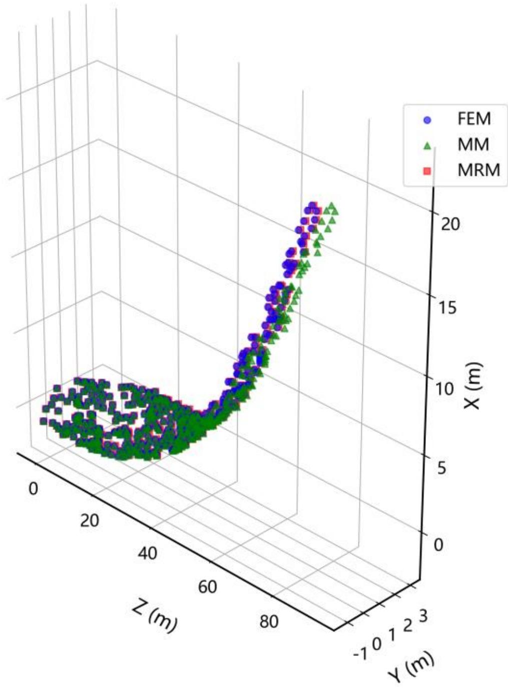
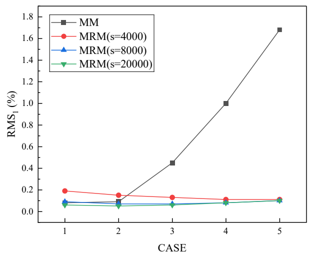
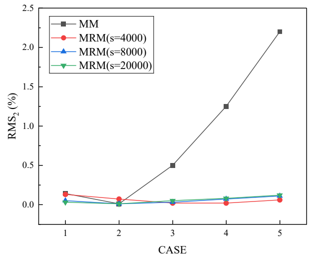


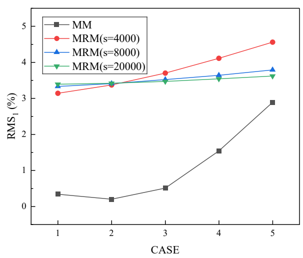
Fig 3 Three-dimensional deformation reconstruction results



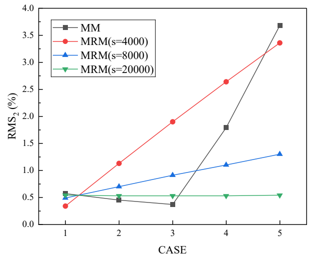
(a) Global deformation reconstruction error in the X-direction



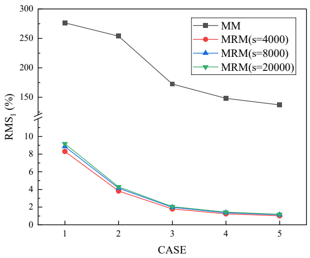
(b) Maximum deformation reconstruction error in the X-direction



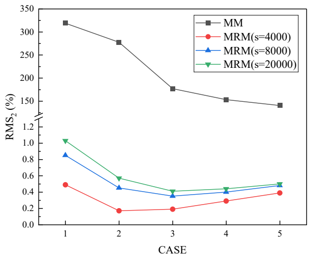
(c) Global deformation reconstruction error in the Y-direction



(d) Maximum deformation reconstruction error in the Y-direction



(e) Global deformation reconstruction error in the Z-direction



(f) Maximum deformation reconstruction error in the Z-direction

Fig 4 The accuracy of each method in different directions

REFERENCES

[1] Drachinsky A., Raveh D. E. Modal Rotations: A Modal-Based Method for Large Structural Deformations of Slender Bodies[J]. AIAA Journal, 2020,58(7): 3159-3173