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Wireless telemetry system for real-time estimation of ship air wakes with UAVs

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ABSTRACT

This paper presents a wireless instrumentation system developed for real-time estimation of air turbulence patterns arising from the interaction of wind with any structure under consideration, which is an important study in the aerospace industry. In particular, this paper focuses on the application of the proposed system in a naval research problem for off-board measurement of ship air wake patterns using an instrumented radio controlled (RC) helicopter. We propose the use of an Inertial Measurement Unit (IMU) as a sensor to measure air wake in the form of induced vibrations on the helicopter while it maneuvers through regions of active air wake. The proposed system makes use of Back Propagation Neural Networks to compensate for the vibrational noise contributed by pilot inputs. The instrumentation system was integrated and tested on a modified training vessel in the Chesapeake Bay, which provided a wide range of wind conditions.

1. Introduction

The aerospace industry has always expressed a need for new technological advancements and techniques capable of redefining design and operational processes, which facilitate the progress of exploration and science. Considerable research has been devoted to monitoring structural vibrations [1]. Yet, determining air turbulences (often the main cause of structural vibrations and risk to aerial vehicles) is a challenging task which researchers continually explore and try to understand.

The most commonly used device for measuring air turbulence is the Hot Wire Anemometer (HWA) which relates the resistance of a wire, held at a constant temperature, to the speed of airflow at a single point in space. Researchers have used HWA for testing wind tunnel streams, model testing, and investigating turbulence problems in boundary layers, wakes of jets and channels [2]. Sonic Anemometers offer additional capabilities of both airflow speed and direction using ultra sonic sound waves; measurements are taken with fine temporal resolution making them very well suited for turbulence measurements [3]. These delicate sensors are expensive, require constant recalibration, and sturdy platforms during data collection since motions of the probe result in additional air flow velocity measurements. In order to obtain information about air turbulence in a wide area, a large number of these sensors should be mounted on sturdy rigging. In some cases riggings cannot be installed to cover an entire area of interest. For example, measuring off deck ship air wake activity for developing safe launch and recovery envelops of aerial vehicles [4]. Alternatively, a single sensor can be placed on a beam and swept about the entire area. This method suffers from deflections of long beams due to pitch/roll motion of the ship and causes random fluctuations in wind measurements and produces false information about the air turbulence.

Computational Fluid Dynamics is a popular method of generating extrapolated velocity fields offering valuable insight to turbulent vortices. The computer-aided designs of the model and environment are often simplified to reduce computation loads making computational methods insufficiently validated for systems with complex structures. In addition, these simulations often need experimental validation using anemometer sensors, which have their respective drawbacks [5–9].

There is a need to develop a new technique that accurately detects turbulence patterns in large, open spaces. A new means of turbulence data collection in the Aerospace Industry will bring about enhanced flight research capabilities, and improvements in both aerial vehicle design and operational safety analysis. Our proposed system named Wireless Telemetry System (WTS) utilizes an RC helicopter flying in an area of interest with active turbulence regions to estimate and detect turbulence patterns in

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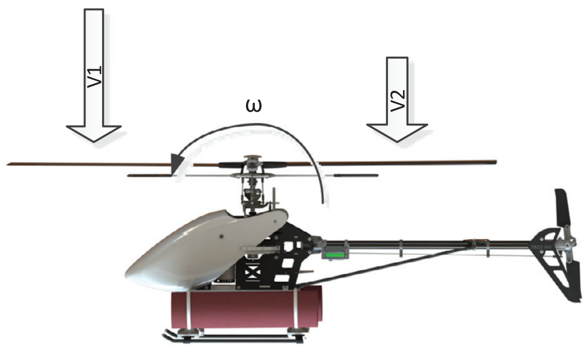

Fig. 1. Interaction of air wake with helicopter resulting in tilting.

real-time. Normally machine learning techniques are used as optimum controller in robotic systems [10–12]. The proposed system utilizes trained neural networks that act as filters to eliminate pilot induced vibrations from recorded vibrational data. Results are mapped out visually on a Graphical User Interface (GUI) to better understand turbulence patterns. Experimental results and validation of our instrumentation system is presented through a case study performed to detect turbulence patterns and monitor helicopter interactions with ship air wakes created by air flowing over the ship superstructure.

2. Proposed System

Air wake is turbulence originating from pressure gradients that result in wind gusts. The motivation of the WTS comes from observing an RC helicopter flying through active air wake zones. During flight, it experiences differential airflow velocities that cause tilting of the aircraft since its center of mass and effective geometric center do not coincide. We can infer that monitoring angular velocity patterns of a helicopter will provide a good description of air wake patterns. Thus, our proposed system detects air wake patterns in wide open areas by monitoring the RC helicopter angular rates using a Gyroscope. Fig. 1 shows tilting of an RC helicopter with angular velocity ω as a result of differential wind velocity (V1 > V2).

It is important to note that the presence of air wake is not the only cause of angular velocity changes of the helicopter during flight. Cyclic pilot inputs change the pitch angles of the rotor blade which result in differential thrust and consequently force moment applied on the helicopter fuselage. Thus, if this angular acceleration due to pilot inputs is known and the data sampling rate remains constant, the angular rate due to pilot input at any point in time can be estimated from the previous angular rate measurement. In general, helicopter is as a non-linear multiple inputs and multiple output (MIMO) system and can be modelled as follows:

$$x(t) = f(x(t-1), u(t-1)) \tag{1}$$

where $x(t)$ represents the system state variables, such as angular and linear positions/velocities at any time t, and u represent external inputs to the system. These external inputs constitute both pilot inputs and ship air wake disturbances. Angular rates of the RC helicopters measured at any time from the Gyroscope mainly depend on parameters related to the previous state variables [13,14] (i.e., linear velocities, angular rates, rotor speed and altitude, etc.) and external inputs as shown in (1). During air wake measurements, if flight parameters such as rotor speed, altitude and linear velocities are not drastically changed, then it is safe to assume that the angular rates mainly depend on pilot inputs, ship air wake and the previous measurements of angular rates. The major components of tilting and oscillations are caused by pilot input responses. The proposed system utilizes machine-learning techniques to estimate and compensate for dynamics arising from pilot inputs in order to isolate air wake induced effects on the aircraft.

The WTS is composed of three components viz. transmitter module, receiver module and transmitter carrier (RC Helicopter). Both the transmitter module and the receiver module are similar custom-made instrumentation boards mounted with sensors like IMU, GPS, Thermometer, and Barometer sensors. The transmitter module measures the dynamics of the helicopter and sends the data to the receiver module over Xbee™ long range RF transceiver. The receiver module measures the dynamics of the boat and sends the measured data along with the transmitter module's data to a computer via a USB channel for real time processing. The RC helicopter was selected to carry the transmitter because of its low cost, high maneuverability and hovering capabilities.

The WTS was used to detect ship air wake turbulence in the aft of a cruising US Naval Academy's YP676 for estimation of safe launch and recovery envelopes. The data measured by the transmitting module on the helicopter was routed wirelessly to the receiver module connected to a laptop located on the ship and displayed on a GUI. During data collection, the YP craft master maintained consistent speed and wind conditions based on the reference anemometer while the pilot swept the RC helicopter back and forth in the lee of the ship. An experienced pilot maneuvered the RC helicopter (with the transmitting module) in a wave-like pattern at constant height in the aft of the boat. During helicopter maneuvers, the pilot responded to wind gusts in order to keep the helicopter stable. Such responses introduce tilting/vibrations in the IMU data and are highly subjective in nature.

In order to accurately measure actual air wake interactions, pilot induced dynamic inputs must be removed from the IMU data. The RC helicopters require five dimensional pilot input in the form of PWM signals. Three of which control swash plate kinematics and the remaining two control the tail rotor pitch and rotor speed. All five pilot input channels contribute to the helicopter's attitude. Since angular velocity measurements are a vector sum of external disturbances and pilot induced dynamics, external air wake disturbances can be obtained by subtracting predicted IMU readings from actual readings. Pilot input from the radio transmitter (Remote Controller) controls the helicopter's attitude and is sent in 'one-to-all' broadcasting mode. Thus, multiple RF receivers can receive the same signal from a single transmitter. Therefore, an additional RC receiver was used in the receiver module to read the pilot inputs sent by the transmitter. WTS uses Back Propagation Neural Networks (BPNN) to find mapping of IMU readings with pilot input signals. The air wake intensity was estimated by subtracting the BPNN generated IMU readings from the actual IMU readings in real-time.

The real-time location of the helicopter was estimated in the boat's frame of reference using GPSs in the receiver and the transmitter modules and a real-time trajectory of the helicopter was obtained. The helicopter trajectory, IMU vibrational components, and pilot inputs are displayed and recorded in real time through GUI software developed using NI Lab VIEW™. By fusing sensor data, possible locations of sharp gradients in the air velocities can be mapped relative to the ship representing helicopter/air wake interaction patterns (accurate within one rotor diameter of the helicopter). Fig. 2 shows the architecture of the WTS proposed to measure ship air wake patterns.

3. Hardware Details

The WTS was used with three different off-the-shelf RC helicopters with rotor diameter of 1.3 m (4.5 ft.) to detect air wake patterns generated by the YP676 vessel. The YP676 vessel was equipped with an eight channel ultrasonic anemometer array for