Wind Measurement System Using Miniaturized Navigation Sensors for Light Aircraft and Sailplanes

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Abstract

An on-board wind measurement system is presented which is based on a new approach for determining wind speed and direction. This new approach uses data from a navigation system for determining the angles of attack and sideslip so that no dedicated aerodynamic sensors are required. Furthermore, the system can be realized using miniaturized hardware components yielding a low-cost solution. Efficient software, which contributes to the low-cost solution, has been developed for operating the system. Results from flight tests are presented for verification of the system.

Introduction

Knowing the speed and the direction of the wind is generally an aid for the pilot in performing flight tasks. This is because the wind can have significant effects for various reasons. For example, take-off and landing in a cross wind require appropriate control actions for compensation. Even more important are wind conditions which can cause difficulties for the pilot or even yield hazards. Such situations can be due to a severe shear wind during a landing approach where the wind can significantly change[1]. Other dangerous situations concern micro bursts.

However, there are also wind conditions which have an advantageous effect. This holds for sailplanes utilizing wind phenomena which allows them to gain altitude, or, more generally to increase the energy state of the vehicle. Such conditions particularly concern thermals or other wind conditions of rising air.

For determining the wind on board an aircraft, it is necessary to know the angles of attack and sideslip. Having knowledge of these angles, they also can be indicated for the pilot. This can have an advantageous effect for various reasons. One is that knowledge of the angles of attack and sideslip, which are important quantities for the air flow at the aircraft, contributes to flight safety by supporting the pilot in critical conditions like the stalling behaviour of the aircraft or with respect to departure characteristics. Another reason is that the pilot can better control optimum flight conditions, e.g. avoiding a sideslip angle and, thus, its detrimental effect on drag.

The angles of attack and sideslip are usually measured with aerodynamic sensors. These sensors require an appropriate location on the aircraft to provide proper measurement data. The sensors, their installation and maintenance are a cost item.

There are other techniques for determining the angles of attack and sideslip. These techniques are based on computational procedures using data from a navigation system. Concepts and systems have been described elsewhere[2-5]. A further aspect of recent research is the accuracy required for wind measurement on board an aircraft[6].

The purpose of this paper is to present a solution for a wind measurement system using navigation data for determining the angles of attack and sideslip. Another issue is a miniaturization of the hardware and a low-cost approach.

System concept

Determination of wind speed and direction is based on the relationship of the motion of the aircraft with respect to the earth and the moving air. The relationship which is graphically presented in Fig. 1 can be described as

$$\vec{V}_W = \vec{V}_K - \vec{V} \tag{1}$$

With reference to this relationship, the basic concept of the system for measuring and determining the speed and the direction of the wind is presented in Fig. 2. Data on airspeed, acceleration, attitude, heading and position as well as on control surface deflections are provided by sensor modules. Using these data, the angles of attack and sideslip can be determined. A further step yields the speed and the direction of the wind.

Procedure for determination of angles of attack and sideslip

The angles of attack and sideslip are determined using data from the navigation system, instead of aerodynamic sensors. This procedure yields a significant contribution to the low-cost solution.

Determination of angles of attack and sideslip

For determining the angle of attack, the following relationship can be derived from the aerodynamic force equation taking into account inertial measurement data, aerodynamic derivatives and control surface deflections:

$$\alpha_A = -\frac{n_z mg/(\bar{q}S) + C_{L0} + C_{Lq} q l_\mu / V + C_{L\eta}\eta}{C_{L\alpha} + n_x mg/(\bar{q}S)} \tag{2}$$

In order to reduce the effect of high frequency disturbances incorporated into the estimation algorithm by accelerometer and gyroscope measurement noise, while assuring high system bandwidth, an additional element is introduced. For this purpose, the following kinematic expression is used as a second relationship in the estimation algorithm, yielding

$$\alpha_K = \frac{\Theta - \gamma}{\cos \Phi} \qquad (3)$$

Although this quantity is usually biased from the aerodynamic angle of attack resulting from the wind influence, its dynamic characteristics can be used to improve the system bandwidth. In Fig. 3, it is shown how the relationships described in Eqs. (2) and (3) were implemented in the computational procedure.

For determining the angle of sideslip, a technique similar to that for the angle of attack is applied. To this end, the following expression obtained from the aerodynamic force equation in the lateral direction is used

$$\beta_A = \frac{n_y mg / (\bar{q}S) - C_{Yp} ps/V - C_{Yr} rs/V - C_{Y\zeta}\zeta}{C_{Y\beta}} \qquad (4)$$

For enhancing the systems bandwidth while reducing the impact of measurement noise from the acceleration sensors, a relationship pertaining to the lateral dynamics of the aircraft is applied in a complementary filter configuration. This relationship reads

$$\dot{\beta}_K = \frac{n_y g + g \sin \Phi \cos \Theta}{V_K \cos \beta_K} - r_K \cos \alpha_K + p \sin \alpha_K \qquad (5)$$

Figure 4 shows the structure of the algorithm for the angle of sideslip determination.

The modules for determining the angles of attack and sideslip are incorporated into the wind measurement system (Fig. 2). This is relating to the block termed AoA/AoS Determination Module.

Refinement of aerodynamic model

The determination of the angles of attack and sideslip as described in the previous section is based on an aerodynamic model of the aircraft. This model needs to have an appropriate degree of preciseness.

For a general application of the approach presented in this paper, it is not necessary that initially a detailed aerodynamic model with aerodynamic derivatives required for the estimation algorithm is available. Rather, there can be a first set of data which yield only an approximate estimate of the aerodynamic model. In this case it is possible to develop a refinement of the model. Such a model refinement process was performed for the aircraft used in the flight test program described in this paper.

For the case under consideration, an approximate set of the aerodynamic derivates was obtained using simple computational methods. Then, as a first step in the refinement process, data for the angles of attack and sideslip as well as for the air speed were generated using an aerodynamic sensor which was installed on the aircraft (Figs. 5 and 6). This aerodynamic sensor, which is at an appropriate location free from flow disturbances, provides high-precision data on the flow angles and the air speed. These high-precision data then were used as reference data for the refinement of the aerodynamic model.

Applying a nonlinear least square-fit algorithm the residuals concerning estimated and true values are minimized using correction terms derived from the following relationship

$$\min_x \left(f(x) \right) = \min_x \left([\alpha_{ref} - \tilde{\alpha}_A(\vec{\mathbf{x}})]^2 \right) < J_{\lim}; \quad \vec{\mathbf{x}} = \left[K_{CL0} \quad K_{CL\alpha} \quad \ldots \right]^{\mathrm{T}} \qquad (6)$$

This relationship holds for the angle of attack with

$$\vec{\mathbf{x}} = \left[K_{CL0} \quad K_{CL\alpha} \quad \ldots \right]^{\mathrm{T}} \qquad (7)$$

being a vector containing the correction terms. A similar approach was used for refining the derivatives related to the lateral dynamics.

Wind measurement system

The described concept for wind measurement has been realized as an experimental system. It is installed in the research aircraft of the Institute of Flight Mechanics and Flight Control of the Technische Universität München (Fig. 5).

The research aircraft is equipped with computer, navigation and air data systems. The calculations for the wind determination are performed using a PC with the following features: Pentium IV, 1.7 GHz, OS Linux, 512 MB RAM. The navigation system which operates at an update rate of 50 Hz provides data on rotational rates and attitude angles. Position data are obtained from a GPS receiver (with a satellite-based Augmentation System signal, a differential code and a real time kinematic capability) at a data rate of 20 Hz.

Furthermore, the test equipment aboard the research aircraft employs an air data measurement beam (Fig. 6). This device comprises aerodynamic sensors for measuring the angles of attack and sideslip as well as the airspeed with high precision. The sensors attached to the measurement beam are placed at a location free of disturbances from the flow around the aircraft (Fig. 5). They are used for calibration purposes.

An important aspect in developing the wind determination system concerns the software. The goal was to achieve a high efficiency. Implementation was performed using C/C+ with emphasis on minimum computational cost. The program comprises several sub-routines. For example, three subroutines are used for sideslip angle determination. Two subroutines are required for computing β_A and $\dot{\beta}_K$ (Fig. 4). The third one is concerned with the implementation of the filtering modules. As the system operates at 50 Hz, the interrupt-driven routine is processed at the same frequency. Tests show that the required computing time on the hardware installed in the aircraft does not exceed 15 µs. The computation time for the wind determination module (Fig. 2) is about 2 ms. Thus, the on-board hardware provides sufficient capabilities for the calculations in real-time.

Flight test results

The wind measurement system was subjected to a comprehensive flight test program. The first flight test series was concerned with testing the method for determining the angles of attack and sideslip. In the second series, the complete wind measurement system was tested.

Results from the flight tests concerned with the determination of the angles of attack and sideslip are presented in Fig. 7. The results are from the described method for determining the flow angles and from the high-precision aerodynamic sensors on the measurement beam. Figure 7 shows that the two data sets which cover a wide angle of attack range compare well. This holds for the amount of the angle of attack values and for their time behaviour, including phases of rapid changes. The results shown in Fig. 7 are representative for the performance of the method for determining the angle of attack as well as the angle of sideslip.

The second flight test series, which was concerned with the wind measurement system, was a systematic approach to test for a great variety of wind conditions. For this purpose, flight tests were conducted in different wind conditions, like a constant wind field, a shear wind region or an area of rising air.

Results from a test flight in a constant wind field are presented in Figs. 8 and 9. The aircraft performed a turn at a given airspeed. Thus, the speed with respect the earth changes in the course of the turn because of the effect of the wind (Fig. 8). The wind speed and direction from the wind measurements are shown in Fig. 9.

Other tests were concerned with flights in an area of rising air. Results from a flight in a thermal are presented in Figs. 10 and 11. In Fig. 10, the vertical wind speed and its changes encountered during the test flight are shown. The time history of the airspeed is given in Fig. 11.

Conclusions

A new approach is presented for determining the speed and the direction of the wind aboard an aircraft. An objective is a low-cost solution of the wind measurement system so that it is affordable for light aircraft and sailplanes. This can be achieved with low-cost hardware components and efficient software. A significant contribution to the low-cost solution is due to the fact that the angles of attack and sideslip are determined using data from the navigation system, instead of aerodynamic sensors. For this purpose, an appropriate computational procedure was developed. Another objective was a miniaturization of the system. Results from the flight tests are presented which show the effectiveness of the system.

References

[1]Hahn, K.-U., "Effect of Wind Shear on Flight Safety," *Progress in Aerospace Sciences*, 26(1), 225-259, 1989.

[2]Looye, G., Joos, H.-D., "Design of Robust Dynamic Inversion Control Laws using Multi- Objective Optimization," *Proceedings of the AIAA Guidance, Navigation and Control Conference, 2001*, AIAA Paper 2001-4285, 2001.

[3]Farineau, J., "Lateral Electric Flight Control Laws of a Civil Aircraft based upon Eigenstructure Assignment Technique," AIAA-89-3594, 1989.

[4]Heller, M., Myschik, S., Holzapfel, F., Sachs, G., "Low-Cost Approach Based on Navigation Data for Determining Angles of Attack and Sideslip for Small Aircraft," *Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit*, 11-14 August 2003, Austin, Texas, ISBN 1-56347-638-X, AIAA 2003-5777, 1-7, 2003.

[5]Myschik, S., Heller, M., Holzapfel, F., Sachs, G., "Low-Cost Wind Measurement System For Small Aircraft," *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit*, 16.-19. August 2004, Providence, Rhode Island, ISBN 1563476819, AIAA-2004-5240, 1-10, 2004.

[6]Cremer, M..“Genauigkeitsanforderungen an Sensorik zur Windmessung an Bord eines Flugzeuges,” DGLR-2004-016, Deutsche Gesellschaft für Luft- und Raumfahrt, Bonn, 2004.

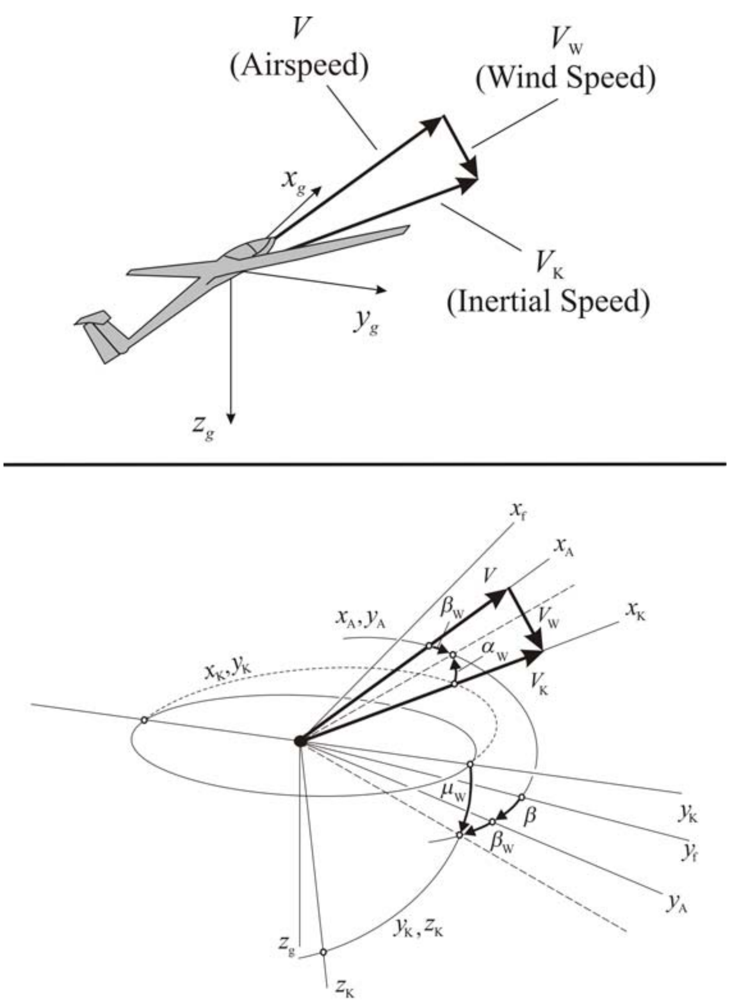

Figure 1 Speed vectors and coordinate systems

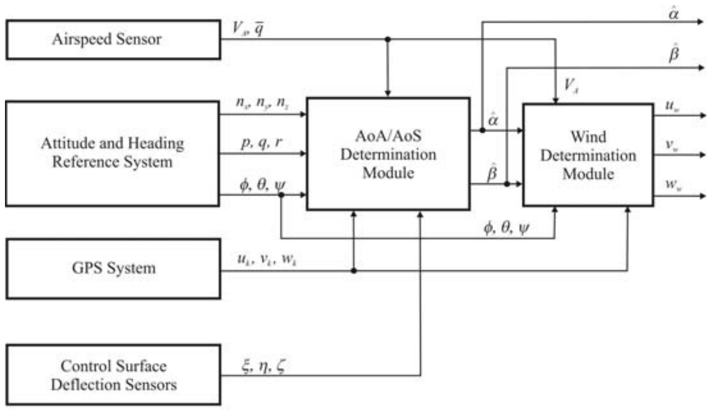

Figure 2 System concept

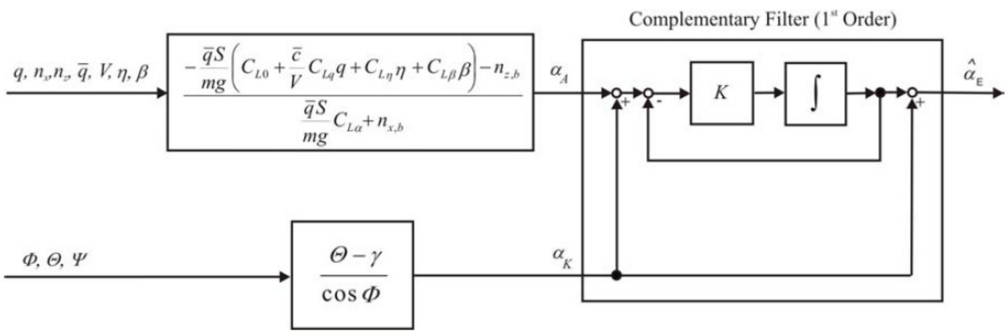

Figure 3 Module for angle of attack determination

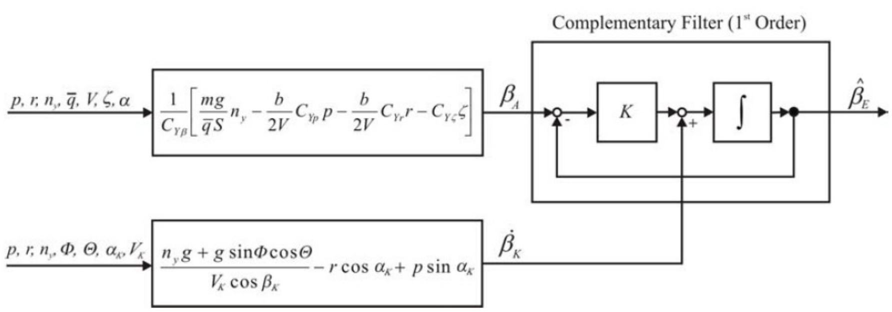

Figure 4 Module for angle of sideslip determination

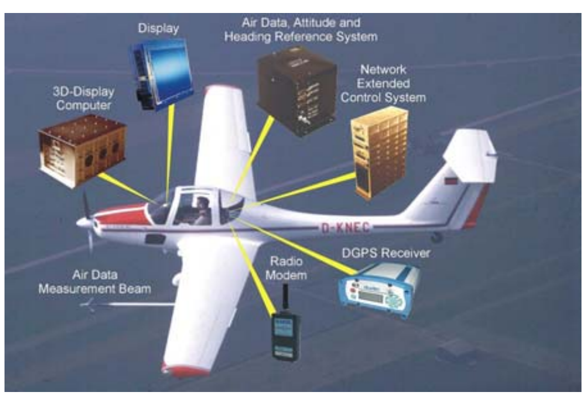

Figure 5 Research aircraft with test equipment

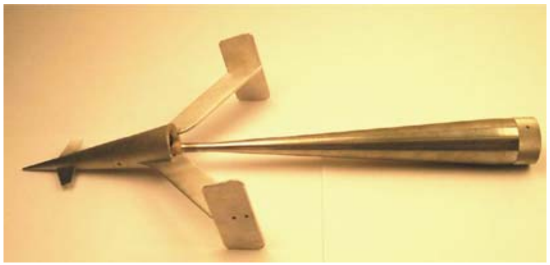

Figure 6 Aerodynamic sensor for angles of attack and sideslip and for true airspeed.

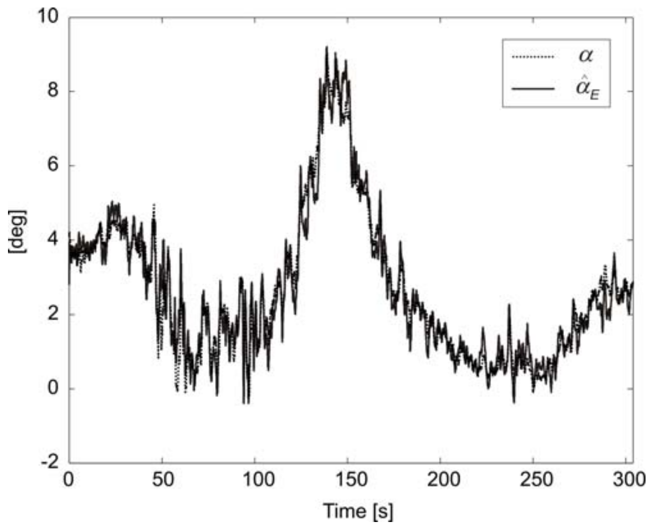

Figure 7 Results from flight tests for angle of attack determination.

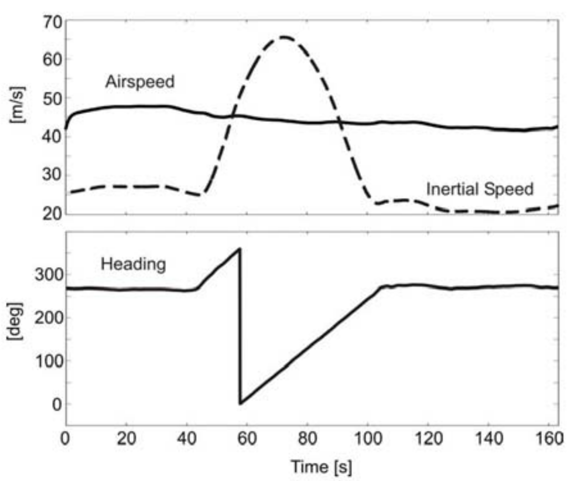

Figure 8 Speeds and heading during a turn in a constant wind field.

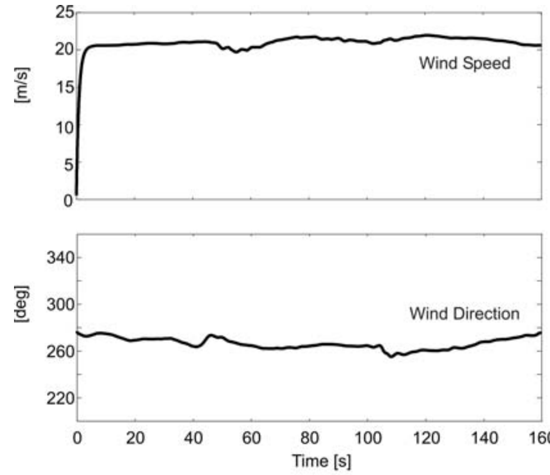

Figure 9 Wind speed and direction during a turn in a constant wind field.

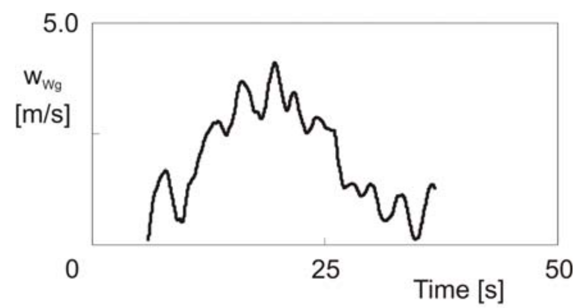

Figure 10 Vertical wind speed component during a test flight through a thermal.

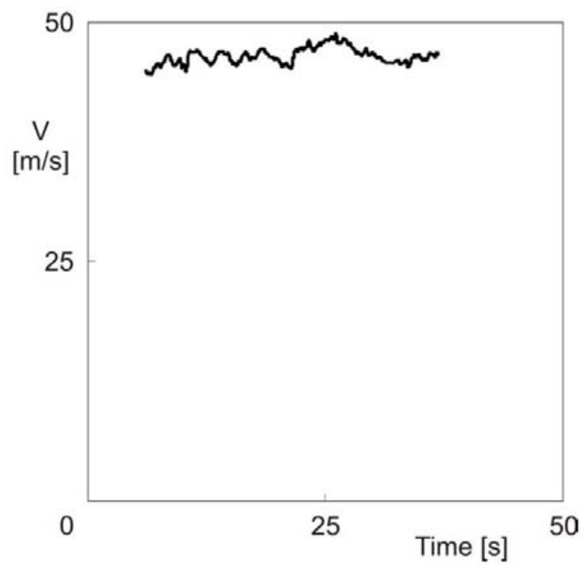

Figure 11 Airspeed during a test flight through a thermal.