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Estimation of Wind Velocity on Flexible Unmanned Aerial Vehicle Without Aircraft Parameters

Noel J. Mangual
Embry-Riddle Aeronautical University

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Noel J. Mangual

Embry-Riddle Aeronautical University, Daytona Beach, FL 32114

Abstract

This research project estimated the wind velocity of a small flexible-wing Unmanned Aerial Vehicle using a software developed the analysis of the data collected by airspeed and attitude sensors. The purpose of this paper is to contribute to the extensive research of destructive vibrations on flexible wing aircraft. The estimation of the wind velocity will be implemented as part of the control design project. This paper is based on literature review of the estimation of wind velocity using only kinematic relationships with a Kalman Filter. The testbed used for wind estimation was a Volantex Ranger EX 757-3. Experimental data of velocity, altitude, and attitude were obtained by performing circular maneuvers at Daytona Beach Radio Control Association. After sampling and processing all the data, the computer code returns the wind velocity estimation of a North-East-Down frame and the airspeed sensor calibration factor. Results show a valid estimation when compared with the local weather data of the date of flight and the sensor calibration factor within typical range. This method of wind velocity estimation is proven to be valid and will yield to the estimation of the incident angles using aerodynamic forces relationships.

Content

Figures

I. Introduction

The need to address efficiency issues on modern aircraft had led designers to adopt lightweight flexible wings. Comparing with a fixed-wing aircraft, flexible aerial vehicles have improved performance and reduced operational costs. A technical challenge associated with these designs is that the in-flight deformations of the wings lead to an adverse interaction between the aircraft aerodynamic forces and structural forces at a certain airspeed. These adverse interactions produce excessive vibrations that can degrade flying qualities such as the ease with which a pilot can handle vehicle maneuvers and may result in severe structural damage. Monitoring airspeed information in real time is required to avoid the generation of these vibrations that can destroy the airplane.

In order to experimentally address this excessive-vibrations problem, an aircraft model that can experience wing deformation is needed with the capability to attach sensors to be able observe the wind interaction with the system. Another factor to consider for the observability of aerodynamics interactions is the proper installment and calibration of the data sensors. In Haering (2015), the installation of sensors in the aircraft is described with the needed calibration for particular sensors. While having the right instrumentation is fundamental for the observability and target of this research, an analytical process is the key factor to generate results.

This paper is of main interest to airplane designers and UAV researchers who are interested in developing more efficient aircraft structures. This research project is also useful to anyone who is invested in finding new ways of overcoming speed barriers in aerospace travel. This means reducing the flight time between two points at major distances.

This project attempts to answer the following research question: Can the wind velocity be estimated with a Flexible-wing Unmanned Aerial Vehicle without using any aircraft parameters? This investigation applies the method developed by Johansen, Cristofaro, Sorensen, Hansen, & Fossen (2015) where they use only kinematic relationships and a Kalman-Bucy filter to estimate the wind velocity of a small fixed-wing UAV. Contrasting with many research methods in the UAV industry, Johansen et al. use minimal instrumentation for the estimations. The method consists in probing an airspeed sensor in the longitudinal axis of the UAV. This will allow the aircraft to collect air data outside the boundary layer, minimizing the noise in the sensor. It is also needed a GPS and an Inertial Measurement Unit to monitor the changes of altitude and velocity and attitude, respectively. After all the data is collected during the test flight, it is processed and resampled (formatted to be useful for application) in a MATLAB software. The resampled data will then be plugged into the state system model developed by Johansen et al. (p. 513) to be solved for the wind velocity using Ordinary Differential Equation solvers and Ricatti Equation applications.

Differing from the study of Johansen et al., this project performs the experiment using a flexible-wing UAV. Although a similar approach can be used to estimate the wind velocity on different Unmanned Aerial Systems, the scope of this research only covers flexible UAVs.

II. Literature Review

Vibrations in wings

Despite the many years of research, although with some progress, the excessive-vibrations problem due to in-flight wing deformation, also called flight flutter, remains unsolved. After numerous attempts, an analytical estimation was obtained for a realistic physical model of a wing perturbated by flutter and experiencing bending and torsional motions (Shubov, 2014). It was possible to optimize the flutter speed, reaching to a faster speed without experiencing adverse vibrations, by 12% by changing the design of the modeled wing. Flutter speed was solved parametrically with respect to the sweep angle and material properties of the wing (Nikbay & Acar, 2011). In order to experience the flutter and further its analysis, an X-56A aircraft was also designed. Many challenges were found in this project with the stiffness and mass distribution to achieve the desired aeroelastic behavior (Burnett, Beranek, Holm-Hansen, Atkinson & Flick, 2016). While all these research projects contribute to the solution of destructive vibrations in flexible-wing aircraft, this problem remains among the top raked NASA Aeronautic investigations (Shubov, 2014).

UAV approach

Because they are needed to experience the similar flight conditions for the flutter to be observable and properly addressed, Unmanned Aerial Vehicles are very useful given their size and controllability. There are numbers of research projects and investigations on the estimation of wind velocity and incident angles, which are steps to the bigger problem, on Unmanned Aerial Vehicles. For instances, in the paper "Estimating Angle of Attach and Sideslip Under High Dynamics on Small Unmanned Aerial Vehicle" Perry, Mohamed, Johnson & Lind (2008) estimated the wind velocity using an airspeed sensor and the inertial speed of the aircraft. This is standardized for this type of estimations. The model presented by Perry et al. is "highly simplified and has not been verified experimentally for accuracy (p. 1168). In the paper "Wind Field Estimation for Small Unmanned Aerial Vehicles" Alley & Neidhoefer (2011) derived a model using vehicle dynamics and kinematics. By running simulations of realistic noise in the sensor, they obtained an accuracy better than 0.5 m/s (p.1025). After having three test-bed UAVs, the NTNU Penguin, the NASA Sierra, and NTNU X8 performing similar maneuvers and assuming slowly time-varying winds and sensors at minimum configurations, it was shown that the variables and the airspeed calibration factor can be estimated provided that the aircraft changes in pitch and yaw (Johansen et al., 2015).

Gap in Literature

While estimation of wind velocity on UAVs and experimental, computational, and numerical analysis of excessive vibrations exist in aviation literature, there is very little or non-existent experimental approach to the flight flutter problem using Flexible-wing Unmanned Aerial Vehicles. This report will fill the gap in literature by estimating the wind velocity on a Flexible UAV without using any aircraft parameters to systematically attempt to solve the excessive vibration problem in further research investigations.

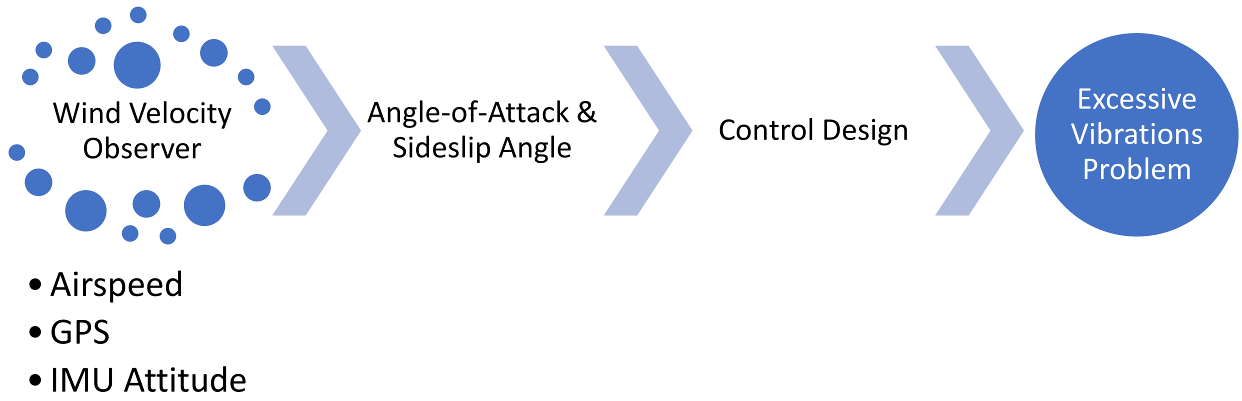

Figure 1. Step-by-Step approach to wing flutter problem.

This flowchart illustrates the systematically approach to solve the more difficult problem of excessive vibrations in the wings of flexible aircraft. It shows how the scope of this paper is part of step-by-step research project.

III. Analysis

Experimental Test Results

The Volantex Ranger EX 757-13 UAV was used as the testbed for this investigation. The aircraft was equipped with a 3D Robotics Global Positioning System Module and a pitot tube with an Pixhawk PX4 Inertial Measurement Unit. The GPS module was used to track the airplane during flight and to measure the speed and altitude of the aircraft as well. The pitot tube was used to monitor the airspeed. The Pixhawk PX4 IMU collected the data for the change in attitude of the plane. This means that the IMU will measure the changes in roll, pitch, and yaw.

Figure 2. UAV Volantex Ranger EX 757-13

This image illustrates the testbed used as the main structure to hold all the sensors. The UAV is landing after gathering data for about 10 minutes of flight.

The flight duration was about 10 minutes including the takeoff and maneuvering. Although the flight time was 10 minutes, the useful data was collected within 6.6 minutes because that was when constant altitude and velocity were reached (Johansen et al., 2015). Figure 3 shows the contrast between useful and non-useful data by illustrating the disturbance in the graph after 200 seconds (approximately 3 minutes) have past. For this reason, the data had to be resampled to only provide the 6.6 minutes as input for the analysis. The vehicle was flown to gather data in two circular maneuvers because this was the necessary and optimal flight dynamics for such experiment (Haering, 2015). Figure 4 shows the flight path, and it is clearly visible the 2 loops performed. The vehicle was held at an average altitude of 60 meters for the benefit of controlling the variables and preserving the vitality of the data. A summarized test conditions can be found in Table 1.

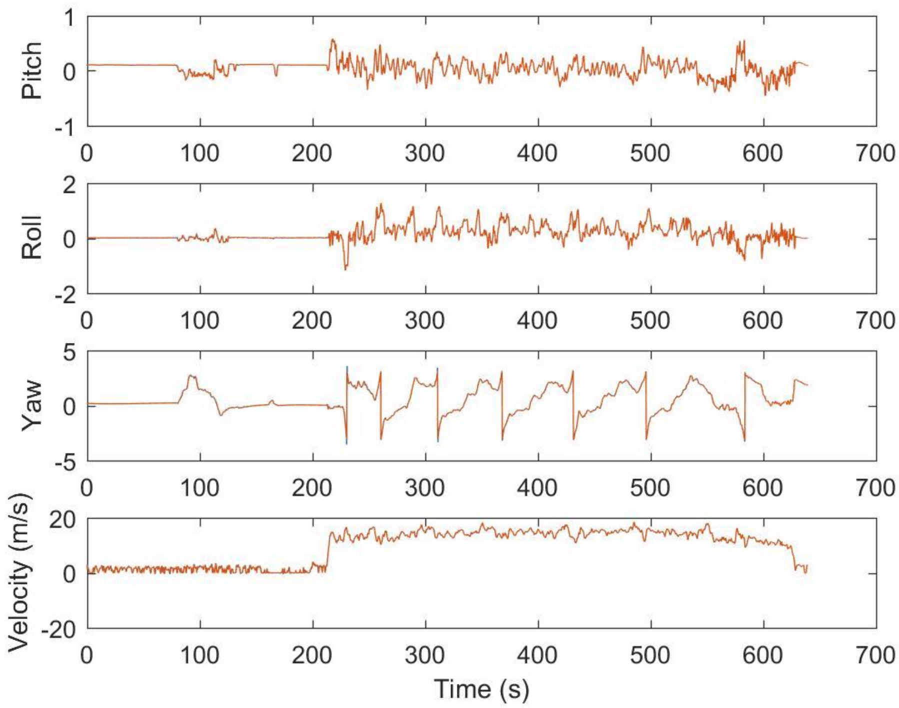

Figure 3. UAV Attitude Change and Velocity

This graph illustrates the change in pitch, roll, and yaw during flight. Also, readings from the velocity of the aircraft provided from the GPS module are shown. These three graphs are merged to demonstrate the relation of constant conditions and useful data between them.

Table 1. Test Flight Conditions

Flight Conditions	
Flight Date	June 10th, 2017 at 1:00 PM
Flight Altitude	60 meters
Flight Time	10 minutes
Useful data	After 3.3 minutes of flight
Speed of UAV	≈ 16 m/s
Maneuvers	Circular loops

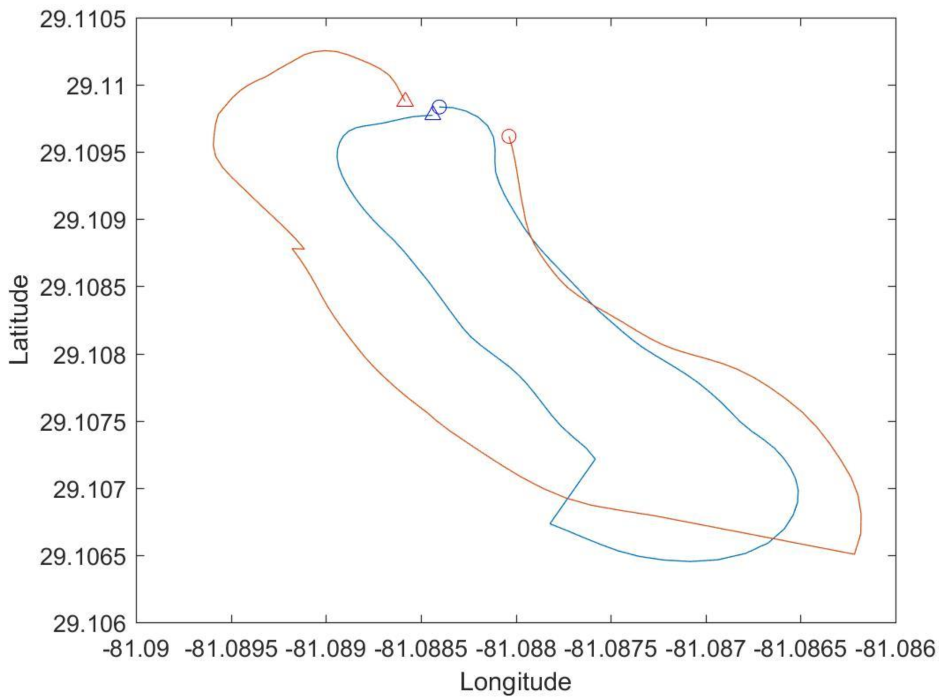

Figure 4. UAV Flight Path

This image illustrates the UAV's flight path, providing latitudinal and longitudinal coordinates. It is also depicted the two circular maneuvers performed to gather data in all directions. This data was collected from the 3D Robotics Global Positioning System Module.

After resampling and processing all the data, a MATLAB program was coded to incorporate the collected data and the model developed by Johansen et al. (2015, p. 513). The state of the system is provided by the following equation:

$$\begin{pmatrix} \widehat{\dot{v_w}^m} \\ \dot{\hat{\gamma}} \end{pmatrix} = K(u - \ u_r{}^m\hat{\gamma} - \ d_1{}^T R_n{}^b v_w{}^m) \qquad (1)$$

where K is the linear time-varying matrix of the Kalman-Bucy filter (Kalman & Bucy, 1961) , u is the velocity of the aircraft provided by the GPS module, $u_r{}^m$ is the airspeed provided by the pitot tube, $\hat{\gamma}$ is the online airspeed calibration factor to be estimated, $d_1{}^T$ is the location matrix, $R_n{}^b$ is the rotation matrix (changes in attitude) provided by the IMU, and $v_w{}^m$ is the wind velocity vector to be estimated.

A challenge found with equation (1) was that it incorporates time-varying matrices. This means that the inputs are changing over time, fast. It handles about 3,000 resampled data points. Because MATLAB does not simply solve time-varying matrices, it was needed to research for applications to solve the state of the system. It was applied and modified the Ricatti Equation to convert equation (1) into an Ordinary Differential Equation to be solved with a MATLAB ODE45 solver.

The computer code returned the estimation of the wind velocity in the North direction, East direction, and Down to Earth direction. Results showed an estimation of maximum wind velocity of approximately -7.4 m/s (16 mph) in the North and East direction. To obtain a valid result, the useful data was extracted (the ones collected 3 minutes after take-off), then the average was calculated to obtain -3.16 m/s (7 mph) for North and East directions. Both showed a negative value, meaning that the wind was moving from South to North and from West to East. Estimation in the Down to East direction was of values of – 10^3. This means that not much wind is coming upwards towards the UAV. Results on estimation of the airspeed calibration factor showed values between 1 and 1.25. Figure 5 shows the respective graphs of the output of the program (estimation of the wind velocity and estimation of the airspeed calibration factor).

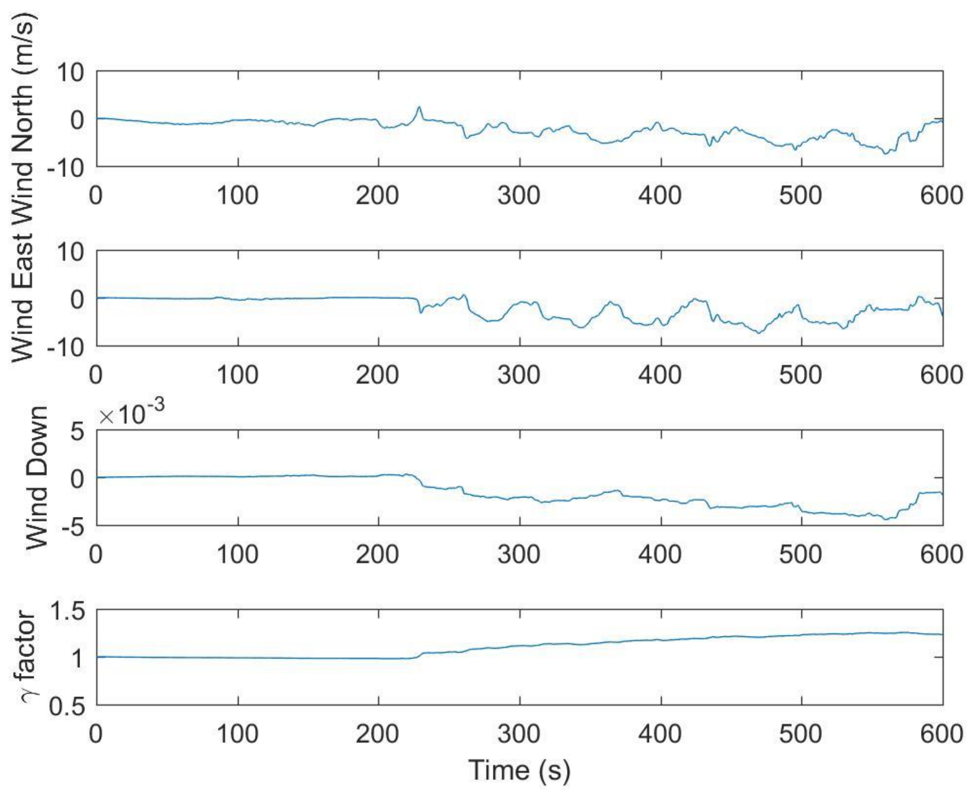

Figure 5. Wind Velocity and Airspeed Calibration Factor

This graph illustrates the estimated wind velocity in the NED frame. It also shows the estimation of the airspeed calibration factor.

Discussion

In order to validate results, they were compared with an online database called Weather Underground. Calculations for validation were based upon data points of June 10th, the date of the flight, at 12.53 PM (the closest available data point to the experimental flight time) with a value of 9.2 mph ENE. This value was compared with the resultant vector of the wind speed shown in Figure 6. When evaluating the magnitude of the actual (9.2 mph) and the experimental (10 mph), results showed an estimation of 8.6% error with the Weather Underground database for the flight location weather. Figure 7 shows the data used for the validation of the results.

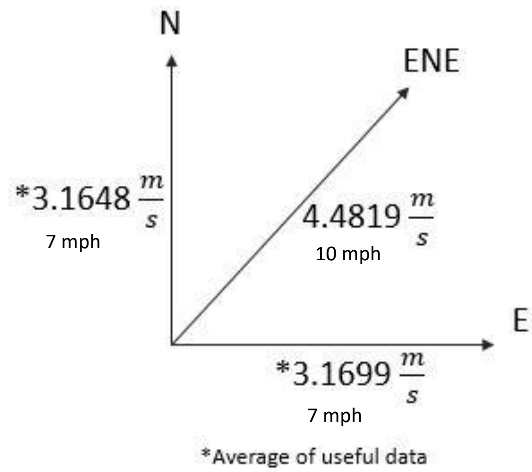

Figure 6. Magnitude and Direction Output from Estimator

This figure illustrates the magnitude of the North and East direction obtained for the average of the useful data (3 minutes after take-off). It also depicts the actual direction of the wind and magnitude calculated by geometry.

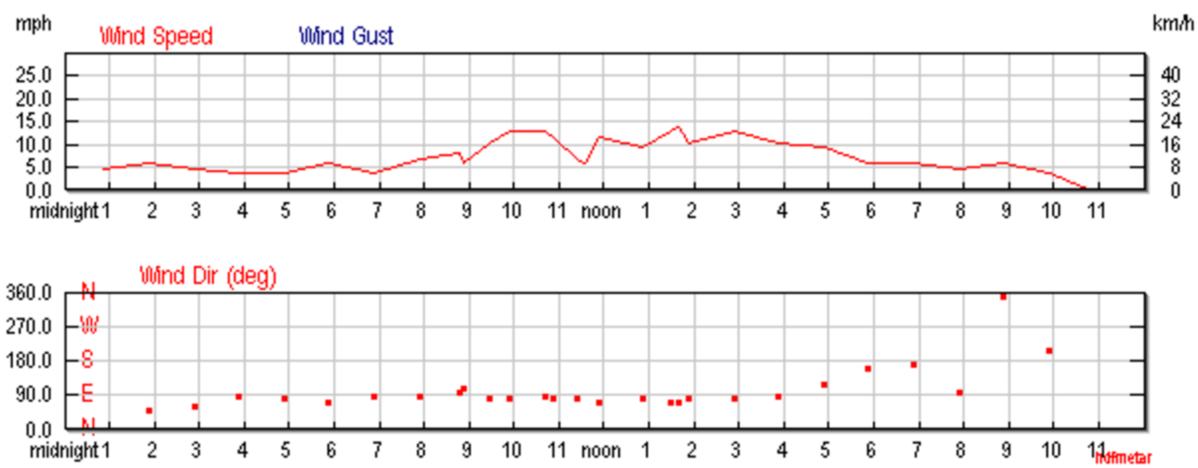

Figure 7. Weather Underground Wind Velocity Database

This graph illustrates the actual wind velocity of the day of the test flight.

Answering the research question, it is indeed possible to estimate the wind velocity on a Flexible-wing Unmanned Aerial Vehicle without any aircraft parameters. To reach such estimation, it was needed to assume the wind to be steady and slow varying. Additionally, all sensors are assumed to be calibrated at the minimum configuration. Connecting with the bigger research project of flight flutter, monitoring the airspeed and wind velocity on an NED frame leads to implementations on the control design of the wind, providing a better understanding of such interactions.

IV. Conclusion and Recommendations

It is used a testbed UAV to estimate the wind velocity by using only kinematic relationships developed by Johansen et al. (2015). The additional instrumentation used was a pitot tube to monitor the airspeed, a GPS module to measure the velocity of the aircraft, and an IMU to measure the change in attitude. This method of wind estimation is proven to be valid and yields a more accurate estimation of the incident angles using aerodynamic forces. This study discards the need of aircraft parameters, consequently optimizing the time an effort of researchers. One important contribution of this paper is that provides an application to the solution of equation (1) by implementing the Ricatti Equation, therefore optimizing the computational approach to the wind estimation. Because results showed 8.6% error with the true and accepted values, this investigation can be further developed in the research of better databases with more data points to compare with. Overall, the target of the research project was met because it accomplished to estimate the wind velocity on a Flexible-wing Unmanned Aerial Vehicle providing the magnitude and direction of the wind speed. Additionally, this paper can contribute to the followings:

- Estimation of the Angle-Of-Attack
- Estimation of the Sideslip Angle
- Implementations on the wing/aircraft control design
- Understand, visualize, and address the excessive vibration problem in flexible-wing aircraft.

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