INFLUENCE OF GEOMETRIC NONLINEARITIES ON INVERSE LOAD IDENTIFICATION FOR HELICOPTER ROTOR BLADES

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ABSTRACT

The validation of predicted load collectives experienced by structures throughout their service life is crucial from structural design and safety perspective. This is especially pronounced for helicopter rotor blades. In the design phase of rotor blades, load collectives can typically be determined by dynamic simulations that account for aeroelastic coupling using efficient, reduced modelling approaches. However, the accurate representation of complex aerodynamic phenomena, such as blade-wake and blade-vortex interaction, and nonlinear structural dynamics within the applied methodologies remains a significant challenge in current research. This results in the strong necessity to validate numerically determined load data. One promising approach for collecting the necessary validation data is operational in-flight monitoring. Operational in-flight monitoring not only enables the validation of aeroelastic models using real-world operational data, but also supports predictive maintenance, fatigue tracking, and damage detection within condition and usage monitoring systems [1].

Direct measurement of transient aerodynamic loads on rotor blades can be achieved using pressure sensors. However, installing pressure sensors on rotor blade profiles is often impractical due to installation complexity, limited sensor robustness, and maintenance challenges. Consequently, pressure sensors are generally unsuitable for in-flight monitoring applications, which require highly integrable sensors with minimal impact on operational performance and efficient data processing algorithms. An alternative approach well-suited for in-flight monitoring is to determine the aerodynamic loads acting on the rotor blade by solving the inverse problem. In this approach, also referred to as inverse load identification, the external forces are reconstructed from measured transient structural responses, such as deformations. These responses can be captured using highly integrable sensors, such as fibre Bragg gratings.

In literature, various approaches to inverse load identification have been explored and discussed. Physics-based approaches typically utilize modal superposition to expand the measured structural response in terms of the mode shapes, combined with either a deconvolution relation between the structural response and external forces based on impulse response functions [2], or an orthogonal decomposition of the external forces [3] [4]. Holzdeppe [5] developed the Inverse Williams Method (IWM), which separates external loads into quasi-static and dynamic components in analogy to Williams' principle [6]. This method demonstrates improved convergence for reconstructing external loads when only a small number of significantly excited eigenmodes are considered, compared to pure modal approaches. Lindert [7] applied the IWM to reconstruct aerodynamic loads on a helicopter rotor blade in flight, thereby confirming its applicability for load identification in rotor blade systems. Since physics-based approaches to load identification are generally ill-posed, numerous regularization techniques have been introduced that define additional constraints to render the problem well-posed [8]. In recent years, Bayesian methods, such as Kalman filters,

have become the subject of numerous publications due to their inherent regularization properties and their ability to account for model uncertainties [9] [10].

While numerous methodologies for inverse load identification have been published, research specifically addressing nonlinear systems remains limited. Existing approaches to load identification in nonlinear systems typically rely on linearization techniques or the use of Extended and Unscented Kalman filters [11]. No studies have yet been published that address the load identification for helicopter rotor blades while explicitly considering their inherent nonlinear structural behavior. Addressing this gap is essential for improving the accuracy and reliability of load identification methods applied to rotor blade structures.

The objective of this work is to numerically investigate the extent to which nonlinear structural behavior must be considered when applying the IWM to determine the external excitation forces acting on a helicopter rotor blade. The analysis focuses specifically on geometric nonlinearities, including large deformations and centrifugal stiffening due to the rotational speed of the rotor blade. Initially, dynamic aeroelastic simulations of a representative rotor blade in hover are performed using the PropCODE simulation tool [12]. Within PropCODE, aerodynamic loads are determined on the basis of an adapted Blade Element Theory (BET) in combination with a linear inflow model, while the structural behavior of the rotor blade is idealized using the nonlinear beam theory in a finite element approach. The mass, damping, and stiffness matrices generated by PropCODE, together with the simulated transient deformations of the rotor blade, serve as input for the IWM, which is implemented entirely in Python. While the dynamic, aeroelastic simulations take into account all geometric nonlinearities in structural behavior that can be modeled within PropCODE, the application of the inverse Williams method systematically investigates and evaluates how different nonlinear effects influence force reconstruction accuracy.

The investigation provides indications that geometric nonlinearities play an important role in reconstructing external aerodynamic loads. Within the framework of the IWM, their influence appears particularly relevant for the quasi-static force components. In contrast, effects on dynamic force components are only observed if significant changes occur in the mode shapes of the excited modes. This tendency can be explained by a Taylor series expansion of the reconstruction formula for dynamic forces: assuming high sampling rates and low structural damping, the dynamic force component primarily depends on mode shapes and remains largely independent of natural frequencies. Consequently, geometric nonlinearities substantially affect the reconstruction of the dynamic force components only when major changes in mode shapes arise.

Overall, these simulation-based findings suggest that geometric nonlinearities should be considered when applying load identification methods to reconstruct transient aerodynamic forces and moments acting on rotor blades during operation. Future work will be required to develop efficient approaches that enable their inclusion within this framework.

References

[1] S. Weber, T. Kissinger, E. Chehura, S. Staines, J. Barrington, k. Mullaney, L. Z. Fragonara, I. Petrunin, S. James, M. Lone and R. Tatam, "Application of fibre optic sensing systems to measure rotor blade structural dynamics," *Mechanical Systems and Signal Processing,* 2021.

[2] E. Jacquelin, A. Bennani und P. Hamelin , „Force reconstruction: analysis and regularization of a deconvolution problem," *Journal of Sound and Vibration,* 2003.

[3] S. Granger und L. Perotin, „An inverse method for the identification of a distributed random excitation acting on a vibrating structure part 1: Theory," *Mechanical Systems and Signal Processing,* 1999.

[4] K. Li, J. Liu, X. Han, X. Sun und C. Jiang, „A novel approach for distributed dynamic load reconstruction by space–time domain decoupling," *Journal of Sound and Vibration,* 2015.

[5] D. Holzdeppe, „Beitrag zur Versuchstechnischen Ermittlung der Instationären Aerodynamischen Belastungen eines Rotorblattes aus Messungen Mechanischer Reaktiones des Elastischen Systems," RWTH Aachen University, Aachen, 1986.

[6] D. Williams, „The Principles Underlying the Dynamic Stressing of Aeroplanes," *The Aeronautical Journal,* 1951.

[7] H.-W. Lindert, „Anwendung einer strukturmechanischen Methode zur Rekonstruktion der Luftkräfte am rotierenden Rotorblatt aus Windkanal- und Flugversuchen," RWTH Aachen University, Aachen, 1994.

[8] J. Sanchez und H. Benaroya, „Review of force reconstruction techniques," *Journal of Sound and Vibration,* 2014.

[9] R. Cumbo, T. Tamarozzi, P. Jiranek, W. Desmet und P. Masarate, „State and Force Estimation on a Rotating Helicopter Blade through a Kalman-Based Approach," *Sensors,* 2020.

[10] Y. Liu, L. Wang und B. F. Ng, „A hybrid model-data-driven framework for inverse load identification of interval structures based on physics-informed neural network and improved Kalman filter algorithm," *Applied Energy,* 2024.

[11] R. Liu, E. Dobriban, Z. Hou und K. Qian, „Dynamic Load Identification for Mechanical Systems: A Review," *Archives of Computational Methods in Engineering,* 2022.

[12] F. Möhren, „Structural Modelling and Design Strategies for Lifting Propellers," RWTH Aachen University, Aachen, 2025.