AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

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SIMULATION OF THE MULTI-OBJECTIVE RESOLUTION OF AIRCRAFT CONFLICT

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Abstract. *The article represents computer simulation of aircraft conflict resolution using the method of multi-objective sequential synthesis of conflict-free space-time trajectories. The results of computer simulation show that the method provides the conflict resolution according to flight regularity, efficiency and maneuvers complexity criteria.*

Keywords: aircraft; computer simulation; conflict resolution; multi-objective decision-making.

1. Introduction

Today the important problem is developing of new methods and systems of aircraft conflicts resolution which should ensure the synthesis of conflict-free trajectories in conditions of high relative dynamics of air traffic according to the selected optimality criteria.

The synthesis of conflict-free flight trajectories for conflict resolution is the multi-objective decision-making problem.

The main limitation is the flight safety. The problem of aircraft conflict resolution is the problem of determination of the flight trajectory which provides maintaining of separation minima.

Optimality criteria for aircraft conflicts resolution are: regularity and economy of flights, aircraft priorities, maneuvers complexity and passengers comfort. Current trends of increasing the intensity of flights causing the need to take into account the criteria of regularity and economy of flights. It is advisable to take into account the individual priorities of aircraft according to their operating conditions, fuel on board, type of flight. The important criterion for air navigation and air traffic control (ATC) is the complexity and duration of conflict resolution maneuver. The criterion of comfort receives much attention from airlines because performing of turns with large bank angles, abrupt changes of altitude and speed causes the deterioration of passengers comfort

2. Analysis of research

The problem of multi-objective resolution of aircraft conflict was considered in articles [1-3].

In the article [1] the mathematical model of multi-objective selection of trajectories for aircraft conflicts resolution was developed and the method for determining of the importance weights in the linear convolution of optimality criteria was proposed. The evolution of this model was considered in the article [2].

In the article [3] the method of multi-objective synthesis of conflict-free flight trajectories using multi-objective dynamic programming was developed, the equations of multi-objective dynamic programming for determination of the set of Pareto-efficient estimations of conflict-flight trajectories are shown, and the procedure for selection of the optimal trajectory from the set of Pareto-efficient was defined.

The **aim** of this article is the computer simulation of aircraft conflict resolution using the method of multi-objective sequential synthesis of conflict-free space-time trajectories, which was developed in article [3].

3. The method of aircraft conflict resolution

To resolve the conflict between two aircraft the method of sequential conflict-free space-time trajectories synthesis, based on multi-objective dynamic programming [3], is used.

In this method the prevention of the potential conflict considered as a sequential multistage decision-making process at discrete time points. Conflict resolution considered as a controlled

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process when one aircraft can perform several manoeuvres assigned at discrete time points. The conflicting aircraft are a dynamic system $\mathbf{S}$. The conflict-free trajectory synthesis is the problem of optimal control of dynamic system $\mathbf{S}$ that can be solved using the dynamic programming.

It is assumed that one aircraft performs maneuvers and another aircraft flies according to planned trajectory.

Trajectories synthesis is considered in the time interval $[t_0, t_k]$, where t_0 – the time of potential conflict detection, t_k – the time of manoeuvring aircraft leaving the ATC area.

The dynamic system $\mathbf{S}$ is discretized in time (the process is decomposed into k stages) and in state space. In general, it is considered that the manoeuvring aircraft can transit into the state $\mathbf{X}(j)$ at the stage j form several states $\mathbf{X}(j-1)$ at the previous $(j-1)$ stage:

$$\mathbf{X}(j) = f(\mathbf{X}(j-1), \mathbf{U}(j-1)),$$

where $f(\mathbf{X}, \mathbf{U})$ – the transition function from the state of $\mathbf{X}$ under the control $\mathbf{U}$ effect.

The state vector $\mathbf{X}$ contains the coordinates, speed, heading of the aircraft. Input vector $\mathbf{U}$ of control signals includes the specified value of the speed and bank angle. The initial $\mathbf{X}_0$ and final $\mathbf{X}_k$ states of the system are conflict-free. The final state $\mathbf{X}_k$ is defined only by horizontal coordinates of the exit point from the ATC area. It is assumed that aircraft can transit into the final state from all states at the penultimate stage.

At each j stage the prediction of the separation minima violations at the transition from states $\mathbf{X}(j-1)$ under the controls $\mathbf{U}(j-1)$ effect is performed and the corresponding sets of conflict-free controls $\mathbf{D}_{\mathrm{U}}^{S}(\mathbf{X}(j-1))$ are defined.

Optimality criteria that characterize the efficiency of conflict resolution are the deviations from flight plan J_1, fuel consumption J_2 and the number of flight profile changes J_3. The chosen optimality criteria constitute the vector $\mathbf{J} = \{J_i\}, i = \overline{1,3}$.

For an arbitrary trajectory $\mathbf{T} = \{\mathbf{X}_0, \mathbf{X}(1), \ldots \mathbf{X}(m)\}$ the values of the optimality criteria J characterizing flight efficiency are defined as follows:

$$J_i(\mathbf{T}) = \sum_{j=1}^{m} \Delta J_i\left(\mathbf{X}(j-1), \mathbf{U}(j-1)\right),$$

where $\Delta J_i(\mathbf{X}, \mathbf{U})$ – the cost for each i-th optimality criterion at transition from the state of $\mathbf{X}$ under the control $\mathbf{U}$ effect.

To determine the set of Pareto-efficient estimates $\mathbf{E}(\mathbf{X}(j))$ of conflict-free trajectories at the transition to a state $\mathbf{X}(j)$ from states $\mathbf{X}(j-1)$ the equation of multi-objective dynamic programming is applied [3]:

$$\mathbf{E}\left(\mathbf{X}(j)\right) = \mathrm{eff} \bigcup_{\mathbf{X}(j-1) \in \Pi} \left(\mathbf{E}\left(\mathbf{X}(j-1)\right) \oplus \Delta\mathbf{J} \right),$$

$$\Delta\mathbf{J} = \left\{ \Delta J_i\left(\mathbf{X}(j-1), \mathbf{U}'(j-1)\right) \right\}, i = \overline{1,3},$$

where eff – the operator of the Pareto-efficient evaluations; $\oplus$ – direct sum; $\mathbf{\Pi}$ – the set of states on $(j-1)$ stage from which the transition to state $\mathbf{X}(j)$ is possible; $\mathbf{U}'(j-1) \in \mathbf{D}_{\mathrm{U}}^{S}\left(\mathbf{X}(j-1)\right)$ – the control that transfers the aircraft from $\mathbf{X}(j-1) \in \mathbf{\Pi}$ state to $\mathbf{X}(j)$ state.

The set $\mathbf{P}$ of Pareto-efficient conflict-free flight trajectories is defined as:

$$\mathbf{P} = \left\{ \mathbf{T} \in \mathbf{K} \middle| \mathbf{J}(\mathbf{T}) \in \mathbf{E}(\mathbf{X}_k) \right\},$$

where $\mathbf{K}$ – the set of complete conflict-free trajectories by which the aircraft is moving from the initial state $\mathbf{X}_0$ to the final state $\mathbf{X}_k$.

The selection of the optimal conflict-free trajectory $\mathbf{T}^*$ is performed by solving the optimization problem [1, 3]:

$$\mathbf{T}^* = \arg\min_{\mathbf{T} \in \mathbf{P}} \max_{\mathbf{W} \in \mathbf{D}_w} \sum_{i=1}^{3} w_i c_i(\mathbf{T}),$$

where c_i – optimality criteria with the domain of allowable value $\mathbf{D}_c = \left\{ c \mid c \in [0,1] \right\}$; w_i – the weighting coefficients reflecting the relative importance of criteria and forming a vector $\mathbf{W} = \{w_i\}$ with the domain of allowable value $\mathbf{D}_w$:

$$\mathbf{D}_w = \left\{ \mathbf{W} \middle| \sum_{i=1}^{3} w_i = 1; w_i \ge w_{i+1}, i = \overline{1,2}; w_3 \ge w_0 > 0 \right\}.$$

The value of the optimality criteria of $\mathbf{T}$ trajectories from the $\mathbf{P}$ set are reduced to the domain of allowable values $\mathbf{D}_c$ using linear transformation:

$$c_i(\mathbf{T}) = \frac{J_i(\mathbf{T}) - \min_{\mathbf{T} \in \mathbf{P}} J_i(\mathbf{T})}{\max_{\mathbf{T} \in \mathbf{P}} J_i(\mathbf{T}) - \min_{\mathbf{T} \in \mathbf{P}} J_i(\mathbf{T})}.$$

4. Computer simulation

The conflict situation between two aircraft Boeing 737-800 flying with constant speed on crossing tracks at FL 360 was simulated. The initial parameters of the aircraft flight and characteristics of predicted conflict situation are presented in Table 1.

The value of the horizontal separation minimum is equal to $d_s = 18{,}5$ km. The geometric method for prediction of separation violations was used.

Table 1. The parameters of the aircraft flight and characteristics of predicted conflict situation

Parameter	Aircraft 1	Aircraft 2
Heading φ, degrees	0	315
Cruising speed V, m/s	220	200
Initial coordinates $(x_0; y_0)$, km	(35; 0)	(60; 30)
Distance to the control point L_0, km	90	–
Planned time of control point overflight t_k, s	409	–
Flight time to the closest point of approach $t_{min\,0}$, s	225	
Predicted minimum distance between the aircraft $d_{min\,0}$, m	14081	

It was assumed that to the avoid conflict the first aircraft should make the manoeuvre. The second aircraft flies by planned trajectory.

The process was discretized in time on 6 stages. Time increment for first 5 stages is equal to $\Delta t = 60$ s.

It was assumed that the first aircraft can change heading and speed to avoid conflict. The bank angle at turns is equal to $\gamma = 20^\circ$. The turning time is limited to 15 s. Speed change increment is equal to $\Delta V = 5$ m/s.

Simulation of trajectories was performed using the kinematics-energy model of the controlled aircraft motion [4], which takes into account the dynamic properties of motion, aircraft performance characteristics stored in the EUROCONTROL Base of Aircraft Data (BADA), and allows to calculate the fuel consumption.

Definition of costs ΔJ_i is performed using nearest-neighbour interpolation. The minimal value of weighting coefficients of the importance of optimality criteria is equal to $w_0 = 0{,}1$.

As a result of the simulation the set $\mathbf{P}$ of 23 conflict-free Pareto-efficient trajectories were determined. The set $\mathbf{P}$ is characterized by the parameters: minimum and maximum absolute deviation from the planned flight time are $\Delta t_{k\,min} = 1$ s and $\Delta t_{k\,max} = 30$ s respectively; maximum decrease and maximum increase of fuel consumption compared to the flight on planned trajectory are $\Delta q_{dec} = -2$ % and $\Delta q_{inc} = 6{,}4$ % respectively; maximum and minimum number of flight profile changes are $n_{min} = 3$ and $n_{max} = 9$.

The parameters of selected optimal conflict-free trajectory $\mathbf{T}^*$ are represented in Table 2.

Table 2. The parameters of optimal conflict-free flight trajectory

Parameters	Value
Deviation from the planned flight time Δt_k, s	4
Additional fuel consumption Δq, %	3,9
Number of flight profile changes n	4

The optimal conflict-free trajectory assumes flight at cruising speed at first 4 stages, speed increase to 225 m/s at stage 5 and flight with speed 225 m/s to control point at stage 6. The graphically optimal conflict-free trajectory is shown in Fig. 1. The dependence of distance d between aircraft from time is shown in Fig. 2

5. Conclusions

The results of computer simulation show that the method of multi-objective synthesis of conflict-free flight trajectories provides the conflict resolution according to selected optimality criteria.

This method can be used for developing of modern conflict resolution algorithms for automated ATC systems and airborne collision avoidance systems.

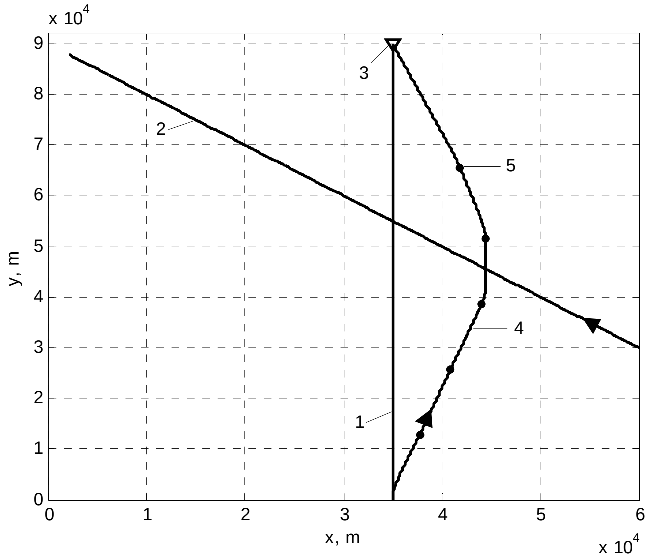

Fig. 1. The aircraft trajectories: *1* – planed trajectory for the first aircraft; *2* – planed trajectory for the second aircraft; *3* – control point on the route; *4* – optimal conflict-free trajectory for the first aircraft; *5* – states at the stages.

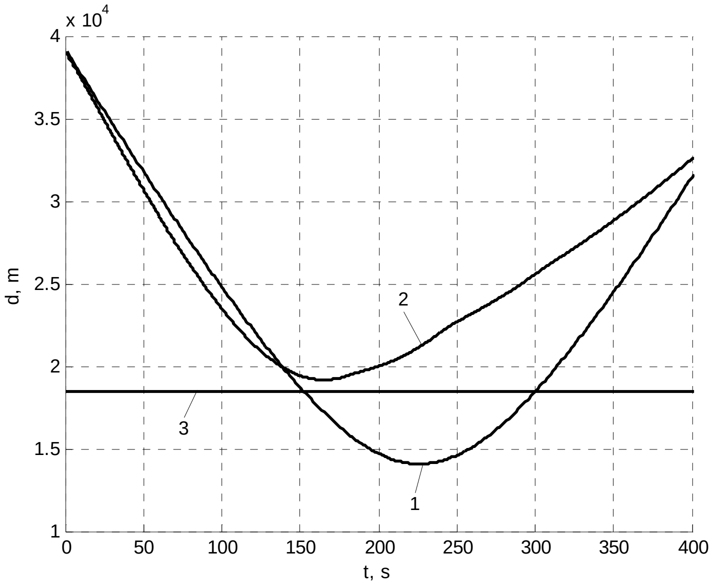

Fig. 2. The dependence of distance d between aircraft from time: *1* – distance at flight by planed trajectories; *2* – distance at conflict resolution; *3* – separation minimum

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В. П. Харченко[1], Д. В. Васильєв[2], Ванг Бо[3]. Моделювання багатокритеріального розв'язання конфліктної ситуації між повітряними кораблями
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Представлено результати комп'ютерного моделювання розв'язання конфліктної ситуації між повітряними кораблями із застосуванням методу багатокритеріального послідовного синтезу безконфліктних просторово-часових траєкторій. Результати комп'ютерного моделювання свідчать про те, що метод забезпечує розв'язання конфліктної ситуації відповідно до критеріїв регулярності польотів, економічності та складності маневрування.
Ключові слова: багатокритеріальне прийняття рішень; комп'ютерне моделювання; повітряний корабель; розв'язання конфліктної ситуації.

В. П. Харченко[1], Д. В. Васильев[2], Ванг Бо[3]. Моделирование многокритериального разрешения конфликтной ситуации между воздушными судами
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Представлены результаты компьютерного моделирования разрешения конфликтной ситуации между воздушными судами с применением метода многокритериального последовательного синтеза бесконфликтных пространственно-временных траекторий. Результаты компьютерного моделирования свидетельствуют о том, что метод обеспечивает разрешение конфликтной ситуации в соответствии с критериями регулярности полетов, экономичности и сложности маневрирования.
Ключевые слова: воздушное судно; компьютерное моделирование; разрешение конфликтной ситуации; многокритериальное принятие решений.

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