29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

SIMULATION OF ON-BOARD MODEL OF AIRLINER TO EVALUATE CAPABILITY OF TRAJECTORIES AND FLIGHT SAFETY

S.G. Bazhenov*, V.S. Korolyov*, E.L. Kulida, V.G. Lebedev****
* Central Aerohydrodynamic Institute (TsAGI), Zhukovsky, Moscow Region, Russia
** Institute of Control Sciences n.a. V.A. Trapeznikov, Moscow, Russia

Keywords: *airplane, control, trajectory, conflict, virtual flight, on-board model*

Abstract

A method is proposed for on-board evaluation of capability and safety of flight trajectories of civil airliner, generated to resolve conflicts. An on-board mathematical model of airplane is used for flight simulation. Parallel simulation of flights along various trajectories is used due to necessity to get results of trajectories evaluation with rate faster than real time operation. It is proposed to develop this technique for implementation in integrated system of trajectory safety on-board system to provide pilots alerts and recommendations to prevent dangerous evolution of flight.

1 Introduction

Today, aviation transport progress has the following features. First, one can see the permanent growth of air traffic. It results in reduction of time and position intervals between airliners, which in turn increases the risk of collisions [1]. In the case of present day avionics, on-ground navigation, air traffic control equipment, and procedures it will result in growth of aviation accidents with the same rate or even larger, that is not acceptable for society. To prevent the growth of aviation accident rate it is necessary to improve efficiency of air traffic planning and control and accuracy of prescribe flight path following both in time and positional aspects.

Second, it becomes obvious that traditional organization of air traffic based on fixed air routes should be modified in direction of more flexible organization. According to these concepts airplane is allowed to fly inside prescribed 4D volume of ATM space (4D contract,…). These concepts mean more autonomy of airplane flight planning and require many functions of air traffic control and management to be implemented with on-board equipment. In future, as a result of “Free Flight” concept materialization on-board systems will play predominant role in planning and control of airplane flight and flight safety provision.

Third, due to harder requirements to flight schedule the airplane should fly in wider range of adverse atmosphere conditions. It requires modernization or development appropriate avionic systems.

Additionally, due to flight safety strongly depends on aircrew actions it is very important to provide crew with comprehensive data of flight situation. This data should be full enough, but not excessive to avoid overload of aircrew, to provide fast and unambiguous understanding of flight situation and to help taking effective actions in proper time for preventing dangerous events. Also, it is very important to predict possible variants of flight situation evolution to provide aircrew with relevant data in advance, to draw attention on hazardous factors and, if necessary, to correct aircrew actions. Special attention is to be drawn to three hazards: weather, terrain and traffic, including wake vortices.

2 Functions of flight situation monitoring and airplane trajectory safety system

It was noted above that airplane trajectory safety system includes tools to improve crew awareness about terrain and obstacles along flight path, atmospheric factors and traffic hazards. Additionally, the system should include intellectual support system, generating recommendations to avoid dangerous scenario [2-9, 13]. The system should have the following functions:

- risk assessment of Controlled Flight Into Terrain (CFIT) in the flight situation;
- generation of trajectories to resolve terrain and obstacles conflicts taking into account airplane state and configuration;
- sorting of these trajectories according to chosen priority logic;
- detection of possible traffic and weather conflicts along these trajectories;
- selection of the most acceptable trajectory to recommend to crew.

To implement these functions the system should have the following data:

- position and speed of airplane from inertial and satellite navigation systems;
- 3D map of terrain;
- air traffic routes, SID and STAR schemes and procedures from FMS;
- data about other air vehicles position and motion from ATM, TCAS, ADS-B;
- atmospheric conditions from weather radar (WR) and other meteo data sources.

Of course, airplane should have appropriate communication tools to receive this data.

Airplane trajectory safety system (figure 1) is proposed to accomplish the following actions.

1. Basing on position, speed, vectoring, angular data of airplane it calculates predictable trajectory of airplane taking into account wind and atmospheric conditions;
2. The system calculates height of terrain under the trajectory basing on digital 3D map to detect terrain conflicts.
3. Also, the system detects conflicts with traffic and atmospheric factors, basing on appropriate data.
4. If conflicts of various nature (terrain, traffic, weather) are detected the system generates set of trajectories to resolve these conflicts.
5. The system analyzes generated trajectories to assess their capability, safety and complexity. This includes steps:
    a. Preliminary analysis basing on approximate evaluation of flight parameters along trajectory [10, 11] to determine the flight envelope (normal, operating or limit – figure 2) the trajectory belongs to. If the parameters go out of the limit flight envelope the trajectory is considered as impossible.
    b. Possible trajectories are sorted according to their priorities. Priority is defined by the following aspects.
        i. Flight envelope trajectory belongs to (normal > operating > limit) and proximity to limit;
        ii. Safety (altitude above terrain, traffic interval, severity of atmosphere);
        iii. Complexity (number and intensity of control action).

Because trajectory parameters evaluation (step 1) is rather approximate the trajectories with maximal priority are analyzed in more detail with on-board mathematical model (figure 3). To get detailed data the airplane model flies virtually along the analyzed trajectory.

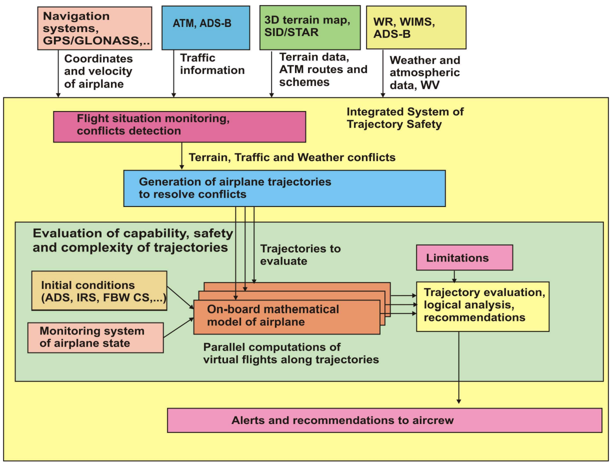

Figure 1. An integrated system of flight situation monitoring and flight path safety

Duration of virtual flight can be long enough (up to 300sec), but calculation should be finished in 1-2 sec, i.e. calculation rate is faster that real time operation. Due to this reason and complexity of airplane model execution of virtual flight requires considerable computational resources. Virtual flights along set of trajectories are possible only with use of parallel calculation technology.

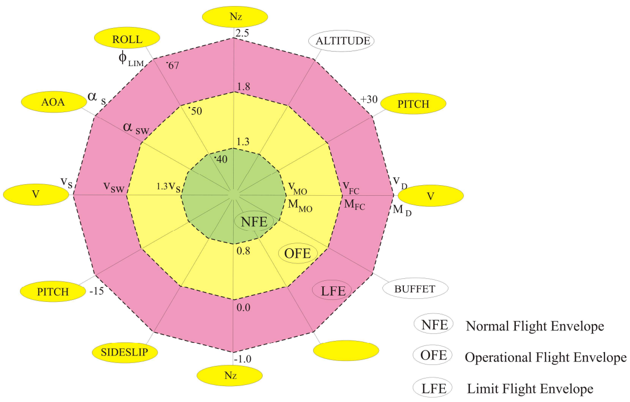

Figure 2 Flight envelopes of airplane

This paper describes generation and analysis of trajectories and main attention is drawn to methods of on-board mathematical model use for detailed analysis of trajectories. According to this technology we can get trajectory parameters from virtual flight of mathematical model along analyzed trajectory (see figure 4). An approach for generation of trajectories to avoid terrain and obstacles is proposed and validated in [14].

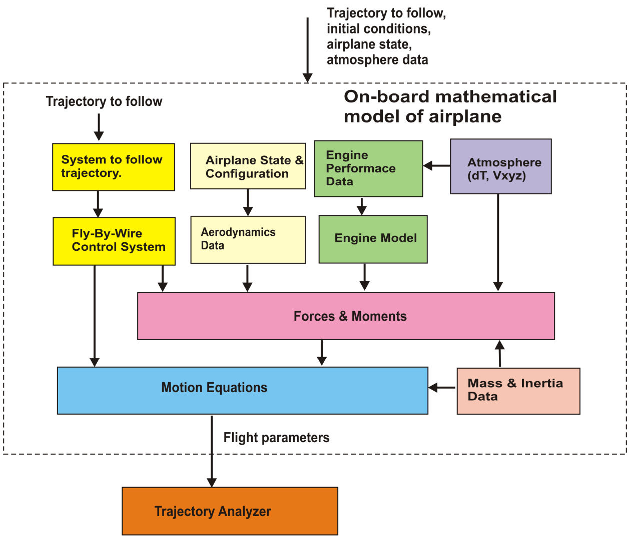

Figure 3 General architecture of on-board mathematical model of airplane

An airplane is considered as mass point and smooth trajectories should be built from initial point (airplane coordinates and velocity vector) to points of STAR scheme avoiding prohibited zones due to terrain.

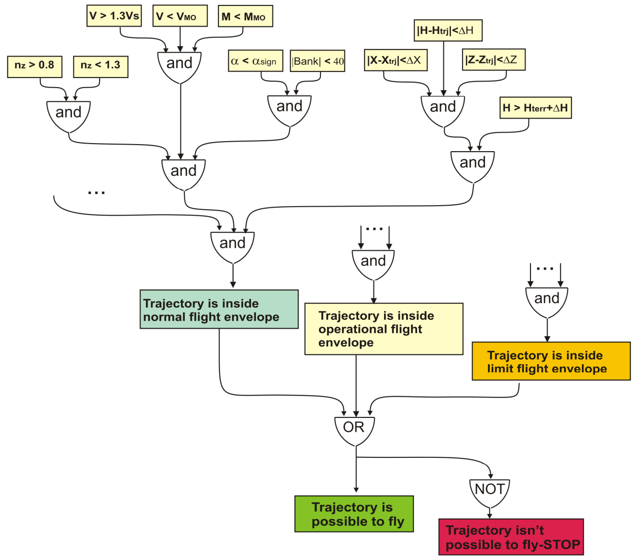

Figure 4 Logic to analyse trajectory possibility

The trajectories generation is based on solution of mathematical problem of shortest path between graph knots. According to this approach airplane trajectory is approximated as set of graph lines between knots and the task is to look for sets with minimal length.

To obtain such path, according to the developed below algorithm, it is necessary to draw a piecewise-linear boundary of terrain on a given height and to construct a terrain avoiding path properly. At first step, such path is built in the flight plane (i.e., on the initial height of an aircraft). Then terrain clearance height gets increased by a preset increment and the next path is constructed. This process terminates when terrain clearance height exceeds terrain height; in other words, the terrain can be avoided by flying along the straight line from the initial point to the end point.

The generation algorithm for terrain conflict free paths includes the following steps.

Step 1. Drawing piecewise linear boundaries of terrain on a given height. To draw the boundary of terrain, construct a uniform grid of nodes in the 2D space. Choose the distance between nodes not smaller than the minimal turn radius R of an aircraft. This guarantees the feasibility of terrain clearance on the boundary. We say that a node is *boundary*, if the set of its adjacent nodes includes admissible and inadmissible nodes. By connecting adjacent nodes through edges, one easily gets the boundaries of terrain.

Step 2. Smoothing of terrain boundaries. Generally, the boundaries generated at Step 1 contain breaks. Figure 5 shows an example of boundary smoothing. Add to the node set of the path graph all points of breaks in smoothed boundaries of terrain.

Step 3. Taking into account additional obstacles. Flight paths (*ergo*, graph edges) must not pass through "no-fly" zones.

Step 4. Taking into account the maneuvering capabilities of an aircraft. Path graph construction allows for the following aspect. In the initial and end points, a "no-fly" zone is represented by circles of radius *R*, which touch the flight direction vector. Therefore, additional nodes on these circles are introduced in the graph to guarantee turning to a desired course at the initial and end points of a route. These nodes include:

—the contact points of a circle and its tangent lines drawn from nodes on terrain boundaries (if these lines do not intersect terrain);

—the contact points of the common tangent lines of two circles (in the beginning and end of a route), if these lines do not intersect terrain.

Step 5. Forming edges in the graph. Connect by edges all pairs of visible nodes.

As a result, one adds edges connecting:

- the initial node with all nodes visible from it;
- each end node with all nodes visible from it;
- all pairs of visible nodes belonging to different boundaries.

Step 6. Constructing paths. Search for shortest paths from the initial node to the end nodes in the graph.

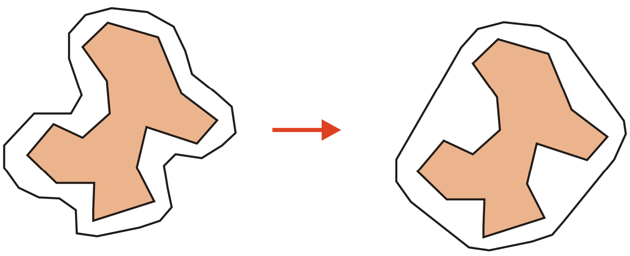

Figure 5 Smoothing of prohibited areas due to terrain conflicts

3 Virtual Flight Organization with On-board Mathematical Model and Trajectories Analysis

The general scheme of virtual flights organization with on-board mathematical model and trajectories analysis is presented in figure 6. Flight path generator, described above creates acceptable trajectories that are inputs to on-board mathematical model to fly along them. It is necessary to calculate normal and tangential accelerations in stability axes and bank angle along trajectory basing on its parameters in ground axes. Then these parameters are used as inputs of trajectory control subsystem to follow trajectory under consideration. This system operation principles are similar to autopilot and auto thrust control laws, but it operates in all flight envelopes, including limit one. To provide high accuracy of trajectory following the system uses filtering of input signal to provide desirable phase lead and trajectory back loops. Command signals are known function of time and it is possible to use lead filter to compensate time lag of airplane time responses. This procedure improve considerably math. model following of input trajectories (accuracy and time responses – see figure 7). Nevertheless, it is impossible to avoid errors growth in open loop operation. Trajectory loopback makes it possible to solve this problem (see figure 7). One can see, that model effectively follow trajectory without time delay and with accuracy high enough. Similar approach is used for lateral motion.

When trajectory following problem is solved there appears another one – to analyze their possibility and effectiveness. It is necessary to develop criteria to make decision if trajectory is possible or not. It depends on the following events (figure 4):

- mathematical model of airplane follow trajectory with acceptable accuracy without exit from normal, operating and limit flight envelopes;
- flight parameters are inside flight envelope, but airplane can't follow command trajectory - accuracy is not acceptable;

- flight parameters are inside flight envelope, but airplane has conflict with terrain;
- flight parameters are out limit flight envelope.

It is necessary to note, that modern fly-by-wire control system includes effective tools of flight envelope protection to avoid violation of limit flight envelope border. Hence, main criterion of trajectory impossibility in limit flight envelope is high difference (above prescribed thresholds) between command and actual trajectories.

Additionally, it is necessary to note, that flight parameters limiters are implemented in primary control system. Back-up control system uses simple control laws without limiters and exit from limit flight envelope can take place. To provide high effectiveness of on-board model of airplane it is necessary to take into account state of the airplane and control system reconfiguration.

4 Modeling of trajectory safety system operation

Main purpose of trajectory safety system is considerable decrease of CFIT risk. To analyze effectiveness of this system we will consider scenario with airplane initial trajectory that has conflict with terrain (figure 8). System should detect this conflict and generate trajectories to resolve conflict (figure 8), analyze their possibility and effectiveness and select the most acceptable one to form and present appropriate recommendation to pilots. Let's consider results of analysis of virtual flights along these trajectories.

Trajectory 1. It is initial trajectory of ~50sec duration, that ends by collision with terrain.

Trajectory 2. It is one of the trajectories generated for terrain conflict resolution. Results of virtual flight along this trajectory are presented in figure 9. This trajectory can be executed with acceptable accuracy and without time delays due to lead filtering of command signal and loopback correction of trajectory following command signal to provide high accuracy. To follow this trajectory airplane should have normal g-factor n_y~1.4, i.e. airplane is out of the normal flight envelope, but inside in the operating one.

Trajectory 3. The trajectory is generated to resolve conflict and avoiding action is to fly to left and nose up (see figure 8). Virtual flight results are presented in figure 10. To follow this trajectory airplane should exceed maximal angle of attack to get command normal g-factor. It can be easily explained by decrease of speed due to airplane deceleration during climbing flight with constant thrust lever. However, angle of attack limiter doesn't allow airplane to exceed maximal angle of attack. Due to this reason actual trajectory of airplane becomes below command one. When difference between actual and command trajectories exceeds prescribed level, the system concludes that airplane can't follow command trajectory, stops the simulation of virtual flight along trajectory and trajectory is considered as impossible.

Trajectory 4. The trajectory is generated to resolve conflict and avoiding action is to fly to right (see figure 8). Preliminary analysis shows this trajectory is inside normal flight envelope. That can be confirmed by the results of virtual flight modeling with the use of airplane mathematical model. Parameters are inside normal flight envelope.

As a general result we can conclude, that two of three trajectories can be executed. After analysis of possible conflicts of these trajectories with weather and traffic system selects the most acceptable trajectory to form and present recommendations for aircrew to follow this trajectory.

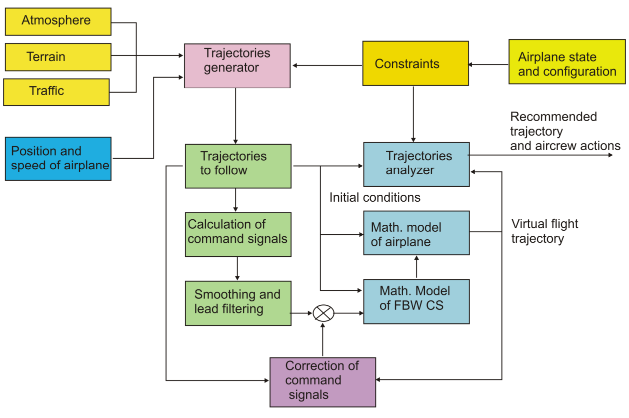

Figure 6. General approach to generate and analyse trajectories with airplane mathematical model

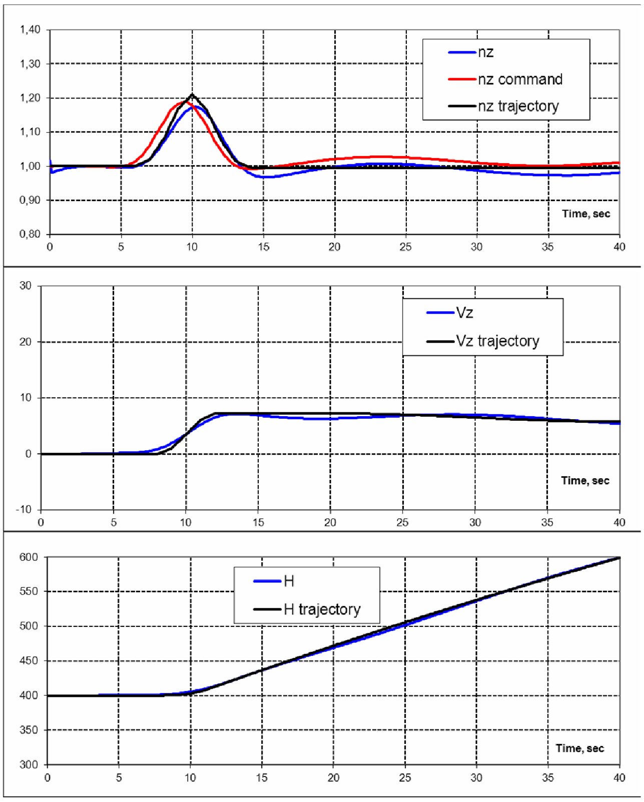

Figure 7. Parameters of command trajectory following by airplane mathematical model. There are lead filter of command signal and back loops to correct trajectory.

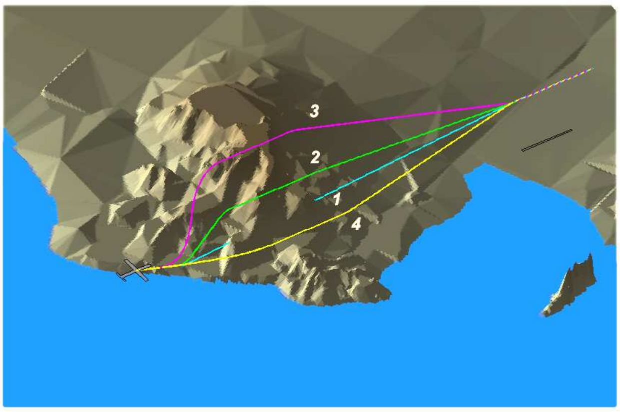

Figure 8. An initial flight path and trajectories to resolve terrain conflict

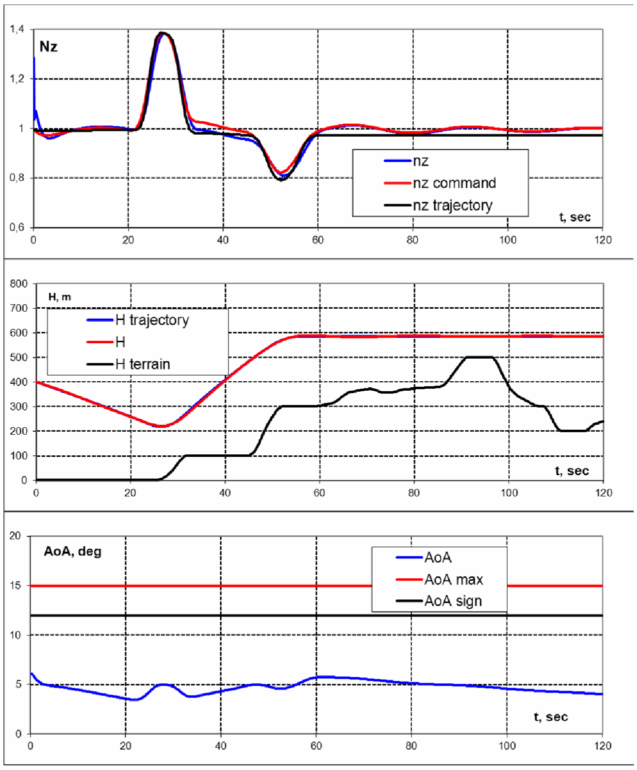

Figure 9 Parameters of virtual flight along trajectory № 2. Trajectory can be realized in operational flight envelope with increased thrust

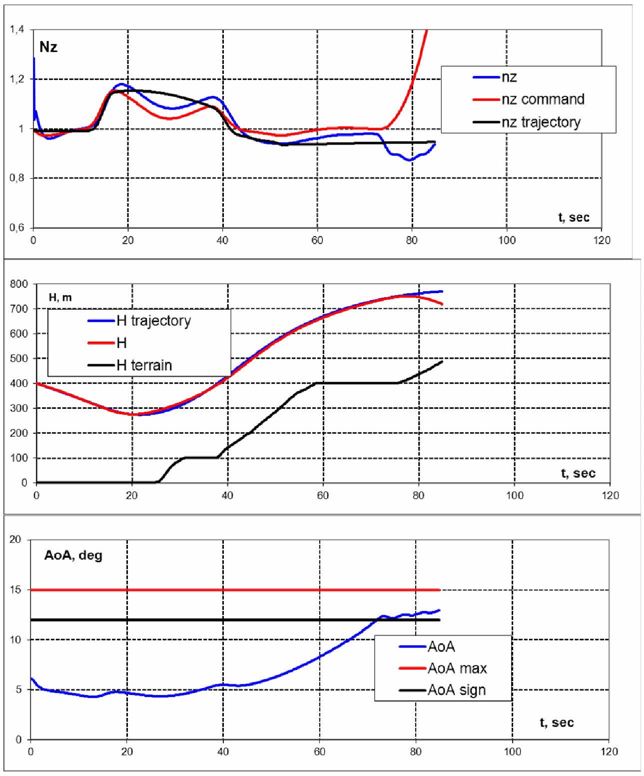

Figure 10 Parameters of virtual flight along trajectory № 3. Trajectory can't be realized due to angle of attack limiter operation

5 References

[1] Shumilov, I.S., *Aviatsionnye proisshestviya. Prichiny vozniknoveniya i vozmozhnosti predotvrashcheniya.* (Aviation Accidents. Reasons of Occurrence and Prevention Capabilities), Moscow: Mosk. Gos. Tekhn. Univ., 2006.

[2] Bazhenov, S.G., An Intelligent System of Aircraft Path Formation and Assessment for Approach Maneuvering, *Iskusstv. Intellekt*, 2005, no. 4, pp. 65–73.

[3] Lebedev, V.G., A Crew Assistance System of a Perspective Aircraft, *Tr. Inst. Probl. Upravlen. Ross. Akad. Nauk*, 2005, vol. 26, pp. 39–46.

[4] Gloubokaya M.G. Bortovaya intellectualnaya sistema podderzhki prinyztiya resheniya na etape vzleta magistralnogo samoleta. // *Iskusstv. Intellekt*, 2004. № 4. pp. 303-312.

[5] Fedunov B.E. Bortovie intellectualnie sistemi upravleniya I navedeniya pilotiruemih letetelnyh apparatov // Moscow, 2006. Proceedings of Science session of MIFI, v.3. Intellectual systems and technologies. pp. 22-23.

[6] Alyeshin B.S., Bazhenov, S.G., Kulida, E.L., Lebedev, V.G., Assessment of Impementability and Safety of Aircraft Flight Paths by an On-Board Mathematical Model // Automation and Remote Control, v.75, №4, Moscow, 2013, pp. 745-754.

[7] Rataj J., Bender K., Kohrs R. Pilot assistant for approach and departure // 27th Evropean Rotorcraft Forum, Moscow, Russia, 2001, p. 17.1-17.12.

[8] Ionita S., Sofron E. The Fuzzy Model for Aircraft Landing Control // Lect. Notes Computer Science. 2002. P. 47-54.

[9] Bass E.J. Architecture for an Intelligent Instructor Pilot Decision Support System // IEEE International Conference on Systems, Man, and Cybernetics, San Deigo, CA, 1998.

[10] Byushgens, G.S. and Studnev, R.V., *Dinamika prodol'nogo i bokovogo dvizheniya samoleta* (Flight Dynamics of Longitudinal and Lateral Motion of an Aircraft), Moscow: Mashinostroenie, 1979

[11] *Aerodynamics and Flight Dynamics of Airliners*, Edited by Byushgens, G.S., Beijing: Aviation Press of PRC, 1995.

[12] Advisory Circular 25-7A. Flight Test Guide for Certification of Transport Category Airplanes, FAA. 1998.

[13] Bazhenov, S.G., An Intelligent System of Aircraft Landing Prediction and Implementability Assessment, *Izv. Taganrogsk. Gos. Radio. Univ.*, 2004, vol. 44, no. 9, pp. 21–28.

[14] Bazhenov, S.G., Kulida, E.L., Lebedev, V.G., Conflict-free Paths Formation for Pre-landing Maneuvering with Existing Constraints on Maneuvering Capabilities of an Aircraft, *Probl. Upravlen.*, 2012, №2, pp. 70–75.

[15] ARINC 660A CNS/ATM Avionics, Functional Allocation and Recommended Architectures.

[16] *Global Air Navigation Plan, Doc 9750 AN/963*, Montreal: International Civil Aviation Organization, 2007, 3-rd ed.

6 Contact Author Email Address

Sergey Bazhenov. Mail to:
bazhenov-s@yandex.ru, flight15@tsagi.ru