Machine Learning based approach to predict the life of damaged wind turbine blade

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1. INTRODUCTION & OBJECTIVE

With the growing significance of wind energy in sustainable power generation, the ability to accurately predict damage in wind turbine systems has become a critical research focus. Recent advancements have highlighted the potential of machine learning techniques in addressing these challenges, particularly within the wind power sector. Several studies have demonstrated that artificial neural networks (ANNs) and other machine learning (ML) algorithms can effectively model the complex, nonlinear relationships governing turbine behavior and have shown promising results in predicting fatigue loads, remaining life in critical components, such as rotor blades [1-2]. This predictive capability is essential for improving structural reliability, reducing maintenance costs, and extending the operational lifespan of wind turbines. In this study, ML algorithms such as Support Vector Machine (SVM), Random Forest, and XGBoost were implemented to determine the remaining life of the blade in term of number of cycles.

2. METHODS OF ANALYSIS

A small-scale wind turbine blade (Air Silent X) is used to estimate the remaining fatigue life in terms of the number of cycles using ANSYS Workbench. To replicate typical damage observed in operational wind turbine blades, intentional defects such as cracks, surface erosion, and holes are introduced, representing common degradation mechanisms caused by lightning strikes, material failure, and environmental factors such as rain and severe weather conditions. The blade geometry is initially modeled in SolidWorks, and the effects of these anomalies are analyzed using a combination of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). Aerodynamic loads are obtained through CFD simulations conducted in ANSYS FLUENT 22R1, which solves the Reynolds-Averaged Navier–Stokes (RANS) equations closed by the k–ω SST turbulence model to achieve accurate results within practical computational limits. A one-way fluid–structure coupling strategy is adopted, where aerodynamic loads obtained from CFD are mapped as boundary conditions for the structural analysis in FEA. Crack defects are represented as semi-elliptical geometries using the fracture tool in ANSYS Mechanical, and the fatigue life in terms of the number of cycles is evaluated through SMART crack growth analysis. An automation script was developed in ANSYS to generate remaining life data, expressed in terms of the number of cycles, for various crack configurations on the wind turbine blade. This dataset was subsequently utilized for machine learning analysis.

3. RESULTS

A total of 6,500 data points representing the number of cycles were generated at different locations on the Air Silent X blade. For the purpose of this study, the problem is formulated as a classification task by discretizing the remaining life into predefined cycle ranges; for instance, a cycle range of 0–1000 is assigned the label "1." Figure 1 illustrates the distribution of the generated remaining life data across these ranges. Machine learning (ML) algorithms, including SVM Random Forest, and XGBoost, were employed to predict the remaining life in terms of the number of cycles. Among these, XGBoost and Random Forest demonstrated the highest predictive performance, achieving an accuracy of 77%. Figure 2 shows the comparison of these three ML algorithms

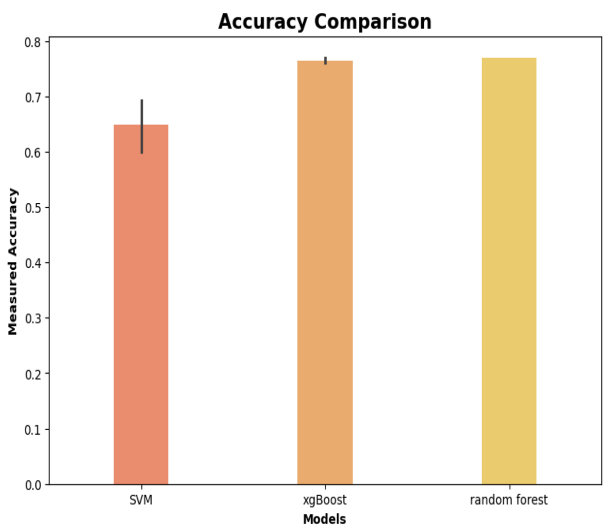

Figure 1 Comparison of ML algorithms

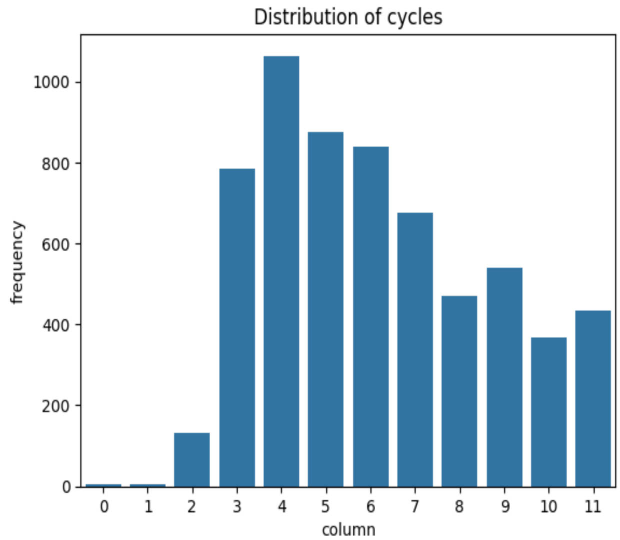

Figure 2 The distribution of remaining life of blade

4. CONCLUSION

This study demonstrated an integrated computational framework for predicting the remaining fatigue life of small-scale wind turbine blades with induced damage, combining CFD, FEA, and machine learning techniques. By introducing realistic defect scenarios, including cracks, erosion, and holes, and simulating aerodynamic loads through ANSYS FLUENT coupled with structural responses in ANSYS Mechanical, a comprehensive dataset of 6,500 life cycles was generated. The discretization of fatigue life into classification ranges enabled the application of machine learning algorithms for predictive modeling. Among the tested approaches, Random Forest and XGBoost achieved the highest accuracy of 77%, highlighting their effectiveness in capturing the nonlinear relationships between blade damage and fatigue life.

5. REFERENCES

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