Mechatronics 52 (2018) 58–69

Contents lists available at ScienceDirect

Mechatronics

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

Novel wireless sensing platform for experimental mapping and validation of ship air wake☆

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ARTICLE INFO

Keywords:
Ship air wake
Particle swarm optimization
Neural networks
RC helicopter dynamics
Wind turbulence

ABSTRACT

This paper presents the mechatronic design and analysis of a wireless sensing platform developed for the experimental mapping and validation of the air wakes generated by cruising naval vessels. The presented sensing system uses an RC helicopter as its carrier platform and uses the helicopter's dynamics for spatial 3D mapping of wind turbulence. In this paper, the proposed telemetry system models the dynamic response of the helicopter to pilot inputs under artificially generated wind conditions and then uses neural network based models to estimate the air wake distribution. The telemetry system uses a wireless sensor network comprising of sensors such as an Inertial Measurement Unit (IMU), optical trackers, and GPS to measure the dynamics of a flying RC helicopter. The system was trained and calibrated in a climate controlled indoor environment with artificially generated wind conditions. This paper focuses on both hardware and software aspects of the latest iteration of the telemetry system (version 3.0). The presented telemetry system is also tested with a modified YP676 naval training vessel in the Chesapeake Bay area, under a wide range of wind conditions and the results were compared against CFD simulations.

1. Introduction

The operation of helicopters on naval vessels is a very risky and challenging task due to ship air wakes and limited flight deck area. Ship air wake is a trail of air turbulence generated in the lee of the superstructure of a cruising naval vessel. To minimize these operational risks, 'safe launch and recovery envelopes' are prescribed for operating helicopters with each class of naval vessel in order to avoid high air wake zones during take-off and landing [1]. Such safe flight envelops are often determined with Computational Fluid Dynamics (CFD) models and/or manual flight testing. Because of the serious naval safety implications of ship air wakes, many navies around the globe have ship air wake study programs [2–4]. Significant research has been done to develop high-fidelity CFD models to predict air wake patterns [3,5] and interactions with rotary wing aircraft [6–11]. However, existing CFD models need extensive experimental data for validation. Manual flight testing, on the other hand, is not only risky but also highly subjective as it depends on the pilot's response. Thus, there is a need for an instrumentation system capable of measuring ship air wake intensities in a non-subjective manner. To obtain experimental ship air wake data, most researchers have pursued either wind tunnel testing or relied on in-situ wind velocity measurements using anemometers.

1.1. Wind tunnel testing

Wind tunnel testing has been the preliminary and most common source for ship air measurement in the naval science community. Such studies often use a scaled-down model of naval vessels in wind tunnel and measure wind flow field. These types of setups have used a variety of sensing modalities including laser Doppler anemometry [12], hot wire based Omniprobe anemometry [3,9] and Particle Image Velocimetry [2,10,13]. In a similar study, Kääriä et al. immersed a model helicopter in a water tunnel to validate the aerodynamic interactions of a helicopter with ship air wakes [11]. The transducers used in these measurements are very sensitive and expensive, so they can safely be operated only in controlled environments like wind tunnels. The wind tunnel testing does provide significant insight into wind flow in ship air wake zones, but lacks fine details in flow pattern due to scaling issues. Additionally, both the model holder and the walls of wind tunnel affect the readings, and their effects must be accounted for in the experimentation.

1.2. In-situ measurements

Use of anemometers is the most common means for in-situ wind

☆ This paper was recommended for publication by Associate Editor Prof. Hamid Reza Karimi.

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https://doi.org/10.1016/j.mechatronics.2018.04.009
Received 20 October 2017; Received in revised form 15 March 2018; Accepted 25 April 2018
Available online 01 May 2018

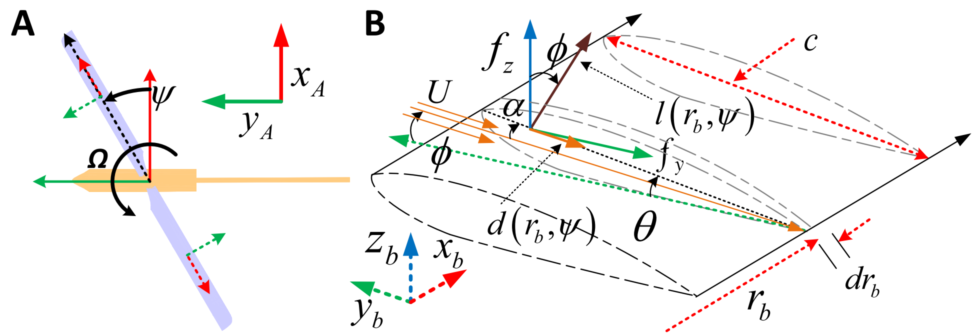

Fig. 1. (A) Frame of reference assignment for the helicopter's fuselage and rotor blades; (B) Aerodynamic loads on an airfoil section of rotor blade.

pattern measurement. Allotta et al. have recently demonstrated the use of MEMS sensor based low cost anemometers mounted on a sail boat mast to measure wind flow for autonomous control of the boat [14]. The sensor gives good temporal resolution but lacks spatial resolution as it depends on motion and dynamics of the sailboat. However, in a more reliable approach, the researchers place ultrasonic anemometers at different locations on the flight deck of naval vessels and compare the measurements with CFD/wind tunnel testing results [3,12,15–17]. This methodology does provide accurate wind flow measurements, but proves to be expensive and time-consuming. The anemometer(s) need to be moved from point to point to get the complete wind flow field. To overcome this limitation, Mallon et al. [18] in a similar study used airborne anemometers mounted on a quadrotor to map ship air wakes. This approach requires compensation for anemometers' motion relative to the inertial frame of reference and, most importantly, is susceptible to quadrotor's own wind turbulence.

1.3. Proposed use of RC helicopters as a sensing platform

Ship air wakes are critical because they effect the aerodynamic operation of a helicopter. Wind sensing instruments like anemometers, Pitot tube, etc., can measure instantaneous wind conditions, but only in a very small volume. Thus, such instruments cannot capture spatial variations in wind condition, a characteristic of turbulent flow, especially from a non-stationary platform. Air wakes result in undesired swaying and tilting of helicopters due to uneven aerodynamic loading effects resulting from wind turbulence. Thus, it is advantageous to use low-cost remotely operated helicopters as a transducer to determine wind conditions. Due to their low mass, RC helicopters are quite sensitive to ship air wakes. The use of an RC helicopter's in-flight angular rates to quantify ship air wakes was first proposed by Metzger et al. [19]. However, this method had limited application, as it ignored the motion induced by the pilot's inputs to the helicopter [20]. This concept was gradually extended by Kumar et al. in multiple iterations by modeling the contribution of pilot inputs to the helicopter's dynamics [20–24].

1.4. Scientific contributions of this study

In contrast to the previously published work of the authors [20–22,24], the current paper presents a calibration strategy for the sensor system through experimental flight testing in a controlled wind setup. The paper presents the design and analysis of a wireless telemetry system intended to simultaneously measure helicopter dynamics, location and pilot inputs at a high update rate. This paper also presents a novel mechatronics platform to generate and map reproducible wind flow conditions in an open indoor environment to calibrate aerodynamics of a flying RC helicopter. This paper presents an extended analysis of the interaction of ship air wakes with a flying RC helicopter using localized wind flow models. This study also presents an analytical analysis to identify factors affecting the helicopter's dynamics and use these parameters with an Artificial Neural Networks-Particle Swarm Optimization (ANN-PSO) based machine learning approach to model the dynamics of an RC helicopter. Also, this analysis demonstrates linear mixing of pilot components and local wind components in the aerodynamics of the helicopter, and then uses the same property to extract and map wind turbulence.

The main benefit of this telemetry system is its non-contact long-range mobility, which does not alter the air wake readings due to physical linkages coupled with ship motion or the formation wakes arising from mechanical linkages (as in the case of wind tunnels). At the same time, pilot input compensation features of the system ensure unbiased ship air wake measurements. The system's capability to extract ship air wakes is tested in an indoor calibration experiment where the helicopter was flown in artificially created wind turbulence. In addition, this paper also models the effect of turbulence from uncertainty in angular acceleration, which delivers better correlation with the wind turbulence pattern. The paper also presents the outdoor testing performance of the system with an YP676 naval patrol craft and compares against results obtained from CFD analysis in previous studies.

2. Interaction between helicopter and ship air wakes

As is widely known, helicopter control is realized through thrust vectoring by using a swash plate mechanism [25]. The swash plate couples the main rotor rotation and rotor pitch control, thus making the blade pitch angle a function of the rotor position.

Fig. 1 shows the frame of reference assigned to the helicopter's fuselage along with the lift and drag generated by an airfoil section of a rotor blade. The lift and drag experienced on an airfoil section of a rotor blade is dependent on the angle of attack of the relative wind, which in turn depends on wind conditions, pilot inputs, and the helicopter's motion. To make the role of wind conditions on the helicopter dynamics apparent, a single blade coordinate system has been followed. Eq. (1) shows lift (l) and drag (d) generated by an airfoil section [25].

$$l(\psi) = 1/2\rho U^2 c a_0(\theta(\psi) - \phi); \quad d(\psi) = 1/2\rho U^2 c(\delta_0 + \delta_2 C_T^2). \tag{1}$$

Here, U and ϕ are the speed and inclination of the wind relative to the airfoil in the plane of rotation, ρ is the density of air, θ is the pitch angle of the rotor blade element, c is the chord length of the rotor blade, andψ is the instantaneous rotor position. In addition, a_0 represents the aerodynamic lift curve slope for the blade, C_T represents the thrust coefficient and the coefficients δ_0 and δ_2 represent the constant and variable aerodynamic drag coefficients. As shown in (1), the pitch angle of the rotor blade depends on the pilot inputs (and rotor position) and the angle of attack (θ-ϕ) of the rotor blade airfoils depends on both pilot inputs and local wind conditions. Due to the high rotor speeds, ϕ has small values (close to zero). As a result, the vertical thrust generated by the airfoil section can be approximated to the generated lift-off force.

$$f_z(\psi) = l(\psi)\cos(\phi) + d(\psi)sin(\phi) \approx l(\psi). \tag{2}$$