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From Strain Measurements to Rotor Blade Shape and Loads Reconstruction: The BeSaME Project

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Abstract. The *BeSaME* (Helicopter Blade State and Loads Reconstruction Through Virtual Sensing for Health Monitoring and Performance Enhancement) project develops a virtual sensing framework for the real-time monitoring of helicopter rotor blades. Strain data from embedded fiber Bragg grating sensors are processed using inverse finite element methods and state estimation algorithms to reconstruct blade deformation and sectional loads. Aeroelastically scaled composite blades are manufactured and experimentally tested under static, dynamic, wind-tunnel, and rotating conditions, supported by a validated digital twin. The placement of the sensors is optimized to maximize the accuracy of reconstruction. Preliminary results show sub-percent shape estimation errors and load reconstruction errors below 5%.

Introduction

The *BeSaME* (Helicopter Blade State and Loads Reconstruction Through Virtual Sensing for Health Monitoring and Performance Enhancement) project aims to contribute to the ambitious ACARE SRIA and Flightpath 2050 targets—namely, an 80% reduction in rotor- craft accident rates and a 65% reduction in perceived noise emissions by 2050—by advancing structural health monitoring and performance optimization of helicopter rotors.

By leveraging fiber Bragg gratings (FBG), inverse finite element methods (IFEM), and augmented Kalman filtering, BeSaME seeks to deliver an experimentally validated real-time virtual sensing system capable of measuring axial and shear strains in rotating blades, reconstructing bending and torsional generalized strains, estimating blade shape, and inferring rotor states and aerodynamic loads under operational conditions.

The experimental program involves manufacturing aeroelastically scaled composite blades with embedded FBG sensors and intentionally introduced defects (delaminations, porosity) for damage-detection validation. Comprehensive testing includes static surveys, modal characterization under free and clamped conditions, aerodynamic and aeroelastic evaluation in a wind-tunnel, and trials on a rotating rig. Strain gauges and accelerometers provide cross- validation of optical sensor signals.

On the numerical side, a digital twin integrates detailed finite element structural models, multibody dynamics for full rotorcraft simulation, and comprehensive aeromechanics analysis to assess virtual sensor performance. Continuous model updating with experimental data ensures convergence and improves prediction fidelity.

The virtual sensing framework employs a hybrid strategy: inverse FEM for full-field deformation estimation, augmented Kalman filtering for spatially distributed load reconstruction, and neural networks for extracting critical load parameters and detecting anomalies indicative of damage. Sensor redundancy enhances resilience to individual failures while supporting accuracy validation with a minimal measurement network.

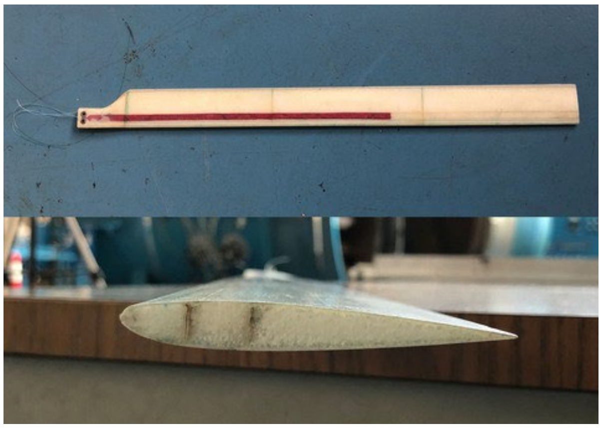

Figure 1: Example of blade specimen manufactured at POLIMI's technological lab.

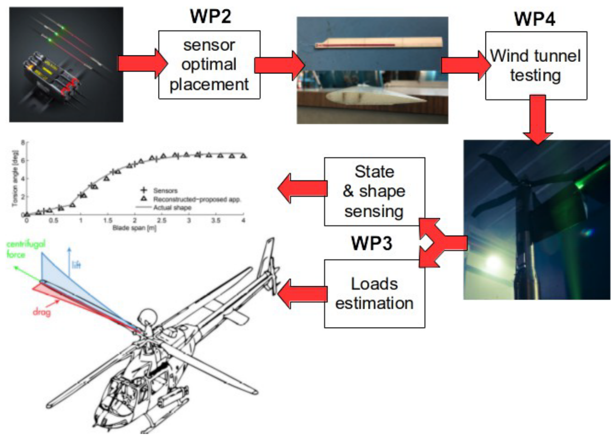

Figure 2: Block diagram of the project execution plan.

Expected outcomes include achieving TRL 5 (component/breadboard validation in relevant environment) for optical sensors in a rotating environment and TRL 4–5 (component/breadboard validation in laboratory or relevant environment) for virtual sensing algorithms, along with defining real-time and quasi-real-time metrics for blade health monitoring and control. The BeSaME system promises reduced maintenance costs, enhanced flight safety, and lower acoustic footprint, directly contributing to ACARE 2050 objectives and the Italian National Advanced Air Mobility (AAM) Strategic Plan.

The project, funded under the PRIN 2022 scheme and coordinated by Politecnico di Milano in collaboration with University Roma Tre, started in early 2025 and builds upon experience from earlier joint initiatives [1, 2, 3].

Shape and load sensing algorithm

The shape and load reconstruction approach is based on a modal method that leverages finite element analysis (FEA) to develop the blade monitoring algorithm. The algorithm consists of two main steps: first, the blade shape is reconstructed using a reduced set of eigenfunctions obtained from the FEM model; second, the loads are reconstructed using the computed displacement field along with the mass and stiffness matrices derived from the same model. Both shape and load reconstructions rely on strain measurements provided by FBG embedded sensors.

Preliminary analysis indicated that the algorithm is highly sensitive to sensor placement. Consequently, a bi-objective optimization is performed to determine the optimal sensor configuration, aiming to maximize reconstruction performance. The objective function combines the Fisher information factor and the conditioning of the reconstruction matrix. Figure 3 shows all the configurations obtained from the bi-objective optimizations, together with the corresponding Pareto front. The solution closest to the utopia point is selected as the optimal sensor layout.

The performance of the algorithm, based on the optimal sensor configuration, is evaluated using a three-dimensional beam model with an I-shaped cross-section. Reconstruction capabilities are assessed under both static and dynamic loading conditions chosen to reproduce the typical load

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states experienced by a rotor blade in flight. In all cases, the results are consistent and satisfactory. For dynamic loads, the most demanding scenario, the mean percentage error in reconstructing the displacement at the tip of the beam along the elastic axis is 0.27%. For load reconstruction, the maximum error observed for the in-plane load component is 4.37%. Figure 4 shows an example of the reconstructed load distribution, where the precision in reproducing the FEM reference data can be inferred.

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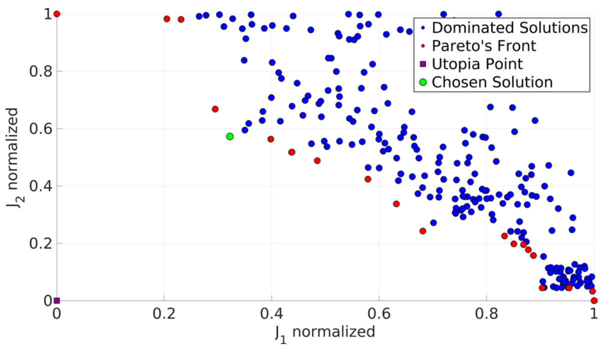

Figure 3: Optimal solutions from the bi-objective optimization, Pareto front, and selected optimal sensor configuration.

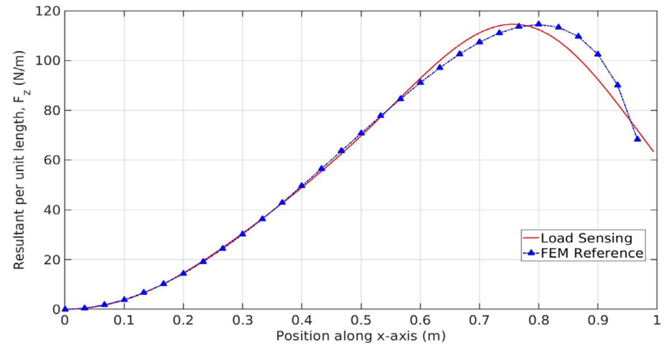

Figure 4: Comparison between reconstructed and FEM reference out-of-plane resultant per unit length.

Overall, the algorithm developed shows excellent capability to reconstruct the shape of the structure and good performance in identifying the section loads acting on it.

Blade manufacturing and testing

The current blade design is based on the one developed in [3], although minor modifications may be introduced to address issues and exploit improvement opportunities identified during the critical design review phase. The blade is constructed as a set of elements, each designed to perform a specific structural or functional role. The spar consists of two glass-reinforced unidirectional (UD) straps running along the entire span of the blade, with fibers oriented along the blade axis. These straps are designed to withstand axial forces from centrifugal loads and transfer them to the bearings around which the straps are wrapped. In the constant-section portion of the blade, each strap comprises four plies of 0.21 mm thickness, which split near the root to accommodate the bearings (Fig. 5).

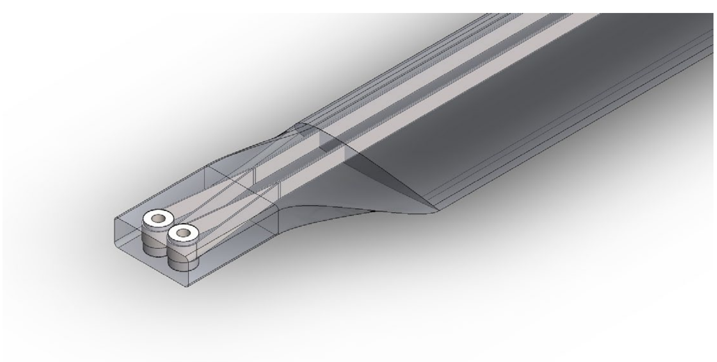

Figure 5: Detail of the root part of the blade, where straps split to wrap the bearings (adapted from [3]).

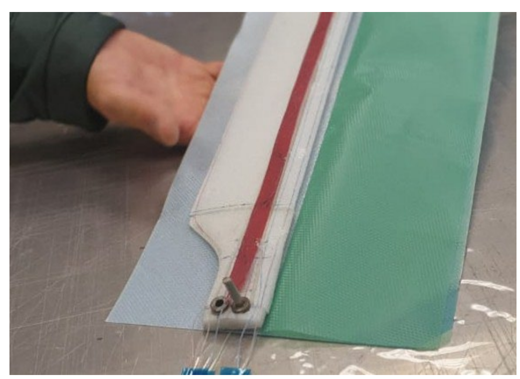

Figure 6: Final assembly of the blade (adapted from [3]).

Unlike more conventional designs, the ±45 deg wrapping that typically forms the torsional box is omitted to intentionally increase the blade's compliance and amplify torsional strains. A

Rohacell 51 WF polyurethane foam core provides the blade profile and the necessary support and pressure during manufacturing. The external skin consists of two plies of glass fabric, 0.12 mm thick, with fibers oriented at ±45 deg to ensure adequate torsional stiffness. A distinctive feature of this blade is the incorporation of two optical fibers that carry the torsion sensors. These fibers require special care to maintain proper orientation during assembly. To address this, an innovative technique called Quick-Pack (QP) is employed [4, 5]. The QP consists of a thin ribbon embedding a well-protected fiber optic along a predefined path (shown in red in Fig. 6). Its flexibility, enabled by the minimal thickness, allows it to adhere perfectly to curved surfaces, while the reinforced glass fiber protective layer ensures the integrity, functionality, and accurate orientation of the fiber optic.

Blade production involves three polymerization steps: fabrication of the UD straps, polymerization of the two QPs (one for the top and one for the bottom surface), and final curing of the external skins after assembly. Prior to polymerization, the Rohacell core is machined and the optical fibers positioned during assembly.

To evaluate the blade sensing capabilities under inertial and aerodynamic loads representative of a rotating rotor, a dedicated test rig is planned. It will feature a rigid mount for a pair of blades clamped at the root, with adjustable root pitch, actuated by an electric motor. Both blades will be instrumented, though limitations may exist in the number of optical channels that can be simultaneously acquired. This part of the project is currently under development.

Conclusions

The BeSaME project is developing a comprehensive framework for real-time virtual sensing of helicopter rotor blades, integrating fiber Bragg grating sensors, inverse finite element modeling, and augmented Kalman filtering. Preliminary numerical studies demonstrate excellent capability in reconstructing blade shape (sub-percent errors) and satisfactory performance in estimating sectional loads (errors below 5%).

The manufacturing and assembly of aeroelastically scaled composite blades with embedded sensors have been successfully designed, incorporating innovative techniques such as Quick-Pack for precise fiber placement. A dedicated test rig is currently under development to evaluate blade performance under representative inertial and aerodynamic loads.

Overall, the BeSaME framework shows strong potential to improve rotor blade health monitoring, support predictive maintenance, and enhance flight safety while reducing operational costs. Ongoing work will focus on experimental validation of the sensing algorithms, optimization of sensor networks, and extension to full rotorcraft systems.

Acknowledgements

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