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Shape sensing and load reconstruction for aerospace structures

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Summary

The in-flight monitoring of the loads and of the induced displacement field is becoming essential in the development of next generation Structural Health Monitoring framework. To achieve the crucial change from its traditional formulation, based on pre-emptive maintenance, to a new philosophy, based on pro-active condition-based maintenance, the monitoring of these characteristics is paramount. The continuous tracking of the loads and the displacements generates information on the real status of the structure and can guide more accurate maintenance and sustainment practices. Moreover, anomalies in the monitored characteristics can also lead to the identification of critical conditions including the detection of structural damage.

Another recent progress in the design of aerospace structures has increased the demand for a more accurate monitoring system for loads and displacements, the development of smart structures. These structures are designed to adapt to the condition that they are exposed to. Therefore, the knowledge of the actual condition, in terms of deformed shape and of loading condition, is fundamental for the correct activation of their morphing capabilities, that allow the structure to obtain load alleviation and a higher aerodynamic efficiency.

Unfortunately, the direct measure of these characteristics, that prove to be so crucial for the development of the future aerospace structures, is usually hard to obtain. For this reason, shape sensing and load reconstruction/identification methods have been developed in the open literature. These techniques are designed to compute the displacement and the loads from easily measurable discrete strains. This research aims to give an important contribution to the further development of the shape sensing and load reconstruction methods, in particular for the specific application on aerospace structures.

The most widespread shape sensing methods emerged in the last few years are the inverse Finite Element Method (iFEM), the Modal Method (MM) and the Ko's Displacement theory. Although a lot of effort has been recently involved in the formulation of these methods, a comprehensive study, that specifically includes the analysis of the effect of the strain sensing configuration on the performances of the methods is missing. In this work, the three methods have been numerically and experimentally tested on the displacement reconstruction of several structures, including a composite wing box, an aluminium swept wing box, an aluminium C-beam and an aluminium stiffened panel. For these analyses, the effect of the measurement error and of the number and location of the strain sensors have been widely investigated. The study has specifically focused on the optimization of the sensing technology for these methods. In particular, a more efficient approach to unequivocally determine the sensors locations for the iFEM quadrilateral elements has been introduced.

The comparative study shows the different scenarios that each method can be suitable for. The iFEM, also considering the introduced improvements, results as the most accurate shape sensing method for application, but a considerable amount of strain sensors is required to achieve this accuracy. The MM, on the other hand, is not able to reach the same level of accuracy, but can generate moderately accurate reconstruction of the displacements with fewer sensors. The Ko's Displacement theory, although can give a rough estimation of the deformed shape requiring very few sensors, is the less accurate of the three explored methods. Considering its impressive results, the iFEM has been selected for a further development and has been enriched with an incremental formulation for the analysis of structures undergoing large displacements.

The study on the load reconstruction methods has involved two different scenarios. The first one being the reconstruction of the internal loads, for the estimation of the fatigue life consumption, of a fighter aircraft's wing, whose physical characteristics were not provided. Only data of strain, loads and some flight parameters have been made available. For this problem data driven system identification methods have been explored. The recent progress in the field of these "black box" approaches has brought to life a vast amount of different model variants and formulations, with a broad landscape of functional parameters, that have never been explored under a single benchmark aircraft loads monitoring problem. For the application on the aircraft's wing, the investigation of this landscape of functional parameters for the linear regression based models and for the Artificial Neural Networks is considered. The broad exploration of these two families of system identification methods and of their functional parameters proves the superior capabilities of the ANNs with respect to the linear regression based models. Within the model variants of ANNs, the Distributed Delay architecture showed the best fatigue life consumption predictions.

The second scenario has concerned the identification of the external loads of a numerical aluminium swept wing box from discrete strain measurements. The loads have been computed using an existing approach, based on the discretization of the loads and on the computation of the coefficient of influence between the discretized loads and the discrete strain measurements. The discretization of distributed pressure fields is obtained using Finite Elements. In previous applications only triangular elements have been adopted, whereas, in this work, the method has been improved with the implementation of quadrilateral elements.

This activity has inspired the formulation of a novel and crucial tool for the progress of the monitoring systems analysed in this work. This is an innovative and integrated approach, able to simultaneously reconstruct the external loads and the displacement field of a structure from the same discrete strain measures. This 2-step approach uses the identified external loads to perform a standard FEM analysis and thus compute also the displacements of the structure. Therefore, the first step of the procedure includes the identification of the loads while the second one provides the application of these loads to the model of the structure to compute the displacement field. The method has been applied on the same structures analysed for the shape sensing campaign. The applications show that the 2-step procedure is able to simultaneously compute the external loads and the displacements with a remarkable accuracy, if a sufficient number of strain sensors are installed on the structure and they are not affected by significant measurement error. If the number of sensors is diminished or they are affected by measurement error, the first step of the procedure loses accuracy. Nevertheless, the method is still capable of impressive reconstruction of the deformed shape, making this a viable tool for the future of the aerospace structures monitoring.

Some of the research and results presented in this thesis have been published in:

A. Tessler, R. Roy, M. Esposito, C. Surace, and M. Gherlone. "Shape Sensing of Plate and Shell Structures Undergoing Large Displacements Using the Inverse Finite Element Method". In: *Shock and Vibration* 8076085 (2018).

M. Esposito and M. Gherlone. "Composite wing box deformed-shape reconstruction based on measured strains: Optimization and comparison of existing approaches". In: *Aerospace Science and Technology* 99 (2020).

M. Esposito and M. Gherlone. "Material and strain sensing uncertainties quantification for the shape sensing of a composite wing box". In: *Mechanical Systems and Signal Processing* 160 (2021).

M. Esposito, M. Gherlone, and P. Marzocca. "External loads identification and shape sensing on an aluminum wing box: An integrated approach". In: *Aerospace Science and Technology* 114 (2021).