Progress in Aerospace Sciences xxx (2018) 1–13

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Shape sensing methods: Review and experimental comparison on a wing-shaped plate

Marco Gherlone *, Priscilla Cerracchio, Massimiliano Mattone

Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

ARTICLE INFO

Keywords:
Shape sensing
inverse Finite Element Method
Experimental test
Surface strains

ABSTRACT

Shape sensing, i.e., the reconstruction of the displacement field of a structure from some discrete surface strain measurements, is a fundamental capability for the structural health management of critical components. In this paper, a review of the shape sensing methodologies available in the open literature and of the different applications is provided. Then, for the first time, an experimental comparative study is presented among the main approaches in order to highlight their relative merits in presence of uncertainties affecting real applications. These approaches are, namely, the inverse Finite Element Method, the Modal Method and Ko's Displacement Theory. A brief description of these methods is followed by the presentation of the experimental test results. A cantilevered, wing-shaped aluminum plate is let deform under its own weight, leading to bending and twisting. Using the experimental strain measurements as input data, the deflection field of the plate is reconstructed using the three aforementioned approaches and compared with the actual measured deflection. The inverse Finite Element Method is proven to be slightly more accurate and particularly attractive because it is versatile with respect to the boundary conditions and it does not require any information about material properties and loading conditions.

1. Introduction: a literature review

In the past few decades, increasing economical ad research efforts have been put into the development of *shape sensing* techniques, which enable the real-time evaluation of the displacement field from discrete strain measurements. The goal is the real-time evaluation of the strain and stress fields from the displacement field, which can be used by structural health monitoring systems or can be stored as usage data [1–4]. The principal benefits are an increased safety and a more cost-efficient maintenance. In fact, the knowledge of the actual structural health state can allow a more accurate failure prediction and less maintenance to be performed based on actual data. Shape sensing is particularly important when applied loads are difficult to determine or measure, as for aerodynamic forces, vibrating excitations transmitted through junctions or impact loads.

Real-time shape sensing techniques play also a key role in the development of smart structures, such as those with morphing capabilities or structures with embedded antenna arrays that need feedback for actuation and control systems [5–7]. In addition, monitoring of the deformed shape is a vital aspect for control of large deployable frame structures that carry antennas [8–10]. For this kind of structures, accurate on-orbit shape estimation is required in order to increase communication quality.

For practical uses, shape sensing algorithms are almost exclusively based on strain measurements, as accurate and lightweight strain sensors are available in commerce, particularly Fiber Bragg Grating (FBG) sensors. The capability of using bonded or embedded FBG based strain sensing systems has been proved for monitoring airplane wings [11], spatial frame structures [8,12] and composite structures [13]. Traditional strain gauges are still employed in laboratory tests as their acquisition systems are simpler and less expensive. Very few works have been proposed in the literature, which make use of displacements or accelerations measured at a limited number of points [14–16].

As for the algorithms, a shape sensing methodology should be computationally fast, robust with respect to inherent errors in the strain measurements and general enough to model complex structural topologies under a wide range of loadings, boundary conditions, material systems and inertial/damping characteristics. Moreover, it is preferable that loading and/or material data are not required, especially if stress are not going to be evaluated, as these kind of information is difficult to obtain precisely outside of a laboratory environment.

Existing methodologies can mainly be grouped in the following four

* Corresponding author.
E-mail address: marco.gherlone@polito.it (M. Gherlone).

https://doi.org/10.1016/j.paerosci.2018.04.001
Received 22 December 2017; Received in revised form 23 March 2018; Accepted 1 April 2018
Available online xxxx
0376-0421/

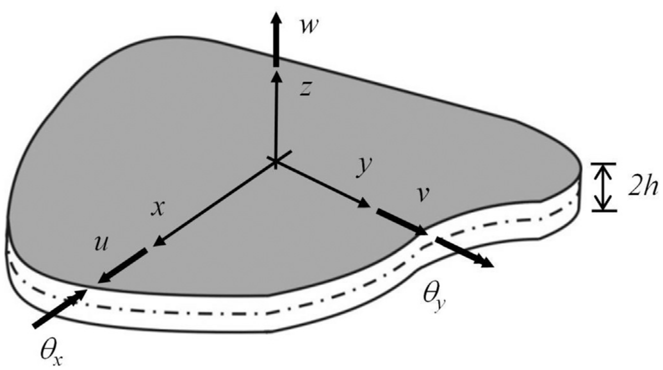

Fig. 1. Plate notation.

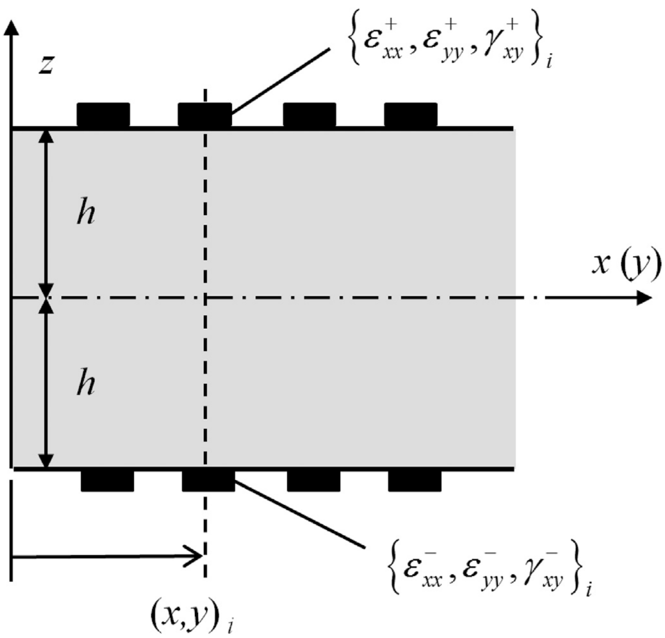

Fig. 2. Strain gauge instrumentation.

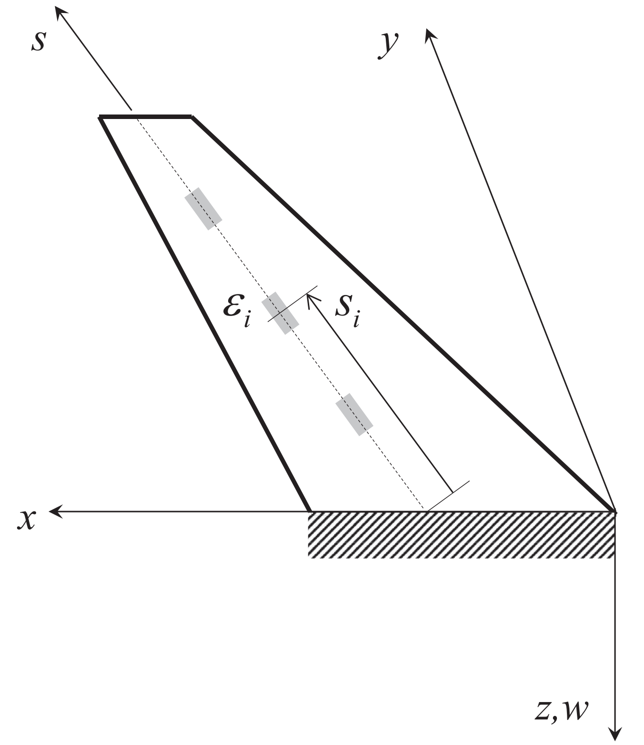

Fig. 3. Wing-shaped plate referred to the Cartesian coordinate system (x,y,z). (N+1) strain sensors are aligned along a measurement line (referred to the coordinate s) and provide axial strains ε_i.

categories: (1) methods based on the numerical integration of experimental strains; (2) methods using global or piecewise continuous basis functions to approximate the displacement field; (3) methods employing Neural Networks (NN); and (4) methods based on a finite-element discrete variational principle. Very few examples of approaches obtained combining different methodologies can be found.

1.1. Methods based on integration of experimental strains

Most of the works which perform the integration of discretely measured strains, deal with beam problems and are founded on classical beam equations [5,11,17–21].

A remarkable effort has been performed by Ko and co-workers in developing and assessing a shape sensing strategy referred to as Ko's Displacement Theory and applicable to beams, wing-boxes and plates [11,17–20]. In Ref. [17] the key idea is proposed, i.e., the reconstruction of the deflection of a beam-like structure from double integration of axial strains measured by sensors (strain gages, optical fibers) aligned on a "sensing line" with a known distance from the neutral axis. For pure bending and sufficiently slender structures, classical Bernoulli-Euler assumptions are adopted. Transverse-shear induced additional deflection can be evaluated by knowing the shear force distribution along the axis of the structure. Similarly to bending deflection, it is possible to reconstruct the cross-section twist angle due to torsion by using strain gages oriented along the 45°-helical (principal) direction. Combined load cases with both bending and torsion can be analyzed. Examples on how to apply the approach are provided for simple beams with several boundary conditions and tapered wing-boxes. For the latter case, a two-line strain-sensing system on the top surface of the box is proposed. The deflection is evaluated at the two sensing lines only and the cross-sectional twist angle is computed by considering the difference in the deflection of the two lines. Moreover, the approach is also extended to plate structures by taking into account multiple parallel strain-sensing lines. In Ref. [18], further mathematical developments of the formulas presented in Ref. [17] are presented in order to make them easier to use. Moreover, a strategy to determine the distance from the sensing lines to the structure neutral axis is provided. New numerical examples are presented that scrutinize the application of Ko's Displacement Theory to wing-boxes: depth-tapered (unswept and swept), width-tapered unswept, and double-tapered unswept wing-boxes. The two sensing lines are located at the front and rear lower edges of each wing-box. In Ref. [11], the approach is applied to the doubly-tapered wing of the unmanned Ikhana aircraft. A high-fidelity FE model of the wing is used to provide both the strain data needed for input to the deformed shape reconstruction based on the Ko's Displacement Theory and the reference deflections and cross-sectional twist angles. In Ref. [19], an experimental assessment of the Ko's shape-sensing approach is presented. Ground tests (with a whiffletree arrangement) are performed on the wing of the Global Observer, a high-altitude long-endurance unmanned aerial vehicle. Strains are measured using optical fibers arranged in the usual two-line strain-sensing configuration (both on the upper and on the lower surface of the wing in order to evaluate the neutral axis location). A photogrammetry system is adopted to measure validation displacements. Further sensitivity analyses are documented in order to investigate the effect of noise in the strain data and uncertainties on the distance between strain stations, on the spanwise location of fibers on the wing and on the wing's cross-section thickness. In Ref. [20], a further experimental