Formation of a director index to assist the pilot in conducting airborne geophysical survey

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Abstract. Airborne geophysical survey of the territory is performed by flying an aircraft along the trajectories covering the studied area of the surface. Naturally, the quality of manual piloting is subject to increased requirements. At the same time, a flight with terrain tracking and in the presence of wind disturbances is a difficult task for the pilot. The paper suggests informing the pilot about deviation from the specified trajectory and indicating in the field of view the director index for thrust control. The task of the pilot is to bring the index to zero by manipulating the power lever and thereby zeroing the piloting error. The solution of the task is achieved by using an original energy approach. The mathematical formulation of the approach is the energy balance equation. A variant of the structure of the energy control system and a prototype of a navigation indicator with a director index is proposed. The results of flights along the route using the director index are presented in the form of graphs and numerical estimates.

1. Introduction

Currently, there are a number of developments of airborne geophysical systems that are successfully used in search and evaluation studies in the field of hydrogeology, in engineering and environmental surveys, as well as in solving problems of searching for minerals (both ore and hydrocarbon).

An example of domestic airborne geophysical systems can be helicopter electromagnetic complexes with remote platforms of the “Impulse-Aero” series (“SNIIGIMS”, “Sibgeotech”, “Aerogeophysical survey”)[1], “Equator” (LLC “Geotechnologies”)[2], airborne gravimetric systems GT-2A (GNPP Aerogeophysica, STE Gravimetric technologies)[3].

The analysis of problems of trajectory control of a manned atmospheric aircraft when flying over territories is made in [4]. The main control strategies for performing aerial surveys are highlighted. An overview of existing implementations of aircraft flight control systems along program trajectories is presented. A comparative analysis of modern control systems is given. The results of the development of the software package and its use in the performance of aerial surveys are presented.

Airborne gravity survey, aeromagnetic survey, airborne electrical survey and thermal infrared aerial photography, performed from the air, impose strict requirements on the accuracy of maintaining a given flight route. So, when performing aeromagnetic survey, the tolerances for deviations according to [5] were: in altitude no more than 130±30 m; at speed no more than 120±30 km/h; in lateral deviation from a given track line no more than ±30 m. Routes were drawn up in the form of parallel lines of various lengths (from 15 to 60 km) with intervals between them 500 and 1000 m.
At the same time, the requirements for the accuracy of determining the navigation and geodetic parameters of airborne electromagnetic (EM) survey using a remote platform are very high and are presented in Table 1.

| Navigation parameters of carrier | Navigation coordinates $X_{nr}, Y_{nr}$ | from 0.8 to 1.2$\times10^{-3}$ $q$ |
|---------------------------------|----------------------------------------|----------------------------------|
| Flight altitude $h_{nr}$        | not worse than 10 m                    |                                   |
| Ground speed $V_g$              | from 10 to 20 km/h                     |                                   |
| Receiving antenna center height (above ground) $h$ | from 0.6 to 1 m             |                                   |
| Helicopter coordinates and geodetic heights $X_1, Y_1, H_1$ | up to 1 m                          |                                   |
| Coordinates and geodetic altitudes of the EM platform $X_2, Y_2, H_2$ | up to 1 m                          |                                   |
| Coordinates and geodetic altitudes of the magnetometer $X_m, Y_m, H_m$ | not worse than 3-5 m |                                   |

In the column of recommended accuracy, $q$ is the denominator of the scale of the airborne geophysical survey. Requirements for the accuracy of these values are formed both on the basis of the relevant instructions and the results of geophysical experiments [1,6,7].

The implementation of such recommendations directly affects the quality of airborne geophysical survey. To help the pilot to control the trajectory, there are many options in the world for visualizing the situation with the indication of the desired coordinates of the aircraft motion in space in the form of, for example, a volumetric corridor, “Way in the sky”, “telegraph poles”, “pitch stairs”, etc. …

During fieldwork, situations arise that require a change in the operating mode of the aircraft engine. This is a flight with tracking the terrain, this is a change in piloting level, it is a stationary and non-stationary wind of a complex structure. When flowing around the relief on a gravimetric survey, it is necessary to limit the overloads to values of 0.1–0.2g (1–2 m/s²) in order to prevent an increase in the range of the measured value and to provide the required sensitivity at a level of $10^{-7}$g and higher. In such situations, maintaining a given spatial trajectory and speed regime on each of the flight routes leads to great psychological tension for the pilot. Therefore, only experienced highly qualified pilots can ensure accurate adherence to a given route with overflying the relief.

This paper aims to provide assistance to the pilot in speed control. The help will consist in the formation of the director index in the pilot’s field of vision. Based on the energy description of flight in a disturbed atmosphere, the paper proposes to display the deviation index of the total energy level from the required one on the flight indicator display.

This index should be taken as a command signal to control engine thrust in order to zero out the apparent energy error. Functionally, the “energy index” is similar to how various forms of directories are used to aid the pilot in manual trajectory control. The presence of such a prompt will help to acquire a “feeling of full energy” for the pilot of the aircraft, facilitate manual control, or serve as an indicator of generalized error in automatic control. The pilot must reset the total energy error by manipulating the throttle control lever.

2. Fundamentals of the energy approach
The methodical basis of our development is the energy approach to control the spatial movement of flying objects [8, 9].

Its essence is as follows. The structure of traditional flight control systems can be represented by the generalized circuit (figure 1).
Figure 1. Structure of traditional flight control systems.

Control $U$ is formed on the basis of error $\Delta X$ of a state variable vector $X$. The performance index is assigned in class $Q_x = Q_x(U, X, \Delta X)$.

The nonconventional control concept (figure 2) is offered instead.

Figure 2. Nonconventional control structure.

Here the total motion energy $E$ is a controllable variable. The performance index is also set at the form $Q_E = Q_E(U, E, \Delta E)$.

Dynamic equations are usually written in a coordinate system associated with moving mass of air. Then, the equations of force in the projection on the axes of the air coordinate system are as follows:

\[ m\ddot{V} = P \cos(\alpha + \phi_{eng}) - D - mg \sin \theta - m(W_x \cos \theta + W_y \sin \theta) \]  
\[ mV\dot{\theta} = P \sin(\alpha + \phi_{eng}) + L - mg \cos \theta - m(-W_x \sin \theta + W_y \cos \theta) \]

and the kinematic equations are follows:

\[ \dot{x} = V \cos \theta + W_x(x, y) \]  
\[ \dot{y} = V \sin \theta + W_y(x, y) \]

The total system of equations involves the necessary aerodynamic forces such as the lift $L = L(y, V, \alpha)$ and drag $D = D(y, V, \alpha)$ engine thrust characteristics $P = P(y, V, \delta)$ and kinematic relationships:

\[ V = \sqrt{x^2 + y^2}, \quad \theta = \arctg \frac{V_x}{V_y}, \quad \varphi = \theta + \alpha, \]

Now we consider the energy characteristics of an aircraft. Airspeed and altitude are the most important variables in problems of flight control. That is why it is advantageous to use the sum of the potential energy in the ground-fixed coordinate system and the kinetic energy in the air coordinate system as the integral energy characteristic of the aircraft.

\[ E = mgy + \frac{1}{2} mV^2 \]

By normalizing (5) in the aircraft weight, we get the specific “pseudoenergy”

\[ E_{nr} = y + \frac{V^2}{2g} \]

which is measured in linear units and, therefore, can be regarded as the energy height

\[ H_E \equiv E_{nr} \]

We differentiate (6) with regard for (7) and obtain
\[ \dot{H}_E = \dot{y} + \frac{\dot{V}}{g} \]

or

\[ \dot{H}_E \equiv V \left( \theta + \frac{\dot{V}}{g} \right). \] (8)

By substituting \( \dot{y} \) from (4) and \( \dot{V}_{air} \) from (1) and introducing the normalized forces \( P_{nr} = \frac{p}{mg} \) and \( D_{nr} = \frac{d}{mg} \) we obtain:

\[ \dot{H}_E = V_{air} \left[ P_{nr} \cos(\alpha_{air} + \varphi_{eng}) - D_{nr} \right] - V_{air} \left( \frac{W_x}{g} \cos \theta_{air} - \frac{W_y}{V_{air}} + \frac{\dot{W}_y}{g} \sin \theta_{air} \right) \]

By assuming that the flight path angle \( \theta_{air} \) is small, we can write

\[ \dot{H}_E = V_{air} \left[ P_{nr} \cos(\alpha_{air} + \varphi_{eng}) - D_{nr} \right] - V_{air} f_w, \] (9)

where \( f_w \equiv \frac{W_x}{g} - \frac{W_y}{V_{air}} \) is called the wind factor or the danger index. By integrating (9), we obtain the equation of work of all forces acting in the aircraft:

\[ \int_{t_1}^{t_2} \dot{H}_E(t) dt = \int_{t_1}^{t_2} V_{air} P_{nr} \cos(\alpha_{air} + \varphi_{eng}) dt - \int_{t_1}^{t_2} V_{air} D_{nr} dt - \int_{t_1}^{t_2} V_{air} f_w dt. \]

The left-hand side is the increment of energy height

\[ \Delta H_E = \int_{t_1}^{t_2} V_{air} \left( \theta + \frac{\dot{V}_{air}}{g} \right) dt \]

and the right-hand side includes the expenditure of the energy of external forces. Obviously, the first term is the work of the propulsive force, which we call the specific work of the engine:

\[ \Delta H_{Eng} = \int_{t_1}^{t_2} V_{air} P_{nr} \cos(\alpha_{air} + \varphi_{eng}) dt. \]

The second term expresses the expenditure of energy for overcoming the harmful drag:

\[ \Delta H_E^D = \int_{t_1}^{t_2} V_{air} D_{nr} dt. \]

The third term describes the work of wind:

\[ \Delta H_E^w = \int_{t_1}^{t_2} V_{air} f_w dt. \]

Therefore, we obtained the energy balance equation

\[ \Delta H_E = \Delta H_{Eng} + \Delta H_E^D + \Delta H_E^w, \] (10)

which relates the energy height, mode of engine operation, aircraft aerodynamics and wind perturbations.

3. Construction of the energy flight control system
We believe that the problem of flight control need not be formulated as that of control of altitude and speed, but must be formulated in the most natural terms of control of the energy height under additional constraints on the distribution of its components. There exists another argument in favor of this choice. Expert estimates of the flight skills of experienced pilots are explicitly correlated with the ability of the pilots to intuitively feel and evaluate the total aircraft energy. This “sense of energy” helps one to better forecast the flight path and coordinate more efficiently the engine and elevator [15].

Thus, the problem of control is formalized as that of minimization of the functional

\[ \Delta H_E \Rightarrow \min \] (11)

Under the constraints on the variables

\[ \Delta y = (y_{ref} - y) \leq \varepsilon_1, \]
\[ \Delta V_{air} = (V_{air}_{ref} - V_{air}) \leq \varepsilon_2 \]
\[ \alpha_{min} \leq \alpha \leq \alpha_{max} \]

And the internal state variables

\[ P_{min} \leq P \leq P_{max} \]
\[ (\delta_{air})_{min} \leq \delta_{air} \leq (\delta_{air})_{max} \]

The thrust \( P \) is the only controllable variable of the aircraft that affects the energy. The deviations \( \delta \) of the elevator result only in a redistribution of the potential and kinetic energies.

We seek a control laws for the engine thrust and elevator.

With some simplifications, we resolve (1) with respect to \( P \) and get

\[ P = mg \left( \theta + \frac{\dot{V}_{air}}{g} \right) + mg \left( \frac{W_x}{g} - \frac{W_y}{V_{air}} \right) + D \]

Or in the normalized variables

\[ P_{nr} = \theta + \frac{\dot{V}}{g} + f_w + D_{nr}. \] (12)

For conditions of stationary flight and the absence of wind, you can get the law of thrust control in increments relative to the set values:

\[ \Delta P_{nr}^{TEC} = \Delta \theta + \frac{\Delta \dot{V}_{air}}{g}, \] (13)

where \( \Delta P_{nr}^{TEC} = (P_{nr})_{ref} - P_{nr}, \)
\[ \Delta \theta = \theta_{ref}, \quad \Delta \dot{V}_{air} = (\dot{V}_{air})_{ref} - \dot{V}_{air}. \]

The elevator is controlled so as to minimize the difference between the potential and kinetic components:

\[ \Delta \delta_{air}^{TEC} = \Delta \theta - \frac{\Delta \dot{V}_{air}}{g}. \] (14)

It is proposed to realize these laws using the PI algorithms having in each channel the proportional and integral components with the weight coefficient \( k_{pr} \) and \( k_i \):

\[ \Delta P_{nr}^{TEC} \left( \Delta \theta + \frac{\Delta \dot{V}}{g} \right) \left( k_{pr} + k_i \frac{1}{p} \right), \] (15)

\[ \Delta \delta_{air}^{TEC} \left( \Delta \theta - \frac{\Delta \dot{V}}{g} \right) \left( k_{pr}^\delta + k_i^\delta \frac{1}{p} \right). \] (16)

The algorithm (15) and (16) are pivotal for the energy control system.
The equivalent structure of energy control system (ECS) is presented in figure 3.

![Figure 3. The structure of the energy control system.](image)

The ECS showed excellent handling quality of transport aircraft at landing approach under strong atmospheric perturbation, engine failures, abrupt glides, etc.

The route along any reference (or set) trajectory is organized by assigning a sequence of required values of the variables $n_x^{\text{ref}}$ and $\theta_{r}^{\text{ref}}$. These variables can be used to calculate the reference trajectory in the coordinates of the total energy of the $E_{r}^{\text{ref}}$.

4. **Formation of the director index for manual engine thrust control**

Traditionally, in the pilot’s field of view in both automatic and manual modes, symbolic information is displayed only about the spatial position of the aircraft, as well as quantitative information about the airspeed. Atmospheric disturbances and terrain envelop maneuvers affect not only the speed, but also, as follows from the energy balance equation, the total energy. If the pilot does not have a sufficiently developed “sense of full energy”, it is very difficult to interpret such heterogeneous information as a measure of the energy state of the aircraft.

For manual piloting modes, we proposed to indicate on the screen of the primary flight display the value of the deviation of the energy height from the required $\Delta H_{E}$, forming a movable index on the screen nearby to the geometric altitude scale [10,11]. This concept is explained in figure 4.

![Figure 4. Variant of the indicator with the director index.](image)
Director index should be perceived as a command signal for engine thrust control in order to reset the total energy error. Functionally, the “energy index” is similar to the various forms of directional “trajectory indexes” for manual piloting. The presence of such a hint will help to acquire a “sense of full energy” for the pilot, facilitate manual control, or serve as an indicator of a generalized error in automatic control.

5. Simulation of fly around routes
The effectiveness of the developed means of assistance the pilot in difficult terrain monitoring conditions was tested on a real flight indicator with a software model of the magnetic reconnaissance equipment of the carrier aircraft.

When performing airborne geophysical survey, one of the factors affecting the quality of the data obtained is the accuracy of the aircraft's guidance along the reference trajectories. To carry out such piloting, it is necessary to receive timely information about the current position of the aircraft relative to the specified trajectory.

One of the options for presenting such information is a “strelka”-type flight indicator (figure 5). This indicator allows the pilot to guide the aircraft along a given trajectory, taking into account the current lateral deviation of the aircraft from the references trajectory.

Any piloting error means the deviation of the aircraft position from a point on the reference trajectory at the current time.

The indicator of the “strelka”-type is used at the moment when performing airborne geophysical survey and allows obtaining high quality data. To solve the problem of precise guidance of aircraft on reference trajectories with variable height, we propose to use the energy index.

As a result, the indicator of the “strelka”-type was extended with a separate window displaying the current energy index (figure 6) of the aircraft.
Figure 6. «Strelka»-type indicator with the ability to display the energy index.

In figure 6, the current energy index $\Delta H_E$ is the energy height error, the deviation of the aircraft energy height from the trajectory at the current time.

For the pilot's convenience, the energy index is presented as a green triangle, which deviates from the zero mark, and in the form of text.

When controlling the aircraft's elevator and thrust, the pilot should try to keep the index at zero.

Since there are restrictions imposed on the values of the energy index, the indicator has the min/max values of the restrictions.

The effectiveness of the developed means of helping the pilot in the complicated conditions of flying around terrain with difficult terrain was tested on a computer simulator with a mathematical model of an aircraft - a carrier of magnetic reconnaissance equipment. At the input of the simulator, a trajectory enveloping the relief was set.

Figure 7. Results of simulation of aircraft flight along a reference trajectory.

The upper graph represents the simulation of an aircraft flight (ProTO) along a reference trajectory (AltA) enveloping the relief (Relief). The bottom graph (Ind) is the energy index in the trajectory tracking mode.
The bursts of the energy index are caused by elevation changes along the route. The presented route is taken from the list of routes used when performing airborne geophysical work in the Republic of Rwanda.

6. Conclusion

Airborne geophysical survey of the territory for the purpose of remote sensing of magnetic permeability, electrical conductivity, density and radioactive properties of rocks is carried out by flying an aircraft of the territory along trajectories covering investigated surface area. Trajectories (routes) are parallel lines that cover the survey area. The main parameters affecting the quality of survey data include the lateral deviation of the aircraft from the trajectory, as well as the deviation in altitude. In the case of using a manned aircraft, increased requirements are imposed on the quality of manual piloting. At the same time, flight with tracking the terrain and in the presence of wind disturbances is a difficult task for the pilot.

In the work, it was proposed in the pilot’s field of view to form a thrust control director index to minimize the deviation of the altitude and, if required, the speed from the required one. Such a “assistant” to the pilot operates on the basis of instrument measurements of aircraft coordinates and calculates quantitative estimates of the pilot’s recommended commands, as opposed to his intuitive ones, based on personal experience. The solution to the tasks is achieved by using an original energy approach of aircraft flight control. The mathematical formulation of the approach is the energy balance equation with the “aircraft-engine-external environment” system. This equation establishes quantitative relationships between the energy source and all its consumers. In contrast to traditional approaches, in the energy approach the controlled variable is the total energy of the object \( E \). To minimize the error in the total energy control, only the engine thrust can be used.

The structure of the energy system has been developed for the automatic flight mode. For the manual piloting mode, it is proposed to indicate deviations of the total energy from the specified one in the form of a director index. To zero deviation, the pilot must bring the index to zero by acting on the engine throttle sector.

Prototypes of electronic indicators with a moving index on the screen of the flight director have been developed.

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