Вестник РУДН. Серия: Инженерные исследования
RUDN Journal of Engineering Research

2024;25(4):427–440

ISSN 2312-8143 (Print); ISSN 2312-8151 (Online)
journals.rudn.ru/engineering-researches

DOI: 10.22363/2312-8143-2024-25-4-427-440
UDC 629.7.01
EDN: AWOHBR

Research article / Научная статья

Real Time Estimation of the Wind Speed Components Based on Measurement Data from Satellite Navigation and Barometric Measurements

Oleg N. Korsun[a,b] ✉, **Moung Htang Om**[b]

[a] State Scientific Research Institute of Aviation Systems, *Moscow, Russia*
[b] Moscow Aviation Institute (National Research University), *Moscow, Russia*
✉ marmotto@rambler.ru

Article history

Received: June 27, 2024
Revised: August 30, 2024
Accepted: September 21, 2024

Authors' contribution

The authors have made an equal contribution to data collection and analysis.

Conflicts of interest

The authors declare that there is no conflict of interest.

Abstract. This research work introduces a robust methodology for estimating three components of wind speed by leveraging airspeed, angle of attack, and sideslip angle measurements from both Satellite Navigation System (SNS) data and on-board sensors. By integrating these diverse sources of information, the proposed algorithm using parametric identification method achieves remarkable accuracy in determining the crucial parameters, i.e. wind speed components, necessary for flight operations. The research was conducted suggesting that the airflow has a constant direction and speed. The estimation of wind speed components is performed for distinct flight duration 20, 31 and 46 seconds in various types of flight maneuver. In order to determine the shortest duration of processing time at which the accurate estimates of three components of wind speed can be ensured, sliding window approach is applied. Notably, this approach yields reliable estimations within an impressive processing time interval of just 0.5 seconds. The findings have significant implications across various domains such as aviation safety enhancement, meteorology applications, and overall operational efficiency improvement of aircraft.

Keywords: parametric identification, flight maneuver, wind speed, angle of attack, sideslip angle, airspeed

Acknowledgements

The authors express their deep appreciation to their teammates for passionate contributions that ensure the completion of this research work. The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which literally improve the presentation of the research work.

For citation

Korsun ON, Om MH. Real time estimation of the wind speed components based on measurement data from satellite navigation and barometric measurements. *RUDN Journal of Engineering Research.* 2024;25(4):427–440. http://doi.org/10.22363/2312-8143-2024-25-4-427-440

Идентификация скорости ветра в режиме реального времени на основе данных спутниковой навигации и барометрических измерений

О.Н. Корсун [a,b] ✉, **М.Х. Ом** [b]

[a] Государственный научно-исследовательский институт авиационных систем, *Москва, Россия*
[b] Московский авиационный институт (Национальный исследовательский университет), *Москва, Россия*
✉ marmotto@rambler.ru

История статьи
Поступила в редакцию: 27 июня 2024 г.
Доработана: 30 августа 2024 г.
Принята к публикации: 21 сентября 2024 г.

Заявление о конфликте интересов
Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов
Авторы внесли равноценный вклад в сбор и анализ данных.

Аннотация. Настоящая исследовательская работа посвящена разработке надежного алгоритма оценивания трех проекций скорости ветра на основе измерений воздушной скорости, угла атаки и угла бокового скольжения как по данным спутниковой навигационной системы (СНС), так и по бортовым датчикам. Путем интеграции этих разнообразных источников информации, предложенный алгоритм, использующий метод параметрической идентификации, достигает значительной точности в определении важнейших параметров, то есть проекции скорости ветра, необходимых для выполнения полетов. Исследование проводилось в предположении, что направление и скорость ветра постоянны. Оценивание проекций скорости ветра производился для различных длительностей полета 20, 31 и 46 секунд при различных типах полетного маневра. Для определения наименьшего интервала времени обработки, при котором могут быть получены точные оценки трех проекций скорости ветра, применяется подход скользящего окна. Примечательно, что этот подход позволяет получать надежные оценки за впечатляющий интервал времени обработки, составляющий всего 0,5 секунды. Полученные результаты имеют важное значение для различных областей, таких как повышение безопасности полетов, применение в метеорологии и повышение общей эксплуатационной эффективности воздушных судов.

Ключевые слова: параметрическая идентификация, маневр полета, скорость ветра, угол атаки, угол скольжения, воздушная скорость

Благодарности
Авторы выражают глубокую признательность коллегам по команде за посильный вклад, обеспечивший завершение исследовательской работы. Авторы также выражают признательность рецензентам за полезные комментарии и предложения, которые повысили качество исследовательской работы.

Для цитирования
Korsun O.N., Om M.H. Real time estimation of the wind speed components based on measurement data from satellite navigation and barometric measurements // Вестник Российского университета дружбы народов. Серия: Инженерные исследования. 2024. Т. 25. № 4. С. 427–440. http://doi.org/10.22363/2312-8143-2024-25-4-427-440

Introduction

The measurement of atmospheric and aircraft motion parameters is of paramount importance during flight tests [1], flight dynamics [2], and airship design [3]. Wind is also important for numerous specific problems in aerospace, such as high angle of attack aerodynamics [4; 5], development of a control law for supersonic transport airplanes in the landing phase [6], and engine thrust estimation from flight data [7–9]. Wind velocity should be considered in the detection of dynamic errors in aircraft flight data [10], aircraft flight simulation [11; 12], and cockpit man-machine interface design [13]. To estimate the wind speed components, this study uses system identification methods [14–19]. System identification methods were also applied in [20, 21] for aerodynamic parameter identification. Satellite navigation systems are also used to determine aerodynamic errors in air parameter measurements during flight tests [22].

Generally, the aerodynamic sensors of on-board measurements estimate the so-called local angles of the angle of attack and sideslip angle because of the limitations of sensors in measuring the true angle of attack and sideslip angle. The local angles depend significantly on the characteristics of the aerodynamic flow of the aircraft at the sensor sites. This is the main reason why the angle of attack and the sideslip angle can be obtained from onboard measurements with significant systematic errors. Therefore, information about the true values of the angle of attack and sideslip angle is required to accurately identify the systematic errors of on-board sensors during flight tests.

The estimation of wind speed components can enhance flight safety by providing pilots with up-to-date information to make timely adjustments and enhance overall flight safety, particularly during critical phases such as takeoff and landing. Airlines can also improve operational efficiency by quickly adapting to changing wind conditions, and they can optimize flight paths, reduce delays, and improve operational efficiency. Moreover, in emergencies or adverse weather conditions, real-time wind speed estimation can help pilots navigate safely and make swift decisions to ensure the well-being of passengers and crew. Therefore, the present scientific research work in this paper on the development of an algorithm for the estimation of wind speed components in a short period of flight interval is relevant.

The proposed algorithm provides estimates of the three components of wind speed in a normal earth-fixed axis system, integrating data from a satellite navigation system (SNS) and barometric air measurements. Parametric identification methods were used to estimate the three components of wind speed, and the sliding window approach was applied to determine the shortest processing time interval. The effect of the airspeed systematic measurement error on the wind speed estimation process was also discussed.

1. Classical method for the estimation of wind speeds during flight test

The determination of the wind speed method has been improved because of the simplicity of determining the actual values of airspeed from ground speed measurements in the modes of horizontal level flight of an aircraft with opposite courses. In addition to the enhancement of a new generation of on-board equipment and satellite technologies, the use of full ratios for calculating airspeed and wind speed was implemented based on measurements of parameters obtained from satellite (SNS) and inertial (INS) navigation systems and air data systems.

The problem for the general case in the horizontal-level flight mode with distinct heading angles was solved in a previous study [23]. It was supposed that in an orthogonal, centering relative to the earth, coordinate system *OXYZ*, the axis of which is normal to the horizon plane, the movement of the aircraft includes the sequential execution of modes of horizontal level flight without sliding with maintaining heading angles, and the corresponding values of airspeed. In this case, the *OX* axis corresponds to the north in the coordinate system WGS-84. The designations of velocity components on the *OX* and *OZ* axes are introduced respectively, with the indices "N" and "E". Under this assumption, the considered motion, the state of the atmosphere in the area of aircraft flight, is characterized by the constancy of the wind speed vector $U = (U_N, U_E)$, which lies in the plane of the horizon, and the motion itself is characterized by low vertical velocities $V_y : \left|\frac{V_y}{V}\right| << 1$. Moreover, the airspeed direction angles ψ_{1V}, ψ_{2V} do not differ from those of the heading angle ψ_1, ψ_2. Then, assuming that in the considered horizontal level flight modes, the ground speed vector takes on values $\overrightarrow{W_1} = (W_{N1}, W_{E1})$, $\overrightarrow{W_2} = (W_{N2}, W_{E2})$ accordingly, and the parameters are measured at the same point in space, the relations are valid for the components of ground speed, air speed and wind speed:

$$\begin{aligned}
&V_1 \sin\psi_1 + U_E = W_{E1};\\
&V_2 \sin\psi_2 + U_E = W_{E2};\\
&V_1 \cos\psi_1 + U_N = W_{N1};\\
&V_2 \cos\psi_2 + U_N = W_{N2};\\
&\psi_1 = \psi_2 + \Delta\psi;\\
&V_1 = V_2 + \Delta V, \qquad (1)
\end{aligned}$$

where $\Delta\psi = \psi_1 - \psi_2$ is the change in the heading angle when the modes are applied.

When the values of the parameters W_{N1}, W_{E1}, W_{N2}, W_{E2}, $\Delta\psi$, ΔV are known, the system of equations determines the heading angles ψ_1, ψ_2, the wind speed components U_N, U_E and the airspeeds V_1, V_2:

$$\sin\psi_1 = \frac{(V_1 - V_2\cos\Delta\psi)\Delta W_E - \Delta W_N V_2 \sin\Delta\psi}{(\Delta W_N)^2 + (\Delta W_E)^2};$$

$$\cos\psi_1 = \frac{(V_1 - V_2\cos\Delta\psi)\Delta W_N + \Delta W_E V_2 \sin\Delta\psi}{(\Delta W_N)^2 + (\Delta W_E)^2};$$

$$V_1 = V_2 + \Delta V = \frac{\Delta V}{2} + \sqrt{a + \frac{\Delta V^2}{4}}, \qquad (2)$$

where $\Delta W_N = W_{N1} - W_{N2}$,

$$\Delta W_E = W_{E1} - W_{E2}, a = \frac{(\Delta W_N)^2 + (\Delta W_E)^2 - \Delta V^2}{2(1-\cos\Delta\psi)}.$$

$$\begin{aligned}
&U_N = W_{N1} - V_1\cos\psi_1;\\
&U_E = W_{E1} - V_1\sin\psi_1. \qquad (3)
\end{aligned}$$

Otherwise,

$$U_N = \frac{W_{N1}+W_{N2}}{2} - \frac{\Delta W_E \sin(\Delta\psi)}{2(1-\cos\Delta\psi)} - \frac{\Delta V(V_1+V_2)\Delta W_N}{2((\Delta W_N)^2 + (\Delta W_E)^2)} + \frac{(\Delta V)^2 \Delta W_E \sin(\Delta\psi)}{2(1-\cos\Delta\psi)((\Delta W_N)^2 + (\Delta W_E)^2)};$$

$$U_z = \frac{W_{E1}+W_{E2}}{2} - \frac{\Delta W_N \sin(\Delta\psi)}{2(1-\cos\Delta\psi)} - \frac{\Delta V(V_1+V_2)\Delta W_E}{2((\Delta W_N)^2 + (\Delta W_E)^2)} + \frac{(\Delta V)^2 \Delta W_N \sin(\Delta\psi)}{2(1-\cos\Delta\psi)((\Delta W_N)^2 + (\Delta W_E)^2)}.$$

The determination of wind speed in this method is only an intermediate element in the calculation of airspeed, aerodynamic angles, and other parameters. As in the case of the method described above, the solution to the problem is based on the relationship among the vectors of wind speed $\vec{U}$, ground speeds $\vec{W}$ and airspeeds $\vec{V}$:

$$\vec{U} = \begin{pmatrix} U_N \\ U_E \\ U_y \end{pmatrix} = \begin{pmatrix} W_N \\ W_E \\ W_y \end{pmatrix} - \begin{pmatrix} V_N \\ V_E \\ V_y \end{pmatrix}. \qquad (4)$$

To solve Equation (4), measurements of the projection of the ground speed obtained from SNS, the air parameters obtained from the air data system, and the parameters of the angular position of the aircraft in the space obtained from the INS are used. The velocity projections were considered in the WGS-84 coordinate system. Based on Equation (4), when flying without roll and sideslip angles, the components of the wind speed vector are determined by the following expressions:

$$\begin{aligned}
&U_N = W_N - V_г\cos\psi;\\
&U_E = W_E - V_г\sin\psi;\\
&U_y = W_y - V_y. \qquad (5)
\end{aligned}$$

The wind velocity module in the horizontal plane can be expressed as

$$U_г = \sqrt{W_N^2 + W_E^2 + V_г^2 - 2V_г(W_N\cos\psi + W_E\sin\psi)}, \qquad (6)$$

where $V_г, V_y$ are horizontal and vertical components of the airspeed; ψ — heading angle.

The method described in this section is fundamental for determining the actual values of the air parameters using the SNS. The results obtained demonstrate the possibility of reducing the errors in determining the atmospheric and flight parameters in flight tests of aircraft and on-board equipment. Despite the current use of the proposed methods in flight tests [23], this method can only be applied when the aircraft maintains its horizontal-level flight without sideslip angles. In addition, it uses airspeed and groundspeed measurements only, and does not use the measurements of the angles of attack and sideslip.

The following publications confirm this conclusion. In [24], wind speed components were estimated using the ground speed derived from GPS position measurements, true airspeed or calibrated airspeed, and pressure altitude. In [25], an interactive procedure was proposed to extract the wind from trajectory data. In this procedure, a human operator selects appropriate subsets of radar data, performs automatic and/or manual curve fitting to extract the wind data, and validates the resulting wind estimates. Wind speed estimation can also be performed using trajectory parameters such as airspeed, initial heading, turn rate, and flight path angle, as aircraft motion depends on these parameters [26] and flight path data [27]. In these studies, wind estimation was based on trajectory parameters, and only two horizontal components were estimated. Kalman filter estimation can also be applied for the estimation of wind speed using airspeed and ground speed [28; 29].

In all the above-reviewed cases, the data from the angles of attack and sideslip angle considered in this present scientific research work were not used for the estimation of wind speed. Normally, the sensors installed in the aircraft are used to collect atmospheric information such as latitude, longitude, and air pressure, and wind estimations, that is, wind speed and wind direction, are drawn from trajectory parameters.

Therefore, a method for the estimation of three components of wind speed using the angle of attack, sideslip angle, and airspeed is proposed in this paper, whereas a method that uses more information can naturally ensure more accurate estimates of wind speed components. To conduct research on the possibility of determining the three components of wind speed in various flight maneuvers in real time, the parametric identification method was used where the SNS data and aerometric measurement data were integrated, and the results demonstrated significant accurate estimates of the three components of wind speed in both steady and unsteady flight modes.

2. Problem statement and algorithm description

The research was conducted suggesting that the airflow has a constant direction and speed. The duration of flight for estimating the three components of wind speed is 20, 31, and 46 s for different types of flight maneuvers, such as barrel, stepwise, snake and snake with a vertical component. This means that for this time interval, the values of the components of the wind speed on the normal earth-fixed axis system are constant. Traditionally, the object model was first formulated to determine the processing sequence to generate estimates of the three components of wind speed. The three components of the airspeed of an aircraft on a normal earth-fixed axis system are defined by the following mathematical equations:

$$V_{xg\_a}(t_i) = V_{xg\_\text{CHC}}(t_i) - W_{xg};$$
$$V_{yg\_a}(t_i) = V_{yg\_\text{CHC}}(t_i) - W_{yg};$$
$$V_{zg\_a}(t_i) = V_{zg\_\text{CHC}}(t_i) - W_{zg}, \tag{7}$$

where $V_{xg\_\text{CHC}}(t_i), V_{yg\_\text{CHC}}(t_i), V_{zg\_\text{CHC}}(t_i)$ are the values of the components of the aircraft velocity on the normal earth-fixed axis system measured by SNS; W_{xg}, W_{yg}, W_{zg} are the unknown values of the components of the wind speed on the normal earth-fixed axis system to be identified.

The magnitude of the airspeed vector is defined as

$$V_a(t_i) = \sqrt{V_{xg\_a}^2(t_i) + V_{yg\_a}^2(t_i) + V_{zg\_a}^2(t_i)}. \tag{8}$$

For the transformation from normal earth-fixed axes to body-fixed axes, the corresponding directional cosine matrix is written as follows:

$$\begin{bmatrix} V_{x\_a} \\ V_{y\_a} \\ V_{z\_a} \end{bmatrix} = \begin{bmatrix} \cos\psi\cos\vartheta & \sin\vartheta & -\sin\psi\cos\vartheta \\ \sin\psi\sin y - \cos\psi\sin\vartheta\cos y & \cos\vartheta\cos y & \cos\psi\sin y + \sin\psi\sin\vartheta\cos y \\ \sin\psi\cos y + \cos\psi\sin\vartheta\sin y & -\cos\vartheta\sin y & \cos\psi\cos y - \sin\psi\sin\vartheta\sin y \end{bmatrix} \times \begin{bmatrix} V_{xg\_a} \\ V_{yg\_a} \\ V_{zg\_a} \end{bmatrix} \quad (9)$$

During the calculations, the orientation angles were taken according to the output signal of the attitude and heading reference system included in the navigation system. The constant yaw error ψ, which can be considered constant in a section with a duration of 30–50 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_α and K_β.

In the presence of nonlinearity, an additional approximation is introduced, which is not fundamentally difficult but increases the dimension of the problem.

By using the components of the airspeed (7) on the body-fixed axes, it is possible to write the formulae for the values of the angles of attack and sideslip:

$$\alpha_u(t_i) = -\text{arctg}\left(\frac{V_{y\_\alpha}(t_i)}{V_{x\_\alpha}(t_i)}\right),$$

$$\beta_u(t_i) = -\arcsin\left(\frac{V_{z\_\alpha}(t_i)}{V_\alpha(t_i)}\right), \quad (10)$$

where $\alpha_u(t_i), \beta_u(t_i)$ are the output signals of the measuring channels of angles of attack and sideslip, respectively.

Therefore, the object model is determined using Equations (7)–(10). The observation model takes the following form:

$$z_2(t_i) = V_a(t_i) + C_V + \xi_V(t_i);$$

$$z_2(t_i) = K_\alpha \alpha_u(t_i) + C_\alpha + \xi_\alpha(t_i);$$

$$z_3(t_i) = K_\beta \beta_u(t_i) + C_\beta + \xi_\beta(t_i), \quad (11)$$

where C_V, C_α, C_β are the additive errors of the aerodynamic measurement channels; K_α, K_β are the multiplicative error coefficients; $\xi_V(t_i)$, $\xi_\alpha(t_i)$, $\xi_\beta(t_i)$ are the random errors of the aerodynamic measurements.

Thus, parameter identification is performed to obtain the estimates of the following values, that is three components of wind speed that are the elements of the vector a^{T}.

$$a^{\mathrm{T}} = \left[\, W_{xg}\; W_{yg}\; W_{zg} \,\right].$$

3. Maximum likelihood estimation (MLE) for parametric identification

The problem of wind speed estimation can be solved using the maximum-likelihood estimation algorithm [15]. In general, the vector model of the object and the observation model are presented as follows:

$$y(t_i) = f(y(t_{i-1}), a, u(t_i)), \quad (12)$$

$$z(t_i) = h(y(t_i), a, u(t_i)) + \eta(t_i), \quad (13)$$

where $y(t)$, $u(t)$ are the vectors of the output and input signals of the object, whose dimensions are *r* and *m*, respectively; $z(t_i)$ is the observation vector of dimension; a is the vector of unknown parameters that must be estimated; $\eta(t_i)$ are random errors, with respect to which assumptions of Gaussian, centering, lack of correlation and availability of information about the covariance matrix $R(t)$ are accepted.

We also assumed that the control $u(t)$ and initial conditions for the state vector $y(t_0)$ are given.

Owing to the errors caused by the lack of correlation, the joint probability distribution density is determined by simply multiplying the product of the probability distribution density at each time.

Under these conditions, the maximum likelihood criterion provides estimates with statistical properties of efficiency and non-bias. The minimized objective function of the maximum likelihood method is expressed as follows:

$$J(a)=\sum_{i=1}^{N}(z(t_i)- -h(y(t_i),a,u(t_i)))^T \times \times R^{-1}(t_i)(z(t_i)-h(y(t_i),a,u(t_i))). \quad (14)$$

Equation (14) is a functional least-squares method with a weight matrix. To minimize this objective function, the modified Newton method was used in this study.

To find the estimates, $Z(t_i,a), i=1,2,...,N$, the models (12)–(13) should be numerically integrated, setting the noise entering it equal to zero.

The identification ends with the condition $|a_{k+1}-a_k|<\delta|a_k|$, where $\delta=0.005$.

The initial data were obtained by modeling a semi-natural stand equipped with controls. This option has an advantage over purely mathematical modeling because the presence of a human operator gives the simulated flight data a greater likelihood degree. A hypothetical training aircraft was simulated in a bench experiment.

4. Estimation of three components of wind speed in distinct types of flight maneuvers

The capabilities of this algorithm were investigated based on bench modeling data. In this case, random errors were simulated in a traditional manner that was similar to a sequence of normal uncorrelated random values. Here, the main focus was on estimating the influence of the type of maneuver and duration of the sliding interval. Maneuvers such as "barrel," "stepwise," "snake" and "snake with a vertical component," that is, with additional movement in the pitch channel, were considered. The northern, eastern, and vertical components of wind velocity were assumed as –7 m/s, 5, and 2 m/s, respectively, while the simulated flight airspeed was 65–105 m/s. In this version of the algorithm, it was possible to significantly reduce the duration of the sliding interval. In this study, the investigation was conducted at intervals of 0.5 and 1.0 seconds. To determine the effects of the motion parameters, the beginning of the sliding interval was shifted sequentially over the entire processing area in increments of 1 s.

4.1. The «barrel» maneuver

The results of the three components of the wind speed estimation conducted for the "barrel" maneuver are shown in Figures 1 and 2. The estimation was performed on one section of the "barrel" maneuver, which lasted for 31 s. The sliding window method was used to determine the shortest processing time at which accurate estimates of the wind speed could be obtained. Figure 1 shows the relative errors of the wind speed estimate performed with a sliding window interval of 0.5 seconds, and Figure 2 shows the results obtained using a sliding window interval of 1.0 seconds.

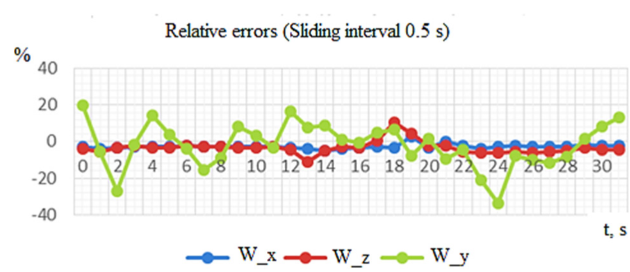

Figure 1. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

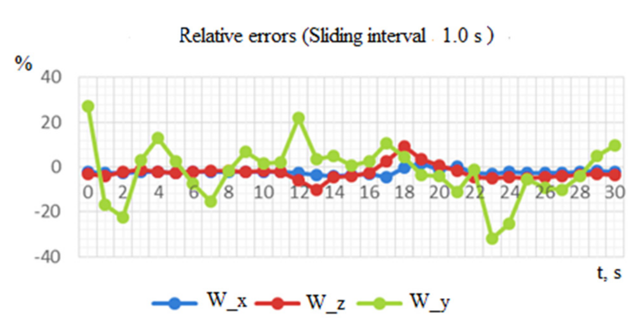

Figure 2. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

It can be observed that the errors in estimating the horizontal components of the wind speed generally do not exceed 5% in the entire section of the maneuver, and the errors in estimating the vertical component are ± 10%. A comparison of the graphs that present the relative errors with Figure 3, which shows the change in signals during the maneuver, demonstrates that some increase in errors occurs at moments of vibrant maneuvering, at high speeds of flight parameters change.

Finally, a comparison of the graphs for the values of 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 measure three components of wind speed within 0.5 seconds, which distinguishes it from other options when the required duration of the observation interval was tens of seconds. The short duration of the sliding interval also allows rapid tracking of wind changes during flight.

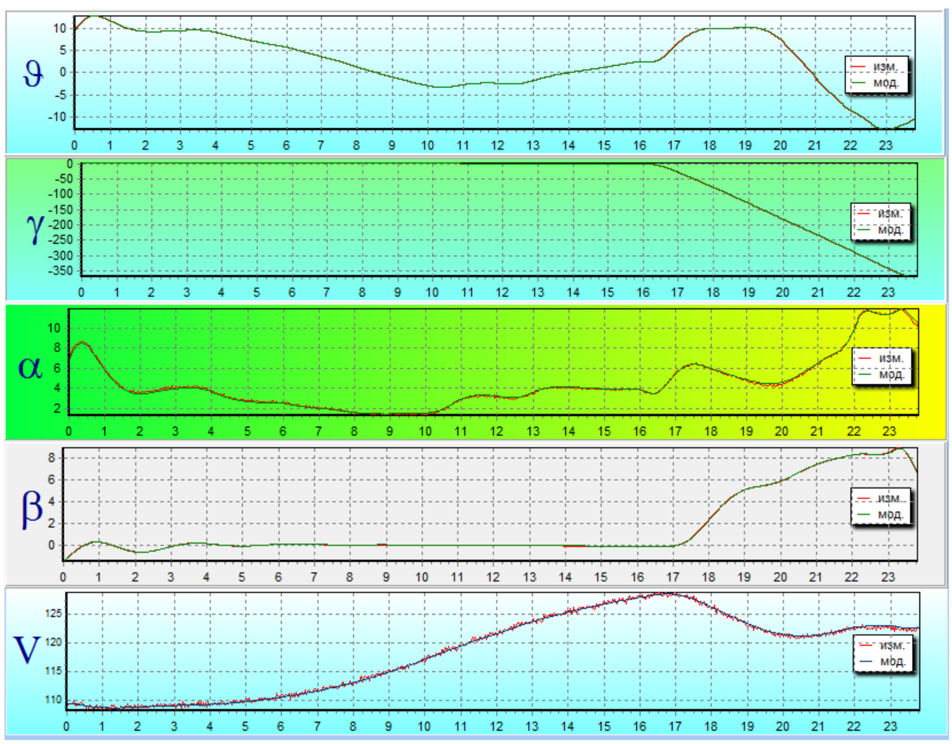

Figure 3. The values of the main flight parameters for the «barrel» maneuver within first 24 seconds
S o u r c e: created by O.N. Korsun

4.2. The "stepwise" mode in the pitch channel

The results of the three components of the wind speed estimation conducted for the "stepwise" maneuver are shown in Figures 4 and 5 and tabular data are excluded for brevity. The estimation was performed on one section of the "stepwise" maneuver, which lasted for 20 s. Figure 4 shows the relative errors of the wind speed estimate performed with a sliding window interval of 0.5 s, and Figure 5 shows the results obtained using a sliding window interval of 1.0 s. The changes in the flight parameters in this section are shown in Figure 6.

According to the graphs, it can be observed that the errors in estimating the horizontal components generally do not exceed 5% in the entire section of the maneuver, and the errors in estimating the vertical component are ± 10%. As in the previous case, a comparison of the graphs for the values of the duration of the sliding window of 0.5 and 1.0 s shows insignificant differences of the order of 2–3%. A comparison of the graphs of relative errors in Figures 4 and 5 with that in Figure 6, which demonstrates the change in signals during the maneuver, shows that an increase in errors in the vertical component occurs at the moments of vigorous maneuvering, as in the previous case. Therefore, the favorable flight modes are close to straight lines with small disturbances.

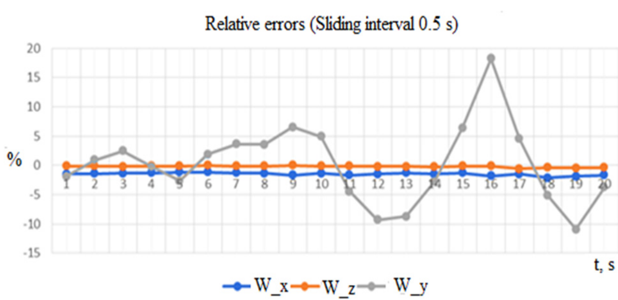

Figure 4. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

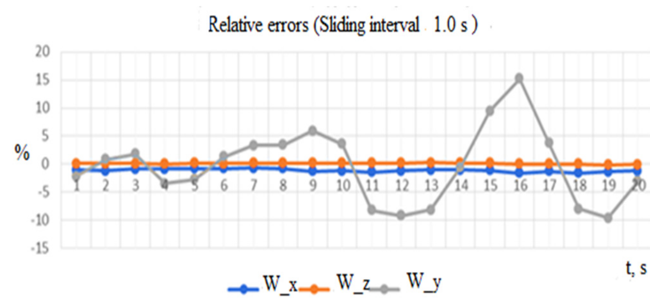

Figure 5. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

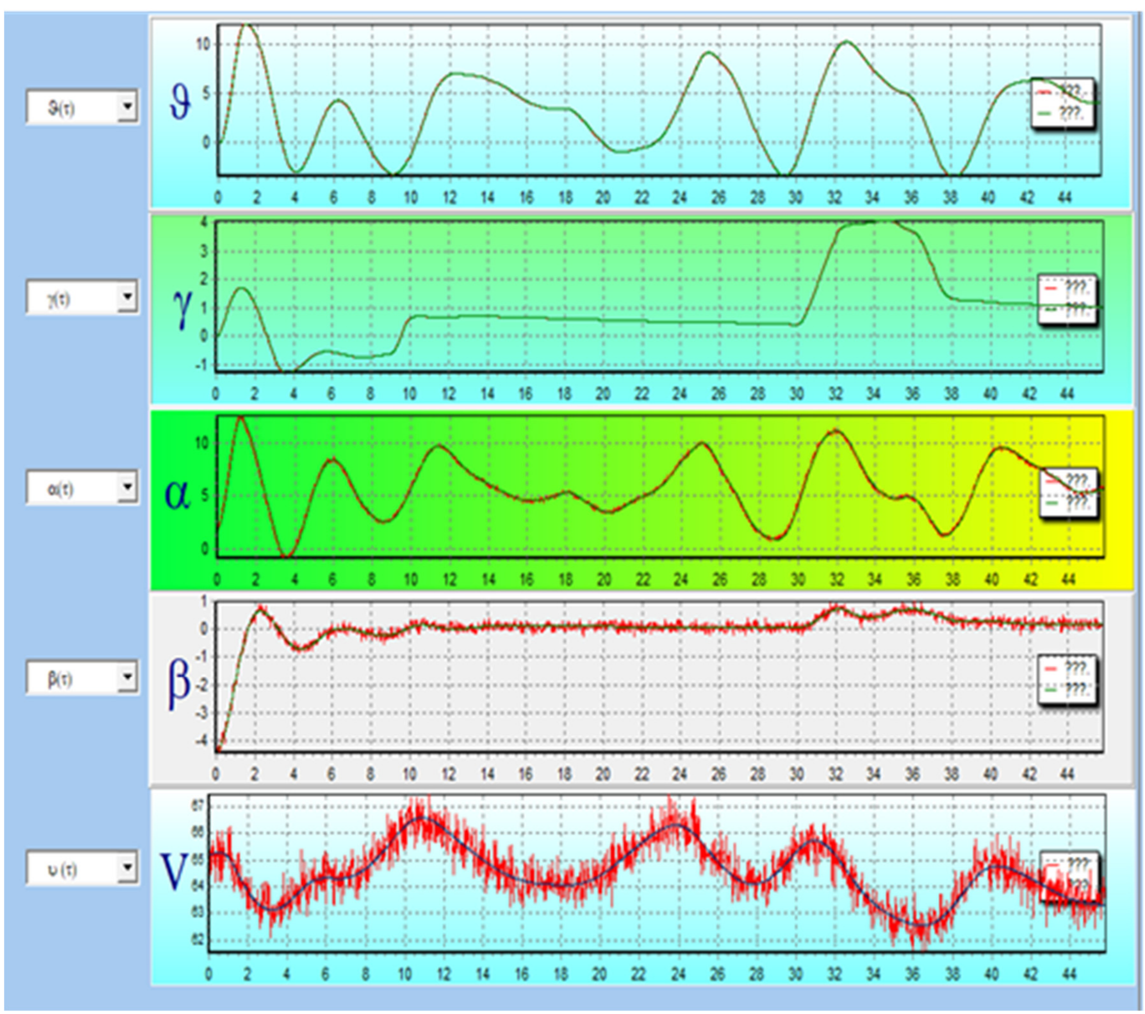

Figure 6. The values of the main flight parameters for the "pitch stepwise" maneuver within first 31 s
S o u r c e: created by O.N. Korsun

4.3. The “snake” maneuver

The results of the three components of the wind speed estimation conducted for the «snake» maneuver are shown in Figures 7 and 8; tabular data are excluded for brevity. The estimation was performed on one section of the “snake” maneuver, which lasted 46 s. Figure 7 shows the relative errors of the wind speed estimate performed with a sliding window interval of 0.5 s, and Figure 8 shows the results obtained using a sliding window interval of 1.0 s. The changes in the flight parameters in this section are shown in Figure 9.

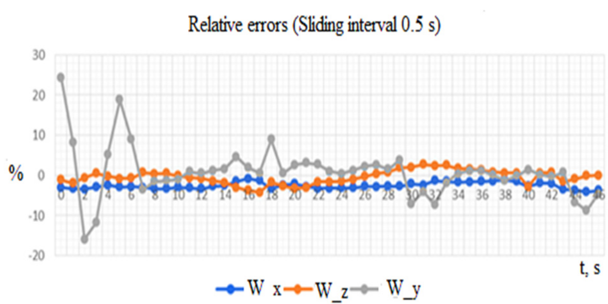

Figure 7. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

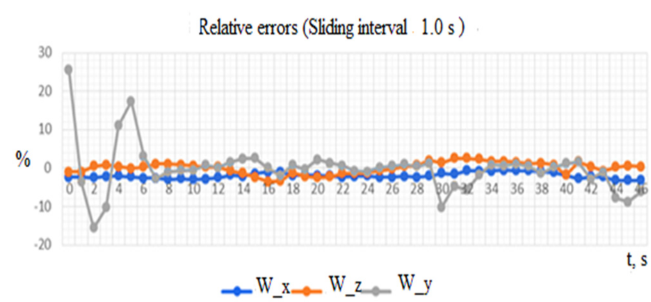

Figure 8. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

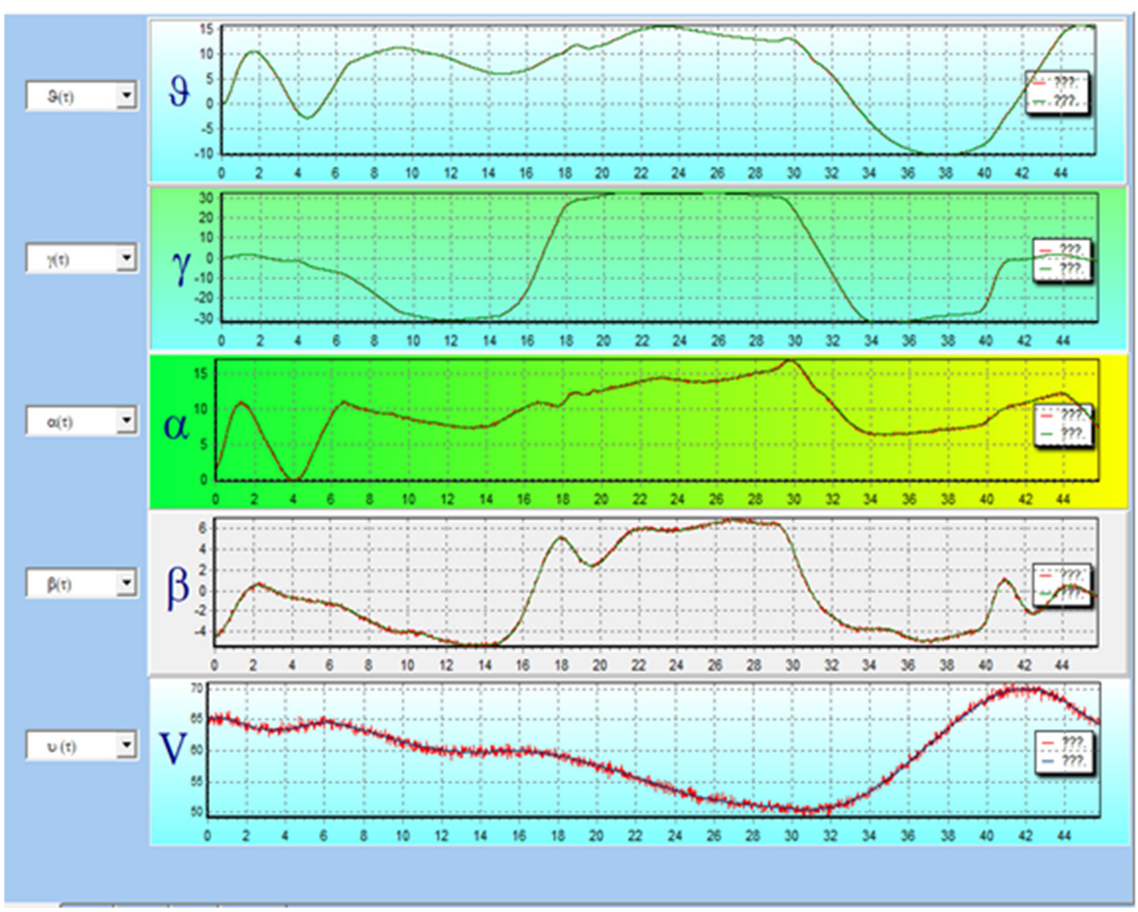

Figure 9. The values of the main flight parameters for the “snake” maneuver within first 46 s
S o u r c e: created by O.N. Korsun

It can be observed in the graphs that the estimation errors of both the horizontal and vertical components generally do not exceed 5% in the entire maneuver section, with the exception of certain short sections, where the estimation errors of the vertical component reach ± 10%. As in the previous case, a comparison of the graphs for the values of the duration of the sliding window of 0.5 and 1.0 s shows insignificant differences of the order of 2–3%. A comparison of the error graphs in Figures 7 and 8 with Figure 9, which shows the change in signals during the maneuver, shows that the increase in errors in the vertical component occurs at the moments of vigorous maneuvering, as in the previous cases. Thus, the previously formulated conclusion confirms that the most favorable flight modes for evaluation are horizontal flights with small disturbances.

4.4. The «snake with a vertical component» maneuver

The results of the three components of the wind speed estimation conducted for the «snake with a vertical component» maneuver are shown in Figures 10 and 11; tabular data are excluded for brevity. The estimation was performed on one section of the "snake with a vertical component" maneuver that lasted 46 s. Figure 10 shows the relative errors of the wind speed estimate performed with a sliding window interval of 0.5 s, and Figure 11 shows the results obtained using a sliding window interval of 1.0 s. The changes in the flight parameters in this section are shown in Figure 12.

It can be observed in the graphs that the errors in estimating the horizontal components generally do not exceed 5% in the entire section of the maneuver, and the errors in estimating the vertical component are ± 10%. As in the previous case, a comparison of the graphs for the values of the duration of the sliding window of 0.5 and 1.0 s shows insignificant differences of the order of 2–3%. A comparison of the error graphs in Figures 4 and 5 with Figure 6, which shows the change in signals during the maneuver, demonstrates that an increase in errors in the vertical component occurs at the moments of vigorous maneuvering, as in the previous case. Thus, it was confirmed that favorable flight modes are close to straight lines with small disturbances.

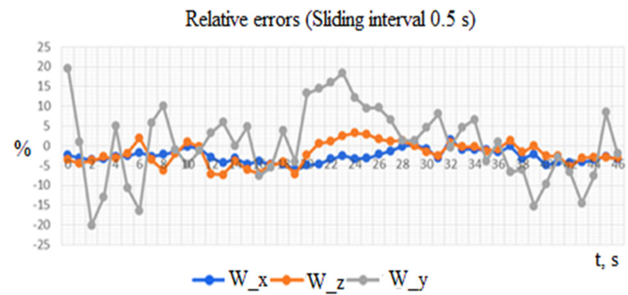

Figure 10. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

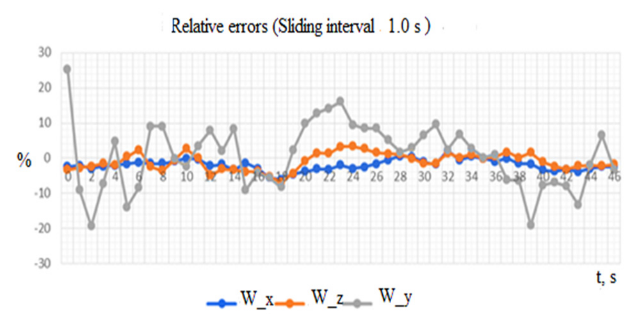

Figure 11. The relative errors of the estimation of three components of wind speed
S o u r c e: created by O.N. Korsun in Microsoft Excel

Therefore, with the full vector of aerometric measurements and the level of non-excluded systematic errors on the order of 3–5% for maneuvers such as straight horizontal flight, steady turn, snake, pitch stepwise, the errors in estimating all three components of wind speed do not exceed 5-7% for the duration of the measurement interval of 0.5–1 s, which allows not only to estimate the constant wind speed, but also to track its changes.

Figure 13 presents the results of fitting the simulated flight data with the wind velocity using the aircraft motion model, which ignores the wind. The graph shows that the discrepancies are considerable, especially for aerometric parameters, such as angles of attack, slideslip, and airspeed. This example illustrates the importance of considering the wind velocity.

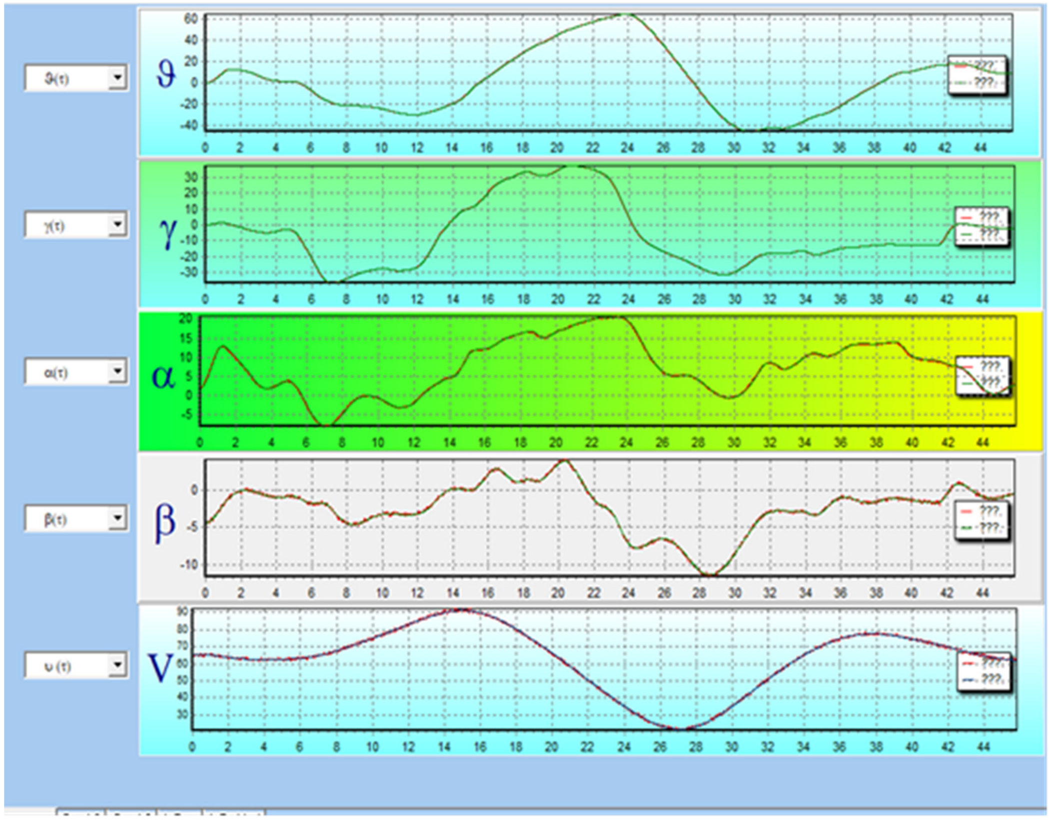

Figure 12. The values of the main flight parameters for the “snake with a vertical component” maneuver within first 46 s
S o u r c e: created by O.N. Korsun

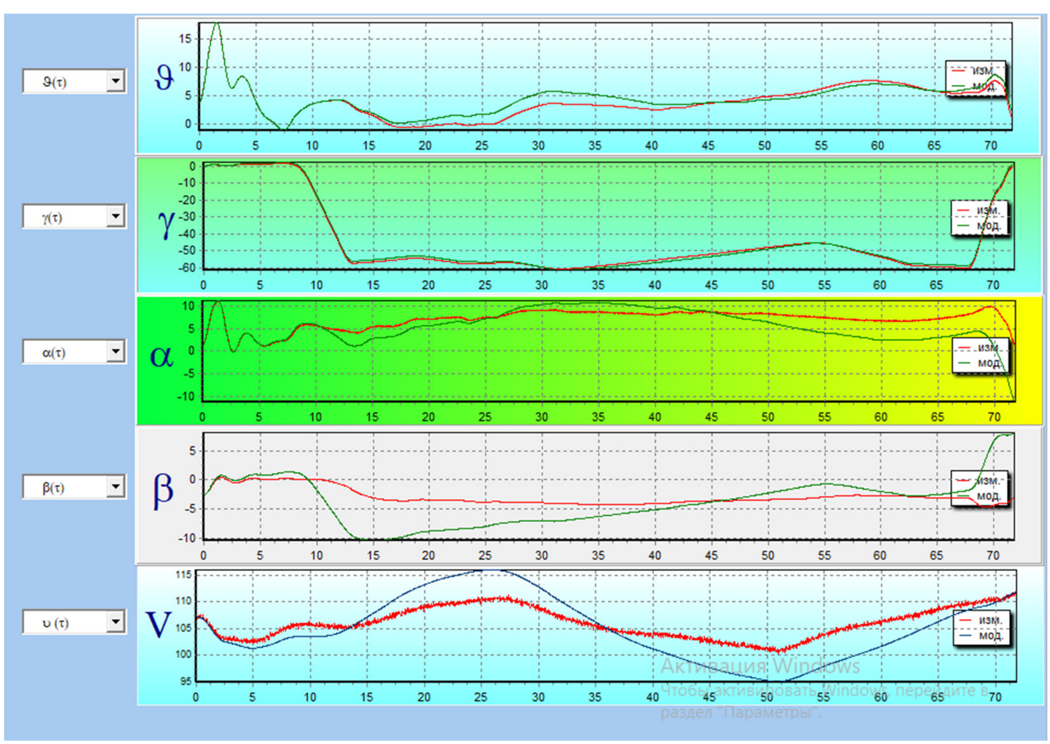

Figure 13. The values of the main flight parameters for the “snake with a vertical component” maneuver within first 72 s
S o u r c e: created by O.N. Korsun

Conclusion

According to the simulation data from the flight simulator, a study on the accuracy characteristics of the algorithm for estimating the three components of wind speed based on the data obtained from the satellite navigation system was performed.

The influence of the duration of the sliding window and types of flight maneuvers, such as pitch stepwise, barrel, straight horizontal flight, steady turn, snake and snake with a vertical component, on the accuracy of identification of the three components of wind speed was investigated.

According to the results given by the proposed method for estimating three components of wind speed using parametric identification where the angle of attack, sideslip angle, and airspeed are applied, it can be observed that more accurate estimates of the three components of wind speed can be ensured when the estimation method utilizes more information about the aircraft's motion.

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About the authors

Oleg N. Korsun, D.Sc. (Technology), Head of the Scientific and Educational Center, State Scientific Research Institute of Aviation Systems (GosNIIAS), Moscow, Russia; Professor, Department of Design and Certification of Aircraft Engineering, Moscow Aviation Institute (National Research University), Moscow, Russia; eLIBRARY SPIN-code: 2472-6853, ORCID: 0000-0003-3926-1024; e-mail: marmotto@rambler.ru

Moung Htang Om, Cand. Sc. (Technology), Post-doctoral Candidate, Department of Design and Certification of Aircraft Engineering, Moscow Aviation Institute (National Research University), Moscow, Russia; ORCID: 0000-0002-7770-2962; e-mail: mounghtangom50@gmail.com

Сведения об авторах

Корсун Олег Николаевич, доктор технических наук, руководитель научно-образовательного центра, Государственный научно-исследовательский институт авиационных систем (ГосНИИАС), Москва, Россия; профессор кафедры проектирования и сертификации авиационной техники, Московский авиационный институт (Национальный исследовательский университет), Москва, Россия; eLIBRARY SPIN-код: 2472-6853, ORCID: 0000-0003-3926-1024; e-mail: marmotto@rambler.ru

Ом Моунг Хтанг, кандидат технических наук, докторант кафедры проектирования и сертификации авиационной техники, Московский авиационный институт (Национальный исследовательский университет), Москва, Россия; ORCID: 0000-0002-7770-2962; e-mail: mounghtangom50@gmail.com