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3D shape sensing of flexible morphing wing using fiber Bragg grating sensing method

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ABSTRACT

The 3D shape sensing of flexible morphing wing using fiber Bragg grating (FBG) sensors is presented in this paper. A morphing wing prototype with polyimide thin film skin is constructed, and forty-eight FBG sensors are glued on the skin surface. The calibration experiments of the FBG sensors are conducted to ensure relative accurate conversion between Bragg wavelength shift (BWS) and bending curvature of the polyimide skin. The relation of the BWS values with the airfoil profiles are analyzed. The bending curvatures of the polyimide skin are calculated. The 3D shapes of the polyimide skin at different airfoil profiles are reconstructed. The 3D precise visual measurements are conducted using a digital photogrammetry system, and then the correctness of the shape reconstruction results are verified. The results prove that the maximum error between the 3D visual and FBG measurements is less than 5%, the FBG sensing method is effective for the shape sensing of flexible morphing wing with polyimide skin.

1. Introduction

The wing is a key component that determines the performance of aircrafts. Generally, the configuration and geometrical shape of the aircraft wings are designed according to several specific flight conditions and environmental parameters, and the wings are made by rigid materials and structures with light weight and high strength. To improve the aerodynamic performance of the wing under specific flight conditions, traditional aircraft wings use certain rigid deformable parts such as flaps and slats to change the aerodynamic shape of the wing in a simple way [1]. But due to the flight missions are multitudinous and the flying environmental parameters are continuously changing, the traditional aircraft wings can achieve the optimal aerodynamic performance at only a few flight conditions. In most cases these wings have a poor performance [1,2]. This limits the further improvement of the flight performance and multi-mission adaptability of advanced aircrafts.

In recent years, with the increasing demands for high performance aircrafts for military and civil use, the novel aircrafts with the features of intelligent, multi-functional and multi-mission adaptable are desired [1–3]. In this case, traditional rigid aircraft wings can hardly meet these demands. Thus, the intelligent and flexible morphing wing technologies attract a wide spread attention [1–4].

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Different from traditional rigid wings, the intelligent flexible morphing wing can change its aerodynamic shape flexibly according to different flight missions and environment parameters, and then obtain optimum performance at different flight conditions. Thus it can dramatically improve the aircraft performance, and has become a vital character of future aircrafts.

Technically, this sort of wing uses sensing system to measure the aerodynamic loads. According to the measured data and aerodynamic principle, the optimum wing shape is calculated, and then the flexible skin and deformable structures of the wing are driven by the actuating and control system to produce deformation and achieve the optimum aerodynamic shape. The real-time wing shape and flight loads are measured by the sensing system synchronously to realize a closed loop control. In the morphing process, the real-time sensing and monitoring of the wing shape is vital to judge that the deformed shape is optimum under the flight condition. Thus, to guarantee the flight performance of the flexible morphing wing aircrafts, the aerodynamic shape of the wing must be monitored in real time using effective shape sensing technologies.

There are various kinds of sensing and measurement technologies for the monitoring of the geometrical shape of the wing, including the strain sheet measuring method, vision measurement method, photo elastic method, laser scan measuring method and three-coordinate measuring method, and so on [5–9]. These conventional methods are suitable for the ground testing of the wing shape, but they are inapplicable for the real-time monitoring of the aerodynamic shape of the morphing wing during flight. Thus, it necessary to develop effective methods for the real-time monitoring of the wing shape in flight, to guarantee the performance of the morphing wing aircrafts.

In response to this demand, the optical fiber sensing method is a promising candidate to realize the real-time monitoring of the wing shape in flight [10,11]. Compared with conventional measurement methods as mentioned before, the optical fiber shape sensing method has several advantages as listed below.

(1) The optical fiber sensors (e.g. Fiber Bragg Grating, FBG) have the characters of small volume, lightweight, high sensitivity and short response time. These sensors can be embedded into the flexible skin of the morphing wing, thus the feature parameters (e.g. Strain) characterizing the flexible deformation of the wing can be measured sensitively and rapidly.
(2) The real-time measurement of the flexible deformation of the morphing wing, and the high rate and large capacity transmission of the measured data can be realized using the distributed optical fiber sensing network. Thus, the real-time monitoring of the wing shape in flight is achievable.
(3) Combing the optical fiber shape sensing method with the three-dimensional (3D) reconstruction and graph visualization method, the 3D shape of the morphing wing can be visualized in real time during the deformation process. Thus, the visualized monitoring of the wing shape can be realized.

Many researchers have studied the optical fiber shape sensing method for various kinds of structures. Blandino studied the sensing of bending shape and motion tracing of an aircraft boom structure with FBG sensors [12]. Three FBG sensors were glued on the surface of the boom structure along the axial direction, and the angle-interval of the three sensors is about 120° along the circumferential direction. Both static and dynamic sensing measurement of the structural deformation and motion tracing were carried out, and the FBG sensing results were verified by the laser displacement sensing method. Childlers developed a structural shape measurement system using multicore fiber sensing method [13]. The fiber grating sensors were inscribed on three-core optical fibers, and the fibers were glued on the surface of the structure, and the bending deformation of the structure was measured by the fiber sensors. The shape of the structure was rebuilt by the 3D reconstruction method. Clements proposed a 3D positioning and shape sensing system using fiber grating sensors [14]. The bending curvature and torsion of the measuring points of the flexible structure were measured by the fiber grating sensors, the relative position and orientation of the measuring points were calculated, and the 3D shape of the structure was reconstructed. Davis measured the shape of a cantilever structure using the fiber grating sensing network [15]. The analysis of the measured strain data was optimized using the Rayleigh–Ritz rule, and the shape of a simple cantilever structure was predicted accurately. Roger constructed an optical fiber sensing system for shape measurement of many kinds of structures [16]. Three hundreds of fiber grating sensors were distributed on the sensing cables consist of three-core fibers, and the measurements of deformation and vibration of cantilever structures were carried out. The 3D shapes of the structures were reconstructed, and the errors were about 1.2%. Prisco embedded the fiber grating sensors into the surgical operating instruments to monitor the shape and position of the mechanisms in real time [17]. Arritt used the integrated fiber grating sensors to monitor the shape of large deployable space structures [18]. Payo measured the deflection of highly-flexible manipulator system with fiber grating sensors [19]. Bang studied the fiber grating sensing of the deformation of wind turbine tower, and realized the dynamic monitoring of the structural modal of the tower [20]. Jutte developed a fiber grating sensing system and realized the ground testing of bending and twisting deformation of a full-scale aircraft wing [21]. NASA reported that Dryden Flight Research Center (DFRC) realized the real-time monitoring of the wing deformation of Ikhana unmanned aerial vehicle (UAV) using fiber grating sensor network [22]. After that, DFRC applied the fiber grating sensing technology to monitor the wing shape deformation of high aspect ratio UAV X-56A [23]. In recent years, LUNA Co. Ltd developed a three-core flexible shape sensing system based on OFDR technology and applied the system for the real-time monitoring of the deformation of various kinds of structures [22,23].

Recently, with the developing of flexible morphing wing technology, the design of novel morphing wings generally uses flexible thin film skins and deformable mechanisms instead of rigid wing materials and structures. In 2017, Massachusetts Institute of Technology (MIT) collaborated with NASA on the design of a novel digital morphing wing with polyimide skin and composite lattice-based cellular structures [1]. The real-time shape sensing of these flexible morphing wings is novel