Algorithm Development for Estimating Projections of Wind Velocity Using Measurements of Airspeed, Angle of Attack and Sideslip

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Abstract

The article considers the problem of estimating wind velocity in flight. The method proposed in this paper provides estimates for three projections of wind velocity in a normal Earth coordinate system using satellite navigation data (SNS), as well as on-board barometric measurements of flight speed. It is assumed that the wind has a constant velocity and direction for the flight interval, the duration of which is 30–31 s. The proposed algorithm can provide measurement of three projections of wind velocity for interval 0.5 s, which compares favourably with other options when the required observation interval was tens of seconds.

Keywords: estimation, maneuver, wind velocity, angle of attack, sideslip, airspeed

1. Introduction

In aeronautical technology, the measurement of atmospheric parameters and aircraft motion parameters is very important during flight tests [1]. To estimate the measurement errors, the system identification method can be utilized [2–5]. Recently, parameter identification algorithms have been proposed for systematic errors in measuring the angle of attack and sideslip angle of an aircraft [6], orientation angles [7] and airspeed [8]. At the same time, determining the actual values of wind velocity during flight test modes is relevant. The possibilities for developing methods of estimating wind speed by using satellite navigation systems in flight tests have expanded significantly, especially in comparison with traditional technologies for optical measurements of the flight path [9]. Accuracy of estimation of wind velocity is necessary for numerous flight test tasks of the aircraft [1–11]. The proposed method in this article provides estimates for 3 projections of wind velocity in the Earth’s normal coordinate system using data from satellite navigation systems (SNS), as well as barometric airborne measurements. In this paper, it’s proposed an algorithm which uses sliding window model, as well as its accuracy characteristics, taken from the processing of simulation data. The influence of airspeed error on the estimation process of wind velocity is also discussed.

2. Problem formulation

It is assumed that the wind has a constant velocity and direction for a short flight interval which duration is 30 s and 31 s. This means, that for this time interval the values of the wind velocity projections on the axis of the normal earth coordinate system are constant. In order to define the sequence of operations to generate estimates of components of wind speed, it’s necessary to create the object model. Equations for projection of airspeed of the aircraft on the normal earth coordinate system are defined as follow:
\[
V_{\text{est},o}(t_i) = V_{\text{est},\text{CHC}}(t_i) - W_{\text{est}}
\]
\[
V_{\text{est},z}(t_i) = V_{\text{est},\text{CHC}}(t_i) - W_{\text{est}}
\]
\[
V_{\text{est},x}(t_i) = V_{\text{est},\text{CHC}}(t_i) - W_{\text{est}}
\]

where, \( V_{\text{est},\text{CHC}}(t_i), V_{\text{est},\text{CHC}}(t_i), V_{\text{est},\text{CHC}}(t_i) \) — the projections values of the airspeed of the aircraft measured by SNS on the axis of the normal earth system; \( W_{\text{est}}, W_{\text{est}}, W_{\text{est}} \) — unknown projections values of wind velocity on the axis of the normal earth system to be identified.

Obviously, the modulus of the airspeed is given as follow:
\[
V_i(t_i) = \sqrt{V_{\text{est},o}(t_i)^2 + V_{\text{est},z}(t_i)^2 + V_{\text{est},x}(t_i)^2}
\]

To go to the body axes, the corresponding matrix of guide cosines is utilized:
\[
\begin{bmatrix}
\cos \beta \cos \alpha & \cos \beta \sin \alpha & -\sin \beta \\
-\sin \alpha & \cos \alpha & 0 \\
\sin \beta \cos \alpha & \sin \beta \sin \alpha & \cos \beta
\end{bmatrix}
\]

During the calculations, the orientation angles should be taken according to the output signals of the vertical direction included in the navigation system. A constant yaw error, which is permissible to be considered a constant over a section of 15 ... 80 s, should be included in the vector of identifiable parameters.

The multiplicative error of the measuring channels is taken into account by the steepness coefficients of the aerodynamic angle sensors \( K_\alpha \) and \( K_\beta \).

In the presence of nonlinearity, an additional approximation is introduced, which is not of fundamental difficulty, but it increases the dimension of the problem.

By using the projection of airspeed on the body axes, the formulas for the values of the angle of attack and sideslip can be written as follow:
\[
\alpha_i(t_i) = -\arctan \left( \frac{V_{\text{est},o}(t_i)}{V_{\text{est},z}(t_i)} \right)
\]
\[
\beta_i(t_i) = -\arcsin \left( \frac{V_{\text{est},x}(t_i)}{V_i(t_i)} \right)
\]

where, \( \alpha_i(t_i), \beta_i(t_i) \) — output signals of the measuring channels of attack and sideslip.

The object model is determined by the equations (1)–(4).

The observation model takes the form:
\[
\begin{align*}
z_\alpha(t_i) &= V_i(t_i) + C_{\alpha} + \xi_\alpha(t_i), \\
z_\beta(t_i) &= K_\alpha \alpha_i(t_i) + C_{\beta} + \xi_\beta(t_i), \\
z_z(t_i) &= K_\beta \beta_i(t_i) + C_{\beta} + \xi_\beta(t_i),
\end{align*}
\]

where, \( C_{\alpha}, C_{\beta}, C_{\beta} \) — additive errors of aerometric measuring channels; \( K_\alpha, K_\beta \) — multiplicative error coefficients; \( \xi_\alpha(t_i), \xi_\beta(t_i), \xi_\beta(t_i) \) — random errors of aerometric measurements.

Thus, the identification is aimed at obtaining estimates of the following quantities, where the first three are the coordinates of the wind velocity vector, and the rest specify the systematic errors of the measuring channels:
\[
\alpha^2 = \begin{bmatrix}
W_{\text{est}}, W_{\text{est}}, W_{\text{est}}, C_{\alpha}, C_{\beta}, C_{\beta}, K_\alpha, K_\beta
\end{bmatrix}.
\]

3. Identification Algorithm

The problem of wind velocity estimation may be solved using the maximum likelihood estimation (MLE) algorithm [2, 4, 6]. In general vector form object model and observation model are presented as follows:
\[
y(t_i) = f(y(t_i), a, u(t_i)),
\]
\[
z(t_i) = h(y(t_i), a, u(t_i)) + \eta(t_i).
\]

where \( y(t_i), u(t_i) \) — vectors of object output and input signals which dimensions are \( n \) and \( m \) respectively; \( z(t_i) \) — vector of observation with dimension \( r \); \( a \) — vector of unknown parameters which have to be estimated; \( \eta(t_i) \) — noise of observations, which is a vector of normal discrete random sequence with zero mean and known variance matrix \( R(t_i) \).

It is assumed that input signal \( u(t) \) is a known function of time. The initial conditions \( y(t_0) \) are also assumed to be known.

Noise observations are normal and independent random vector variable. It is known that the maximum likelihood method under the specified assumptions about the properties of noise leads to unbiased and efficient estimates [2].

The minimized functional of the maximum likelihood method is expressed in the following form:
\[
J(a) = \sum_{i=1}^{n} ((z(t_i) - h(y(t_i), a, u(t_i)))^2 \times R^{-1}(t_i) ((z(t_i) - h(y(t_i), a, u(t_i))))
\]

It is easy to see that (8) is a functional of the least squares method with the matrix of weight coefficients \( R(t_i)^{-1} \).

For the minimization of (8), it is proposed to use the modification of the classical Newton method
\[
a_{k+1} = a_k - \left( \frac{d^2 J(a_k)}{d a_k^2} \right)^{-1} \frac{d J(a_k)}{d a_k}
\]

where:
\[
\frac{d J(a_k)}{d a_k} = -2 \sum_{i=1}^{n} \frac{d^2 J(a_k)}{d a_k} \times R^{-1}(t_i) (z(t_i) - h(t, a_k)),
\]

\[
\frac{d^2 J(a_k)}{d a_k^2} = \sum_{i=1}^{n} \frac{d^2 J(a_k)}{d a_k^2} \times R^{-1}(t_i) \cdot R^{-1}(t_i)
\]
The derivative estimates are determined numerically for the discrete time \( t_i, i = 1, N \) according to the formulas:

\[
\frac{dz(t_i, a)}{da} = \left[ \frac{\hat{z}(t_i, a_1) - z(t_i, a_1)}{a_1} \right]_{a_1, \ldots, a_j} ,
\]

\[
\frac{\hat{z}(t_i, a)}{\partial a_j} = \frac{z(t_i, a + \varepsilon e_j) - z(t_i, a)}{\varepsilon} .
\]

where \( e_j \) — vector of dimension \( p \), all of elements of which are equal to zero except \( j \) element and \( j \) element is equal to 1; \( \varepsilon \) — a small number, usually specified at the level of 0.001 ... 0.1% from the nominal parameter values.

Estimates \( z(t_i, a), i = 1, N \) are determined by numerical solution of equations of the object and observations in \( \eta(t_i) = 0 \). Identification is finished when we meet the condition \( |a_{i+1} - a_i| < \delta |a_i| \), where \( \delta = 0.005 \).

4. Estimating projections of wind velocity using sliding window

The capabilities of this algorithm were investigated according to bench simulation. According to the research [kzl] the dimension of the observation vector, that is, an increase in the amount of information used to identify wind speed, will increase the accuracy of the estimates. In this case, random errors were modeled. The main attention was paid to assessing the influence of the type of maneuver and the duration of the moving interval. Such maneuver as pitching dachas, “barrel” is considered. In this version of the algorithm, it was possible to significantly reduce the duration of the sliding interval. In this work, investigation was performed in sliding interval of 0.5 and 1.0 s. To determine the influence of the motion parameters, the beginning of the sliding interval was shifted sequentially throughout the processing area with a step of 1 s.

5. Maneuver "barrel"

The results for the “barrel” maneuver are presented in tables 1 and 2, as well as in fig. 1 and 2.

### Table 1. Relative errors of three projections of wind velocity estimation for the “barrel” maneuver with sliding interval 0.5 s in processing time 31 s.

| Processing interval starting time, s | Relative estimation errors for \( W_x \), % | Relative estimation errors for \( W_z \), % | Relative estimation errors for \( W_y \), % |
|-------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| 0                                  | -2.742657143                            | -1.1                                    | 23.5                                    |
| 1                                  | -3.742657143                            | -2.06                                   | 0.4                                     |
| 2                                  | -3.2                                    | -0.44                                   | -23.4                                   |
| 3                                  | -2.714285714                            | 0.22                                    | 0.75                                    |
| 4                                  | -2.857142857                            | -0.4                                   | 17.65                                   |
| 5                                  | -2.642857143                            | -0.7                                   | 7.45                                    |
| 6                                  | -2.228571429                            | -0.26                                   | -1.3                                    |
| 7                                  | -2.8                                    | -0.12                                   | -12.85                                  |
| 8                                  | -2.671428571                            | -0.16                                   | -5.95                                   |
| 9                                  | -2.814285714                            | -0.46                                   | 11.75                                   |
| 10                                 | -3.085714286                            | -0.5                                    | 6.6                                     |
| 11                                 | -2.685714286                            | -0.4                                    | -0.1                                    |
| 12                                 | -3.171428571                            | -1.54                                   | 21.35                                   |
| 13                                 | -3.957142857                            | -7.16                                   | 18.8                                    |
| 14                                 | -5.028571429                            | -0.06                                   | 13.7                                    |
| 15                                 | -3.814285714                            | 1.16                                    | 3.55                                    |
| 16                                 | -3.171428571                            | -0.18                                   | 2.75                                    |
| 17                                 | -3.085714286                            | 3.74                                    | 4.05                                    |
| 18                                 | -3.371428571                            | 13.86                                   | -4.15                                   |
| 19                                 | 2.657142857                             | 1.82                                    | -12.15                                  |
| 20                                 | -3.557142857                            | 1.42                                    | 3.55                                    |
| 21                                 | -0.285714286                            | -1.94                                   | -7.45                                   |
| 22                                 | -2.2                                    | -3.28                                   | 0.95                                    |
| 23                                 | -3.814285714                            | -2.3                                    | -15                                    |
| 24                                 | -2.685714286                            | -3.54                                   | -27.5                                   |
| 25                                 | -2.457142857                            | -2.98                                   | -2.5                                    |
| 26                                 | -3.014285714                            | -3.08                                   | -4                                     |
| 27                                 | -2.928571429                            | -2.84                                   | -5.65                                   |
| 28                                 | -2.628571429                            | -2.38                                   | -3.2                                    |
| 29                                 | -1.657142857                            | -1.84                                   | 5.15                                    |
| 30                                 | -2.214285714                            | -2.3                                    | 12.8                                    |
| 31                                 | -2.071428571                            | -2.2                                    | 17.65                                   |

### Table 2. Relative errors of three projections of wind velocity estimation for the “barrel” maneuver with sliding interval 1.0 s in processing time 30 s.

| Processing interval starting time, s | Relative estimation errors for \( W_x \), % | Relative estimation errors for \( W_z \), % | Relative estimation errors for \( W_y \), % |
|-------------------------------------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
| 0                                  | -2.128571429                            | -0.74                                   | 30.2                                    |
| 1                                  | -2.814285714                            | -1.24                                   | -12.75                                  |
| 2                                  | -2.5                                    | 0.44                                    | -20.6                                   |
| 3                                  | -1.957142857                            | 0.68                                    | 4.3                                     |
| 4                                  | -2.342857143                            | 0.02                                    | 15.15                                   |
| 5                                  | -2.457142857                            | 0.04                                    | 5.1                                     |
| 6                                  | -2.357142857                            | 0.3                                     | -5.3                                    |
| 7                                  | -2.2                                    | 0.56                                    | -13.7                                   |
It’s obvious, the errors in estimating horizontal projections generally do not exceed 5% over the entire area of the maneuver, and the errors in estimating the vertical component are ±10%.

A comparison of the graphs with Fig.3, which shows the change in the signals during the maneuver, shows that a certain increase in errors occurs at the time of energetic maneuvering, at high speeds of changes in flight parameters.

6. Conclusion

The comparison of the graphs for the sliding window duration of 0.5 s and 1.0 s shows insignificant differences, of the order of 2–3%. This means that the algorithm can provide measurement of three projections of wind velocity for 0.5 s, which compares favorably with other options when the required observation interval was tens of seconds. The short duration of the sliding interval also allows to quickly monitor the change in wind during the flight.

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