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Rotor blade shape reconstruction from strain measurements

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ABSTRACT

Traditional helicopter blades are subject to significant deformations, which influence control forces and moments, as well as the helicopter aeroelastic and aeroacoustic behavior. Thus, the knowledge of rotor elastic states could help improving flight control efficiency, and reducing vibration level and acoustic emissions of next-generation helicopters. This paper presents an original and computationally efficient modal approach aimed at dynamic shape sensing of helicopter rotor blades. It is based on strain measurements in a limited number of points over the blade surface. Although the algorithm is based on the cascaded solution of linear algebraic equations, much like other modal-based algorithms, it is able to reconstruct nonlinear, moderate lag, flap and torsional deflections, which are typical in helicopter structural dynamics. The algorithm is tested on non-rotating and rotating hingeless blades through numerical simulations based upon a multibody dynamics solver for general nonlinear comprehensive aeroelastic analysis. Its capabilities are assessed against those of classical modal approaches. Numerical investigations show that the proposed algorithm is reliable, accurate and robust to measurement noise.

1. Introduction

Rotor blades are subject to significant deformations in standard and critical operating conditions, owing to aerodynamic and inertia loads. They are slender structures, whose flapping deformation, controlled by cyclic pitch, is used to generate rolling and pitching moments and direct rotor thrust. Moreover, it reduces aerodynamic asymmetry between the advancing and retreating sides of the rotor, thus alleviating vibratory loads transmitted to the airframe. Blade shape sensing is a desirable alternative to state observers for Flight Control Systems (FCS) of next-generation helicopters (it is well known that the knowledge of tip–path plane improves the performance of FCS, Refs. [1–5]), as well as for aeroelastic and aeroacoustic control (see for example the Clean Sky GRC5 MANOEUVRES project, which was aimed at demonstrating the possibility to reduce helicopters noise emission in terminal maneuvers through an in-flight monitoring of the main rotor state, Ref. [6]).

Although the potential benefits of placing sensors on rotor blades are very clear, two main issues remain open:

(i) the optimal positioning of the sensors on the blade, associated with the risk of accidental breaks during manufacturing or operational life, as well as with the need to avoid bonding delamination (see Ref. [7] for a complete review of technological issues for the case of sensor application on wind turbines);
(ii) the most efficient way of powering and connecting sensors, in relation with the rotational motion of the rotor.

Both these issues make the use of a large number of sensors more challenging than in fixed wing applications. Following the approach introduced in Refs. [8–10], in this work the authors propose the use of a limited number of strain gauge measurement points for the real-time determination of the rotor blades shape. Due to both the low cost and reduced weight of the sensors needed to implement such technique, it is easy to foresee its application to a wide range of rotorcraft, including lightweight helicopters, whose overall performance could be significantly improved.

Although the potential benefits of blade shape sensing are very clear, a viable technological solution to the problem has not yet been identified. Two main classes of shape sensing techniques have been proposed: optical and strain-based. The latter has received more attention in the recent past due to technological and practical problems related to the former. Indeed, while a direct optical measurement (photogrammetry) represents a viable option in some cases (Ref. [11]), it may suffer from several disadvantages:

(i) only in-sight parts of objects may be monitored;
(ii) optical markers field of view must be sufficient, i.e. marker plane must form a sufficiently great angle with the direction between camera and marker;

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(iii) operating conditions (water, ice, absence of light or direct sun exposure of the camera) make the measurement problematic;
(iv) for real-time, high speed measurements, expensive equipment is required;
(v) camera vibrations heavily affect the accuracy of the measurement.

All these problems are harshly present in rotor blade shape reconstruction, making the application of optical measurements very difficult. On the other hand, shape sensing from strain measurements is an area of growing interest in recent years in many fields of application, ranging from automotive to medical, aerospace and civil engineering. Moreover, Fiber Bragg Gratings strain gauges represent a great improvement in terms of bandwidth and ease of installation with respect to traditional electric resistance solutions. In particular, they drastically reduce the need of cables, as a single fiber may host hundreds of measurement points, whereas each traditional strain gauge needs a dedicated wiring. Their use in rotor blade fatigue monitoring is under investigation (Ref. [12]). Several numerical approaches have been recently proposed for the determination of the deformed shape of bodies from strain measurement; some of them are based on the direct integration of strain field data at the measurement points (Refs. [13–15]), whereas others use modal expansion, exploiting the use of preliminary FEM analysis on the monitored object (Refs. [16–18]). The latter are usually more efficient in terms of number of required sensors (in the order of tens instead of thousands), but require the knowledge of the object structure. Moreover, with notable exceptions (Ref. [19]), the approaches in the literature are inherently linear, whereas in finite strain theory the general relationship between strain and displacement is nonlinear. The modal shape functions may be conveniently evaluated for helicopter rotor blades through an equivalent 1D beam model. However, for linear approaches, rotors may be a challenging application, being subject to moderate deflections in standard operating conditions. Analogous considerations may be drawn for fixed wing aircraft which are becoming more and more flexible.

2. Proposed approach

In the present work, a modal shape sensing approach is proposed, capable of reconstructing the shape of a beam-like structure subject to general deformations including torsion, in-plane, and out-of-plane bending. It is able of handling nonlinear terms up to second order. This is particularly interesting for flight dynamics and aeroelastic control applications, in which the knowledge of limited information on rotor kinematics may give unsatisfactory results. It is worth mentioning that, at present, devices for the identification of the rotor state (e.g. by measuring cyclic flapping components β_c and β_s, or flapping-related displacement on a point along the blade) are still under development (Ref. [11]).

2.1. Strain-displacement relationship

Consider the approximation proposed in Ref. [20] for the strain-displacement relationship of a bent and twisted beam, which is valid for moderate deflections

$$\begin{aligned}\varepsilon_{\xi\xi} &= u' + \frac{1}{2}(v'^2 + w'^2) - \lambda\phi'' + (\eta^2+\zeta^2)\left(\vartheta'\varphi' + \frac{\varphi'^2}{2}\right)\\ &\quad - v''[\eta\cos(\vartheta+\varphi) - \zeta\sin(\vartheta+\varphi)]\\ &\quad - w''[\eta\sin(\vartheta+\varphi) + \zeta\cos(\vartheta+\varphi)]\end{aligned} \tag{1a}$$

$$\varepsilon_{\xi\eta} = -\frac{1}{2}\left(\zeta + \frac{\partial\lambda}{\partial\eta}\right)\varphi' \tag{1b}$$

$$\varepsilon_{\xi\zeta} = \frac{1}{2}\left(\eta - \frac{\partial\lambda}{\partial\zeta}\right)\varphi' \tag{1c}$$

where η and ζ are the coordinates along the cross-section principal axes, ξ is the coordinate along the elastic axis, u, v, and w are the axial, lead-lag and flap displacements of the elastic axis, whereas ϑ and φ are the built-in twist angle and the blade cross-section elastic rotation (torsion), respectively. Note that, in the following, the warping function λ in Eqs. (1) will be neglected for the sake of simplicity. However, its contribution may be easily included if necessary (e.g. when the method is applied to composite blades [21,22]), following one of these approaches:

i) numerically, evaluating the warping function with a finite element (or equivalent) analysis;
ii) experimentally, in a known-displacement calibration test, determining the warping function and its derivatives in the measurement points exploiting strain measurements and the free–contour boundary condition (see Ref. [23]);
iii) during the use of the device, using the strain components at the measurement points, and exploiting the fact that in cylindrical portions of the blade the warping function only depends on η and ζ. In this case, it is worth noting that an iterative procedure for the simultaneous evaluation of the unknowns in Eqs. (1a)–(1c) is needed, due to their intrinsic nonlinearity.

In the proposed formulation, the displacement $\boldsymbol{\delta} = \{u, v, w\}^T$ and the elastic torsion angle φ are first expressed as the linear combination of suited shape functions ($\boldsymbol{\Psi}_i$ and Φ_i), with coefficients q_i and r_i

$$\boldsymbol{\delta}(\xi, t) = \sum_i \boldsymbol{\Psi}_i(\xi)\, q_i(t) \tag{2a}$$

$$\varphi(\xi, t) = \sum_i \Phi_i(\xi)\, r_i(t) \tag{2b}$$

Then, Eqs. (1b) and (1c) are combined into a single equation which gives the shear strain in the direction orthogonal to ξ and tangent to the external surface,

$$\varepsilon_t := t_\eta \varepsilon_{\xi\eta} + t_\zeta \varepsilon_{\xi\zeta} = \frac{-t_\eta\zeta + t_\zeta\eta}{2}\varphi' \tag{3}$$

where t_η, t_ζ are the components of a unit vector lying in the plane of the section, thus with $t_\xi \equiv 0$, and tangent to the surface in the measurement point, or

$$\varepsilon_t = \boldsymbol{k}\boldsymbol{r} \tag{4}$$

where $\boldsymbol{r} = \{r_1, r_2, \ldots, r_M\}^T$ contains the M torsion modal amplitudes, and $\boldsymbol{k}$ is a row vector evaluated in a straightforward manner from the knowledge of the torsion shape functions and the location of the evaluation point. After the torsion amplitudes are obtained from a suitable over-collocation of Eq. (4), Eq. (2b) is used to calculate the terms that depend on φ in Eq. (1a), leaving the displacement components as the only unknowns.

Finally, evaluating Eq. (1a) at two points of the same cross-section, and subtracting the corresponding $\varepsilon_{\xi\xi}$ values, one obtains

$$\begin{aligned}\Delta\varepsilon_{\xi\xi} &= \varepsilon_{\xi\xi_2} - \varepsilon_{\xi\xi_1}\\ &= \left[\left(\eta_2^2+\zeta_2^2\right) - \left(\eta_1^2+\zeta_1^2\right)\right]\left(\vartheta'\varphi' + \frac{\varphi'^2}{2}\right)\\ &\quad - v''[(\eta_2-\eta_1)\cos(\vartheta+\varphi) - (\zeta_2-\zeta_1)\sin(\vartheta+\varphi)]\\ &\quad - w''[(\eta_2-\eta_1)\sin(\vartheta+\varphi) + (\zeta_2-\zeta_1)\cos(\vartheta+\varphi)]\end{aligned} \tag{5}$$