Mechanical Systems and Signal Processing 91 (2017) 183–197

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Real-time estimation of helicopter rotor blade kinematics through measurement of rotation induced acceleration

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ARTICLE INFO

Article history:
Received 10 August 2015
Accepted 2 January 2017

Keywords:
Kinematics
Estimation
Helicopter
Accelerometer
Neural network
Rotor Blade

ABSTRACT

This paper presents a novel approach to monitoring rotor blade flap, lead-lag and pitch using an embedded gyroscope and symmetrically mounted MEMS accelerometers. The central hypothesis is that differential accelerometer measurements are proportional only to blade motion; fuselage acceleration and blade bending are inherently compensated for. The inverse kinematic relationships (from blade position to acceleration and angular rate) are derived and simulated to validate this hypothesis. An algorithm to solve the forward kinematic relationships (from sensor measurement to blade position) is developed using these simulation results. This algorithm is experimentally validated using a prototype device. The experimental results justify continued development of this kinematic estimation approach.

1. Introduction

With the recent expansion of Health and Usage Monitoring Systems (HUMS) for helicopters and tilt-rotor aircraft [14] and the development of active rotor control methodologies [6,7,13], accurate measurement of rotor blade kinematics during flight has taken on new importance. Data from real-time blade motion monitoring could be used to extend the benefits of HUMS maintenance to rotor head components [16]. When used as feedback for flight control algorithms, such data could also improve the performance of active rotor systems. These interests, combined with the difficulties of accurately simulating rotor head loads [10], have resulted in the development of various approaches for blade motion monitoring.

Mechanical approaches for monitoring rotor blade kinematics include NASA's "crab arm", which incorporates displacement and load sensors that extend over the blade root attachment [17]. While the technology demonstrated reasonable wind tunnel performance, it was unsuitable for field use due to its wiring and slip ring channel requirements, as well as its detrimental effect on rotor head balance. Another approach features linear displacement sensors embedded into a high capacity laminate (HCl) bearing, which serves as the blade root attachment for many fully articulated rotor heads [1]. While this approach featured improved environmental robustness and data transmission capabilities, its application is limited to specific rotor head configurations and could degrade HCl part life. NASA has also investigated an optical approach which utilizes lasers mounted to the blade root and aimed at reflectors on the rotor hub [17]. Other optical methods using lasers [11] and LED position tracking systems [18] have been investigated for estimating blade bending. While nominally effective in wind tunnel and laboratory environments, measurement accuracy can be significantly reduced by the presence of dust or moisture in the air.

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http://dx.doi.org/10.1016/j.ymssp.2017.01.003
0888-3270/

Estimation of rotor blade kinematics has been demonstrated using single axis MEMS accelerometers mounted along the blade span [15]. Changes in measured acceleration due were related to flap and lead-lag blade motion. Drawbacks of this method include the necessity to compensate for blade bending to determine the associated blade root position, the high maximum acceleration rating and associated low resolution necessitated by placement at relatively large distances from the center of rotation, and the lack of methods to compensate for helicopter frame accelerations.

This paper presents a novel approach to monitoring rotor blade flap, lead-lag and pitch using an embedded gyroscope and symmetrically mounted MEMS accelerometers. The central hypothesis is that differential accelerometer measurements are proportional only to blade motion; fuselage acceleration and blade bending are inherently compensated for. The inverse kinematic relationships (from blade position to acceleration and angular rate) are derived and simulated to validate this hypothesis. An algorithm to solve the forward kinematic relationships (from sensor measurement to blade position) is developed using these simulation results. This algorithm is experimentally validated using a prototype device.

The remainder of the paper is organized as follows: Section 2 introduces the inertial measurement implementation, develops position to acceleration relationships and the algorithm used to map acceleration measurements to blade motion, and describes the prototype and test stand fabrication. Simulation and experimental results are presented in Section 3 with corresponding discussion in Section 4. Concluding remarks and potential future work are presented in Section 5.

2. Materials and methods

Helicopters feature two important rotating reference frames: those of the fuselage and blades, as illustrated in Fig. 1. Fuselage rotation occurs about the X, Y and Z axes, and is designated roll (δ), fuselage pitch (θ), and yaw (φ), respectively. Inertial acceleration in the fuselage frame results from maneuvers such as banked turns and flare stops. Rotation of the blade occurs about the x, y, and z axes, and is designated flap (α), lead-lag (β), and blade pitch (γ), respectively. The rotor blade reference frame combines inertial acceleration from the fuselage with periodic rotation and centrifugal acceleration induced by the rotor head rotation.

To enable the real-time estimation of blade kinematics in this environment, four pairs of MEMS accelerometers can be mounted equidistant from the blade root center of rotation, together with a MEMS gyroscope, as shown in Fig. 2. While each measured acceleration will include contributions from the fuselage and rotor blade reference frames, differential measurements from each accelerometer pair will be proportional only to the flap, lead-lag and blade pitch. The gyroscope, which provides angular rate measurement dominated by rotor head rotation, is included to improve the estimation of blade pitch.

2.1. Materials

MEMS accelerometers were selected for this application due to their low power requirements and DC acceleration measurement capabilities. Accelerometer selection was based on helicopter simulations, which revealed maximum DC accelerations of approximately 24*g*. Endevco model 7290A-30 variable capacitance microsensors (Meggitt Sensing Systems, Irvine, CA), with a maximum acceleration of 30*g* and sensitivity of 66.6 mV/*g*, were selected for experimental testing. Accelerometer data was collected using a V-Link wireless node (LORD-Microstrain, Williston, VT). Similarly, a MEMS gyroscope was selected

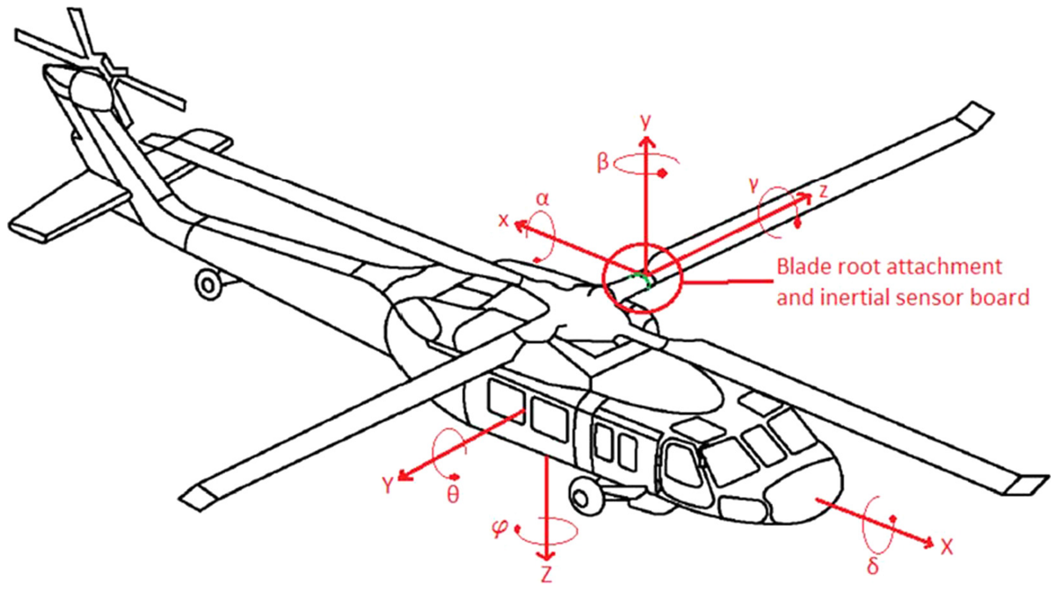

Fig. 1. Helicopter fuselage reference frame (XYZ), rotor blade reference frame (xyz), and associated angular displacements (roll (δ), fuselage pitch (θ), yaw (φ), and flap (α), lead-lag (β), blade pitch (γ), respectively). Location of inertial sensor board on rotor blade root is indicated.