ON-BOARD WIND MEASUREMENT SYSTEM BASED ON MINIATURIZED NAVIGATION SENSORS

S. Myschik and G. Sachs
Institute of Flight Mechanics and Flight Control, TU München, Germany

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Abstract

An approach for an on-board wind measurement system for aircraft is presented, directed at a low-cost solution and a miniaturization of the hardware elements. An efficient software has been developed which contributes to the low-cost solution. With appropriate computational procedures, it is possible to determine the angles of attack and sideslip using navigation data. Thus, dedicated aerodynamic sensors are not needed. Results from flight tests are presented for showing the performance of the system.

1 Introduction

The wind plays an important role in aircraft operation. There are beneficial effects, contributing to improve the flight performance. This holds for decreasing the ground roll distance required for take-off utilizing a head wind, or for reducing the fuel consumption in aircraft cruise with a tail wind. However, there are also detrimental effects of the wind. These can range from unwanted effects causing difficulties in controlling the aircraft to dangerous consequences yielding hazardous flight conditions. Among detrimental effects can be a landing approach in a shear wind which shows changes of the wind speed with altitude (Ref. 1). Other detrimental flight conditions may be due to micro bursts.

For responding to possible wind conditions, particularly for coping with detrimental effects, knowledge of the speed and the direction of the wind is an aid for the pilot. In order to provide the pilot with such data, a measurement system is required which continuously gives the wind speed and direction with an appropriate update rate.

For determining the wind on board of an aircraft, it is necessary to know the angles of attack and sideslip. They are usually measured using dedicated aerodynamic sensors. It is necessary to install the sensors at an appropriate location of the airplane in order to yield proper measurement data. The sensors, their installation and maintenance are a cost item.

However, the angles of attack and sideslip can also be determined with other techniques, Refs. 2-5. Using such techniques, aerodynamic sensors are not needed. An issue in determining the wind on board of an aircraft is accuracy. This is subject of recent research (Ref. 6).

The purpose of this paper is to present an approach for an on-board wind measurement system. Emphasis is placed on a solution which features a miniaturization of the hardware and a low-cost solution. Furthermore, an efficient software was developed, contributing to the objective of a low-cost solution.

2 Conceptual Approach

For determining the wind speed and direction on board an aircraft, reference is made to the relationship between the inertial speed, the airspeed and the wind speed as shown in Fig. 1. Accordingly, the following relation holds:

$$\vec{V}_W = \vec{V}_K - \vec{V} \qquad (1)$$

Based on this relationship, the conceptual approach for measuring and determining the speed and the direction of the wind was developed. It is graphically presented in Fig. 2. Sensor modules are used to provide data on airspeed, acceleration, attitude, heading and position. These data are transferred to the wind determination module which will be described in more detail in a subsequent paragraph.

In Fig. 2, it is also shown that data on the rotational rates and the deflections of the control surfaces are measured. The data are used to determine the angles of attack and sideslip, together with other data. For this purpose, an appropriate computational procedure is applied. Determining the flow angles in the described manner is a means to avoid the use of aerodynamic sensors. This contributes to achieve a low-cost solution.

A presentation showing more details on data processing and computation for the wind determination is provided by Fig. 3. This Fig. shows how measurement values of the navigation system and flow condition data are used for determining the wind. The wind speed vector can be given in components of body fixed or geodetic reference systems.

In the computational process, a coordinate transformation from the geodetic to the body-fixed systems is performed, using the following relation:

$$\mathbf{M}_{fg} = \begin{bmatrix} \cos\Theta\cos\Psi & \cos\Theta\sin\Psi & -\sin\Theta \\ \sin\Phi\sin\Theta\cos\Psi - \cos\Phi\sin\Psi & \sin\Phi\sin\Theta\sin\Psi + \cos\Phi\cos\Psi & \sin\Phi\cos\Theta \\ \cos\Phi\sin\Theta\cos\Psi + \sin\Phi\sin\Psi & \cos\Phi\sin\Theta\sin\Psi - \sin\Phi\cos\Psi & \cos\Phi\cos\Theta \end{bmatrix} \quad (2)$$

Furthermore, Fig. 3 shows that filter are applied, yielding

$$F_{TP}(s) = \frac{1}{T_W s + 1} \quad (3)$$

The Euler angles necessary for the coordinate transformation, Eq. (2), and the inertial speed vector, given by

$$\vec{V}_K = \begin{bmatrix} u_{Kg} & v_{Kg} & w_{Kg} \end{bmatrix}^{\mathrm{T}}$$

are obtained from an INS/GPS navigation system.

For improving the quality of the data provided by the installed low-cost sensors for accelerations and rotational rates, Kalman filtering technique are applied. For this purpose, a linear error model is used, yielding

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{F}\mathbf{x} + \mathbf{w} \\ \mathbf{y} &= \mathbf{H}\mathbf{x} + \mathbf{v} \end{aligned} \quad (4)$$

3 Experimental Wind Determination System

The described conceptual approach resulted in an experimental system for determining the wind speed and direction. The system is installed in the research aircraft of the Institute of Flight Mechanics and Flight Control of the Technische Universität München, Fig. 4. The research aircraft is equipped with computer, navigation and air data components which are applied for the wind determination.

The computations are performed using a PC based hardware. It shows the following data: Pentium IV, 1.7 GHz, OS Linux, 512 MB RAM. The navigation system provides data on rotational rates and attitude angles, operating at an update rate of 50 Hz. 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.

The test equipment of the research aircraft also employs an air data measurement device (Fig. 4). With this device comprising aerodynamic sensors for measuring the angles of attack and sideslip as well as the airspeed, measurement data of high accuracy are available. The sensors attached at the measurement beam are placed at location free of disturbances of the flow around the aircraft (Fig. 4). They are used for reference and calibrating purposes with respect to the data provided by the wind determination system on the angles of attack ad sideslip.

In regard to the software, a high efficiency was a development goal. Implementation was performed using C/C+ with emphasis on minimum computational cost. The program comprises several sub-routines. 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.

4 Flight Test Results

The wind measurement system is subject to a comprehensive flight test program. A systematic approach is conducted, testing for a great variety of wind conditions. This concerns flights in a constant wind field, a shear wind region, areas of rising air (thermals, wind over a hill), etc.

Results from test flights in a constant wind field are presented in Figs. 5 - 7. The results given in Fig. 5 which shows the wind speed and direction provided by the wind measurement system refer to a straight flight. The results depicted in Figs. 6 and 7 concern another flight manoeuvre. Here, the aircraft performed a turn at a given airspeed. Accordingly, the speed with respect the earth changes in the course of the turn because of the effect of the wind, Fig. 6. The wind speed and direction provided by the wind measurement system are shown in Fig. 7.

A wind condition with changes in the speed and the direction of the wind is subject of the test flight results of which are presented in Figs. 8 - 10. In these Figs., the wind speed components related to the geodetic system are shown. Significant changes took place in the course of the flight. They concern the wind speed in the longitudinal (Fig. 8), the lateral (Fig. 9) as well as the vertical (Fig. 10) directions.

Another wind condition with changing characteristics is dealt with in Figs. 11 and 12. The flight test results of which are shown in these Figs. is concerned with a shear wind. The aircraft performed a take-off, a traffic pattern and a landing (Fig. 10). In the climb and descent phases of this test flight, a wind the strength of which shows changes with altitude was encountered. The data obtained from the wind determination system are presented in Fig. 11.

5 Conclusions

A system was developed for determining the speed and the direction of the wind on board of an aircraft. Development objectives are a low-cost solution and a miniaturization of the hardware. An essential feature of the conceptual approach of the system is the determination of the angles of attack and sideslip using navigation data. This feature and an efficient software contributed to the low-cost solution. The wind determination system is tested in a flight test program from which results are presented for showing its performance.

6 References

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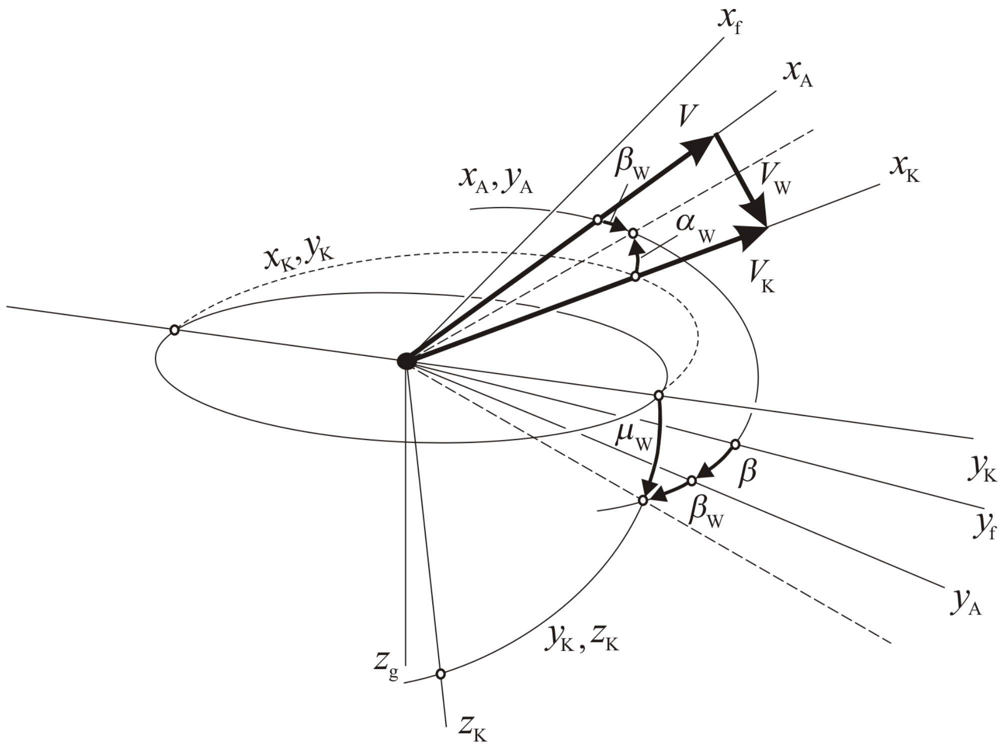

Fig. 1: Speeds and coordinate systems

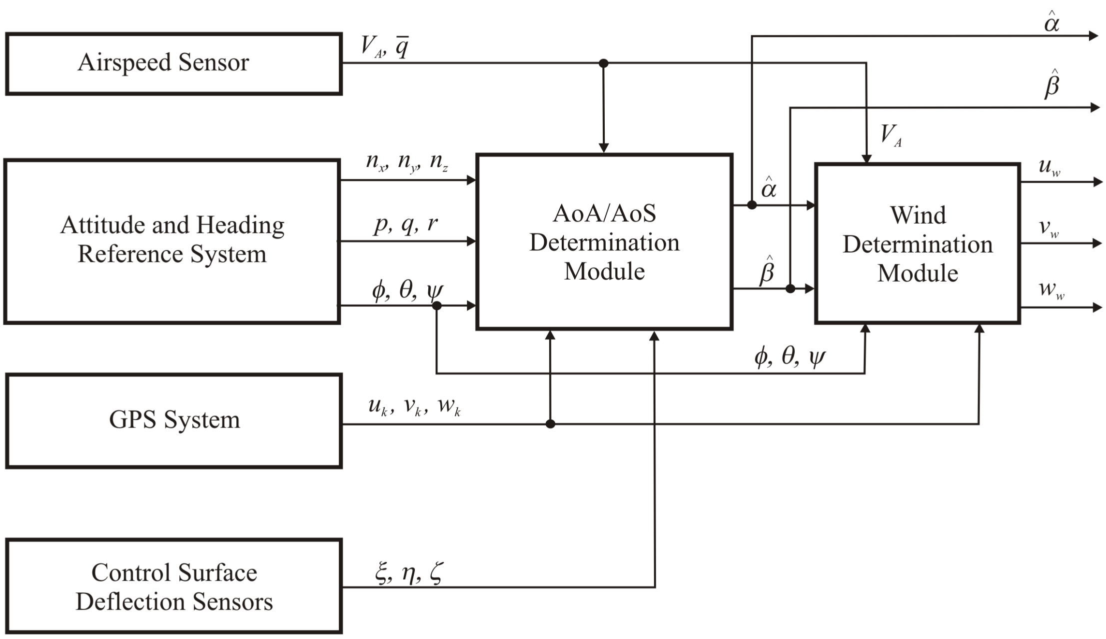

Fig. 2: Concept of wind determination system

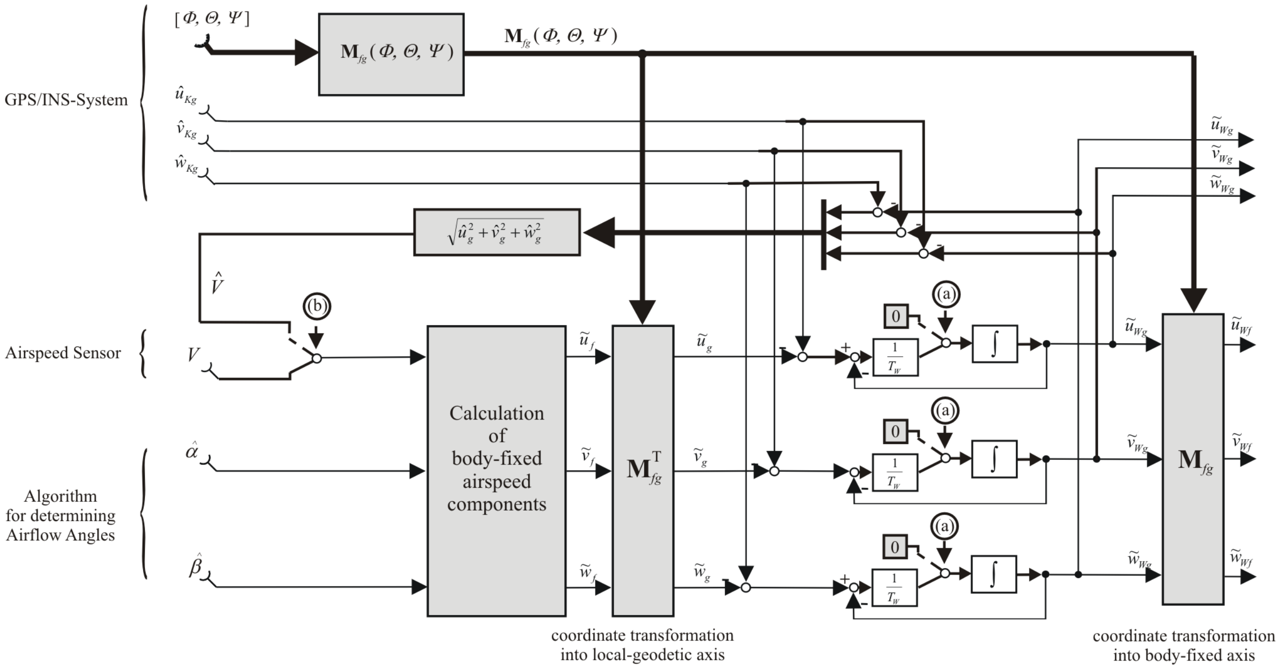

Fig. 3: Determination of wind

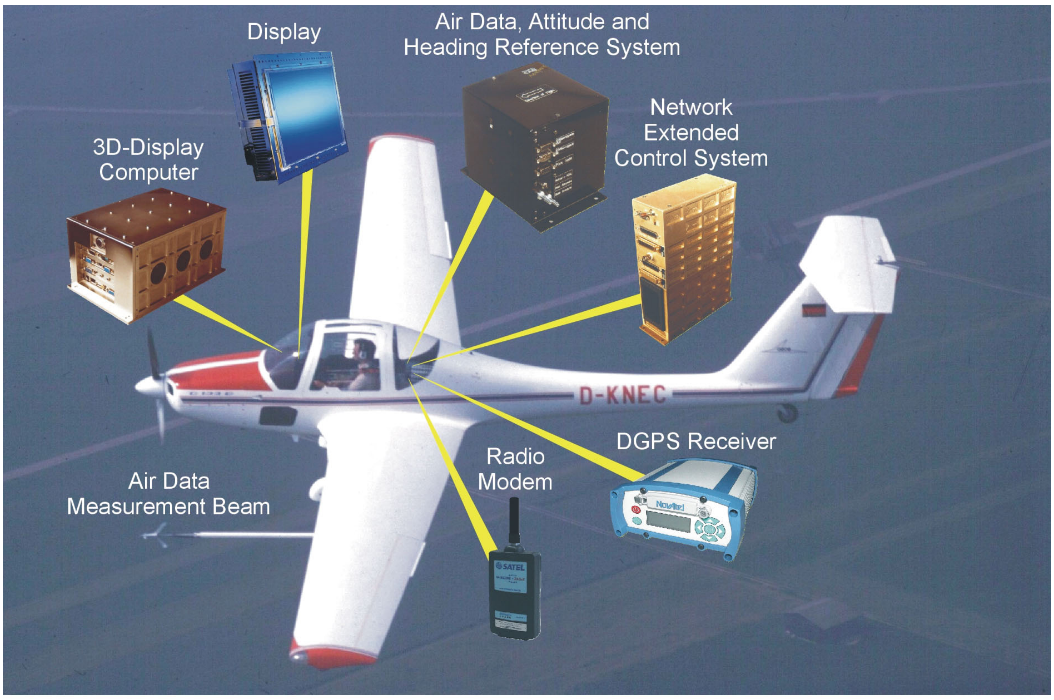

Fig. 4: Research aircraft with test equipment

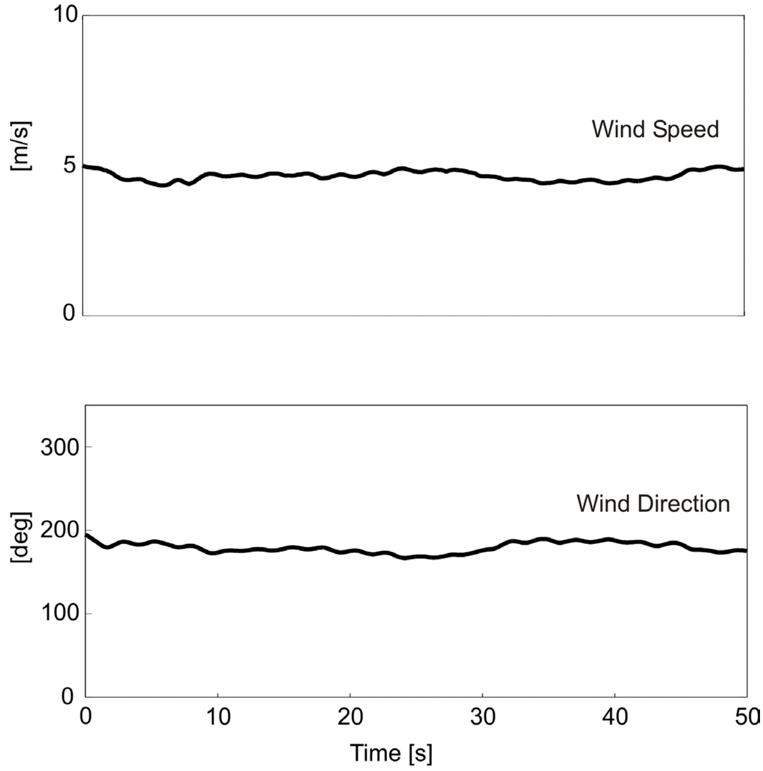

Fig. 5: Wind speed and direction during straight flight in constant wind field

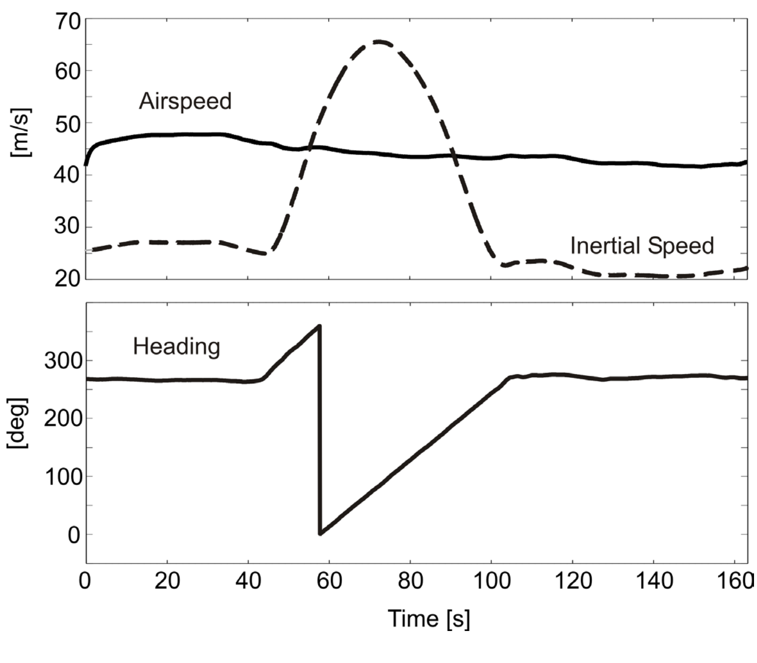

Fig. 6: Speeds and heading during 360 deg turn in constant wind field

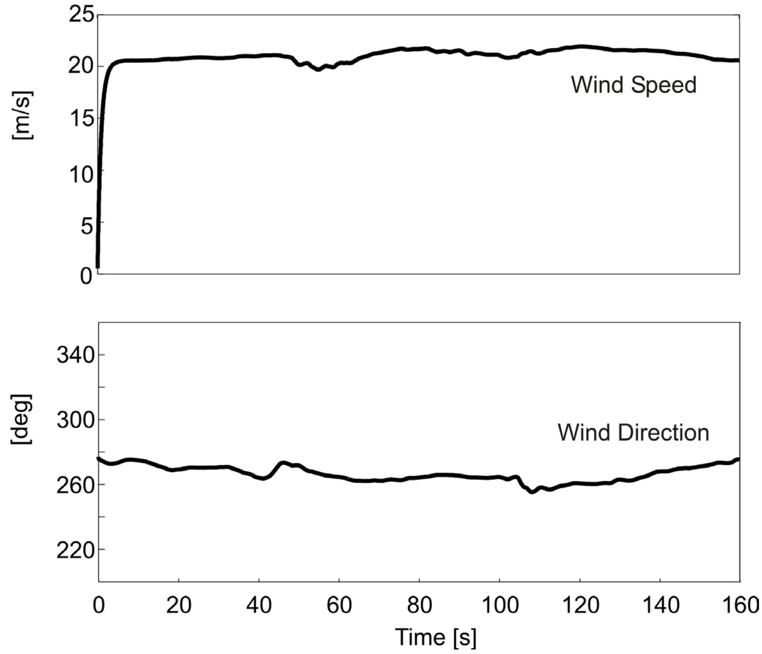

Fig. 7: Wind speed and direction during 360 deg turn in constant wind field

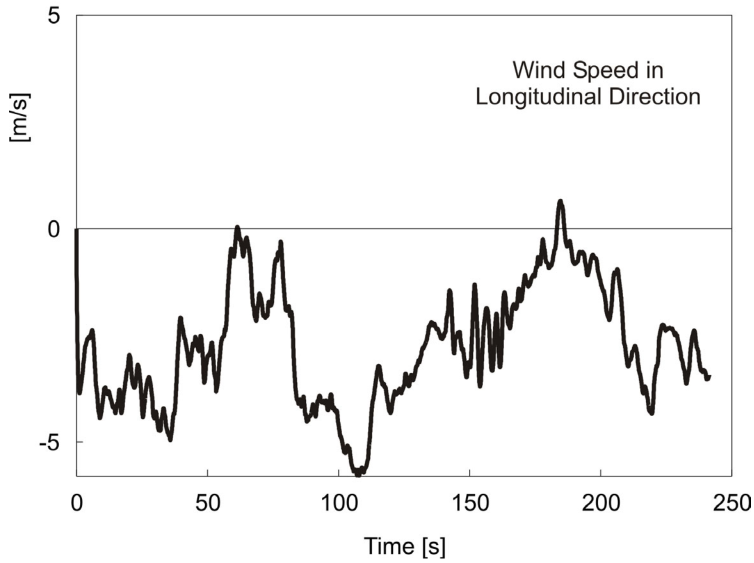

Fig. 8: Longitudinal wind speed component during test flight in varying wind field

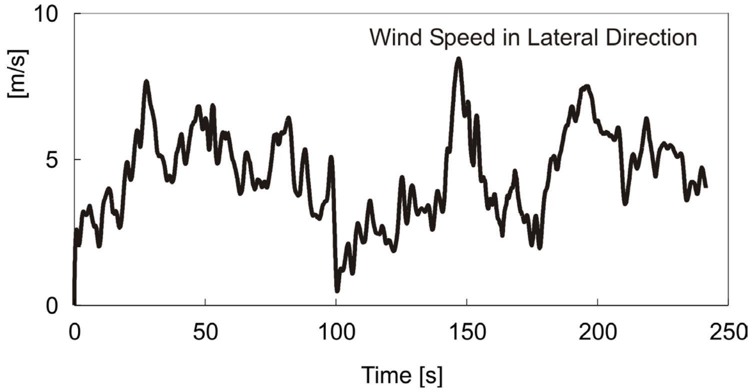

Fig. 9: Lateral wind speed component during test flight in varying wind field

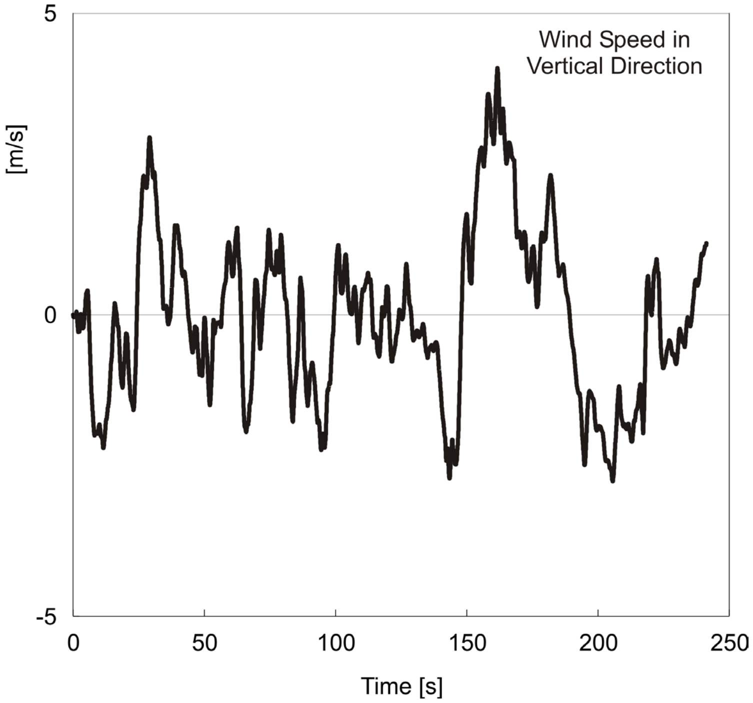

Fig. 10: Vertical wind speed component during test flight in varying wind field

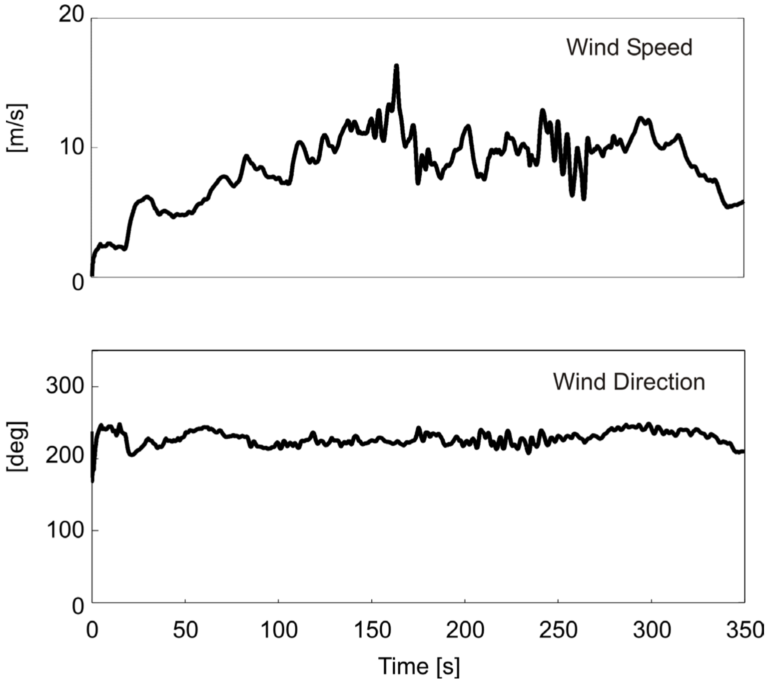

Fig. 11: Wind speed and direction during test flight involving take-off, traffic pattern and landing

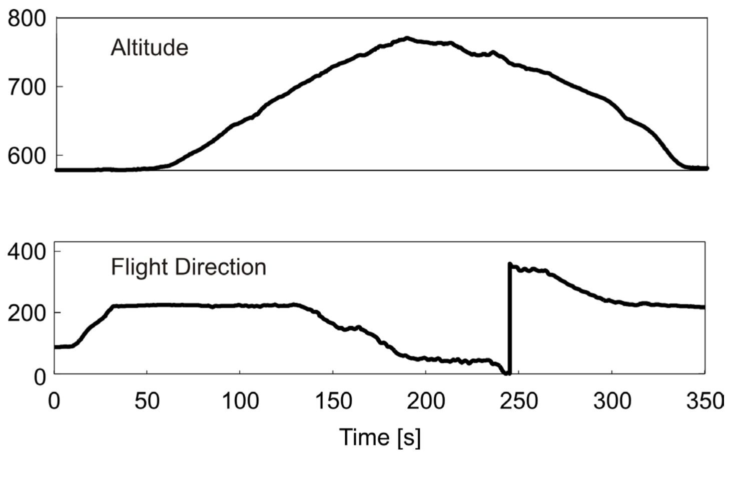

Fig. 12: Altitude and flight direction during test flight involving take-off, traffic pattern and landing