Abstract

Inspection and maintenance operations are essential for the long-term operation of current and future aircraft structures, ensuring health, safety, and optimal performance. Structural Health Monitoring (SHM) systems have facilitated real-time monitoring and condition-based maintenance solutions, resulting in improved inspection efficiency and safety, and lower cost and human effort. Despite widespread SHM research, practical adoption has been limited due to the complexity of industrial structures, influence of the operational environment, high sensor requirement, etc. Developing advanced monitoring strategies to address these challenges forms the central aim of the work done.

The developmental effort is centred on the inverse Finite Element Method (iFEM), a variationally-based shape sensing approach that solves the inverse problem of reconstructing structural displacements from measured surface strains. iFEM's inherent independence of the structure's material properties and loading conditions, combined with its accuracy and robustness in producing results using a sparse set of sensors, makes it an appealing solution for the displacement, strain, or stress monitoring of future aerospace vehicles. Both 1D iFEM, for beams and frames, and 2D iFEM, for plates and shells, have been proposed in literature. The present work focuses on further development of these existing formulations to bridge the gap towards their practical adoption.

The formulation of novel 1D inverse beam elements for analysing complex aerospace structures constitutes the primary part of the work done. The complexities modelled include an accurate treatment of transverse shear and torsional deformation for beams with any general cross-section. This is achieved by introducing certain shear coefficients and functions that reconcile the cross-sectional variation of transverse shear strain with classical 1D beam theories. Numerical and experimental validation of these novel beam elements is also presented, where accuracy, robustness, and practical feasibility are discussed. An additional novelty of the work done is the experimental investigation of additively manufactured beam specimens, constituting a first of its kind in shape sensing literature. The new beam elements developed are further adapted to model thin-walled beams undergoing cross-sectional warping, necessitating an update to the interpolation order of torsional rotation within an element. The element so-developed is also validated numerically.

This work also addresses certain key limitations of the 2D iFEM: the large number of sensors required and their optimal locations to generate accurate shape-sensing results. The proposed solution involves designing simple and easily reproducible strain-sensor patterns that guarantee stable and accurate iFEM predictions. These patterns are further coupled with virtual strain expansion strategies to reduce sensor quantity. The lessons learned from the above two approaches are subsequently used to develop an efficient iFEM-based damage detection strategy for SHM applications. As both 1D and 2D iFEM have been demonstrated to be effective monitoring strategies, work also focused on maximising their benefits and minimising their limitations by developing a Multi-Resolution monitoring approach. This concept marries the low cost (sensor and computational), low-fidelity results of the 1D iFEM with the high cost and high fidelity results of 2D iFEM to create an optimised monitoring framework. This new approach is demonstrated numerically for the damage detection of a complex wing box structure, revealing the 1D iFEM as an effective tool for damage detection and 2D iFEM for damage localisation.

The iFEM-based monitoring strategies developed in this work can also be instrumental for the operation of the next generation of shape morphing structures. This work also lays the foundation for this research by developing an iFEM-based closed-loop control architecture for monitoring and controlling morphing structures instrumented with a limited number of actuators and under the effect of unknown external loads.