AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

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SELECTION OF AIRCRAFT CONFLICT-FREE TRAJECTORIES USING DIFFERENT CONVOLUTIONS OF VECTOR OPTIMALITY CRITERION

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Abstract. *The multi-objective decision-making problem of conflict-free flight trajectories selection is solved using linear, multiplicative and Germeier's convolution of vector optimality criterion, which contains the flight regularity, economy and maneuvers complexity criteria. The computer simulation of multi-objective selection of conflict-free trajectories for resolution of the typical conflict was performed.*

Keywords: aircraft; conflict resolution; convolution; multi-objective selection; vector optimality criterion.

1. Introduction

Nowadays the actual problem is the development of decision support methods and tools for aircraft conflicts resolution.

Conflict resolution is a multi-objective decision-making problem of conflict-free trajectories selection taking into account different optimality criteria, which characterize the efficiency of flight. The main optimality criteria are the regularity and economy of flight, maneuvers complexity.

2. Analysis of research

The problem of multi-objective selection of trajectories for aircraft conflicts resolution was considered in articles [1, 2], which show that it is advisable to select the optimal trajectory from the set of Pareto-optimal conflict-free trajectories.

In general there are different methods of optimal alternative selection from a Pareto set [3, 4]. For problem of trajectories selection the method of main criterion selection is unusable due to the difficulty in determination of thresholds for other criteria, application of lexicographic criteria ordering is inappropriate because in many cases the solution is defined after optimization by first criterion. Therefore it is proposed to use the convolutions of vector optimality criterion [1, 2].

3. Problem statement

The problem of multi-objective selection of the flight trajectories to resolve the potential conflict situation between two aircraft in air traffic is considered. Alternative choices are the possible flight trajectories of the one aircraft performing maneuvers to avoid the conflict (second aircraft flies according to planned trajectory). Maneuvering is defined as a change of heading and speed of flight.

The problem is to select the trajectory $\mathbf{x}^*$ that provides the resolution of a conflict and meets the defined optimality criteria [1]:

$$\mathbf{x}^* = \arg\min \mathbf{C}(\mathbf{x}), \mathbf{x} \in \mathbf{X}, \mathbf{x} \notin \Omega, \quad (1)$$

where $\mathbf{x}$ – the possible flight trajectories of the one aircraft performing maneuvers; $\mathbf{X} = \{\mathbf{x}_j\}, j = \overline{1,k}$ – the set of admissible trajectories ; Ω – the area of a conflict between aircraft; $\mathbf{C} = \{c_i\}, i = \overline{1,3}$ – vector optimality criterion, which contains the regularity criterion c_1, economy criterion c_2 and maneuvers complexity criterion c_3; $\mathbf{C}(\mathbf{x})$ – the vector of numerical estimations $c_i(\mathbf{x})$ of trajectory $\mathbf{x}$ by optimality criteria.

The numerical estimation $c_1(\mathbf{x})$ is equal to the deviation from the planned flight time, the numerical estimation $c_2(\mathbf{x})$ is equal to the fuel consumption and the numerical estimation $c_3(\mathbf{x})$ is equal to the number of the flight profile changes.

The **aim** of this article is to solve the problem (1) using different convolutions of vector optimality criterion $\mathbf{C}$.

4. Selection of aircraft conflict-free trajectory

Selection of aircraft conflict-free trajectory is provided in three steps. The first step is the determination of the set of conflict-free trajectories $\mathbf{S}$ from the set of admissible trajectories $\mathbf{X}$:

$$\mathbf{S} = \{\mathbf{x} \in \mathbf{X} \mid \mathbf{x} \notin \Omega\}.$$

The second step is the determination of the set of Pareto-optimal trajectories $\mathbf{P}$ from the set $\mathbf{S}$:

$$\mathbf{P} = \left\{\mathbf{x}_p \in \mathbf{S} \middle| \neg\exists\, \mathbf{x} \in \mathbf{S} : \mathbf{C}(\mathbf{x}) \le \mathbf{C}(\mathbf{x}_p), \mathbf{x}_p \ne \mathbf{x} \right\}.$$

The third step is the determination of the optimal trajectory $\mathbf{x}^*$ from the set of Pareto-optimal alternatives $\mathbf{P}$ using convolution of vector optimality criterion $\mathbf{C}$, i.e. formation of a scalar function F, which is a generalized criterion regarding to vector criterion.

It is purposed to use following convolutions [3, 4]:

1. Linear convolution

$$F(\mathbf{x}) = \sum_{i=1}^{3} w_i \bar{c}_i(\mathbf{x}). \qquad (2)$$

2. Multiplicative convolution

$$F(\mathbf{x}) = \prod_{i=1}^{3} \bar{c}_i^{\,w_i}(\mathbf{x}). \qquad (3)$$

3. Germeier's convolution

$$F(\mathbf{x}) = \max_{i=\overline{1,3}} w_i \bar{c}_i(\mathbf{x}). \qquad (4)$$

In functions (2)-(4) $\bar{c}_i(\mathbf{x}) \in [0,1]$ is the normalized values of estimations $c_i(\mathbf{x})$; w_i is the weighting coefficients reflecting the relative importance of optimality criteria, $\sum_{i=1}^{3} w_i = 1$.

The normalized values of estimations are determined using following transformation:

$$\bar{c}_i(\mathbf{x}) = \begin{cases} \dfrac{c_i(\mathbf{x}) - \min\limits_{\mathbf{x}\in\mathbf{P}} c_i(\mathbf{x})}{\max\limits_{\mathbf{x}\in\mathbf{P}} c_i(\mathbf{x}) - \min\limits_{\mathbf{x}\in\mathbf{P}} c_i(\mathbf{x})}, \\ 0{,}01, \text{ if } c_i(\mathbf{x}) = \min\limits_{\mathbf{x}\in\mathbf{P}} c_i(\mathbf{x}), \\ 0{,}99, \text{ if } c_i(\mathbf{x}) = \max\limits_{\mathbf{x}\in\mathbf{P}} c_i(\mathbf{x}). \end{cases}$$

It is assumed that relative importance of optimality criteria is equal, i.e. $w_i = 1/3$.

The optimal conflict-free trajectory is selected by the minimum of function F. The problem (1) is reduced to the following optimization problem:

$$\mathbf{x}^* = \arg\min_{x\in\mathbf{P}} F(\mathbf{x}).$$

5. Computer simulation

The conflict situation between two aircraft Boeing 737-800 flying with constant speed on crossing tracks at FL 330 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	90
Cruising speed V, m/s	220	200
Initial coordinates $(x_0; y_0)$, km	(60; 0)	(0; 50)
Distance to the control point L_0, km	100	–
Planned time of control point overflight t_k, s	455	–
Flight time to the closest point of approach $t_{min\,0}$, s	260	
Predicted minimum distance between the aircraft $d_{min\,0}$, m	10763	

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

First aircraft can re-route the flight to the control point through the given Fly By waypoints, i.e. aircraft can fly to the control point by several alternative routes (Fig. 1). During the flight from one waypoint to another aircraft can do not change the speed or increase/decrease it on 5 m/s. The set of admissible space-time trajectories $\mathbf{X}$ is formed from the combinations of possible maneuvers.

Simulation of trajectories was performed using the kinematics-energy model of the controlled aircraft motion [5], which takes into account the dynamic properties of motion, aircraft performance characteristics from EUROCONTROL Base of Aircraft Data (BADA), and allows to calculate the fuel consumption.

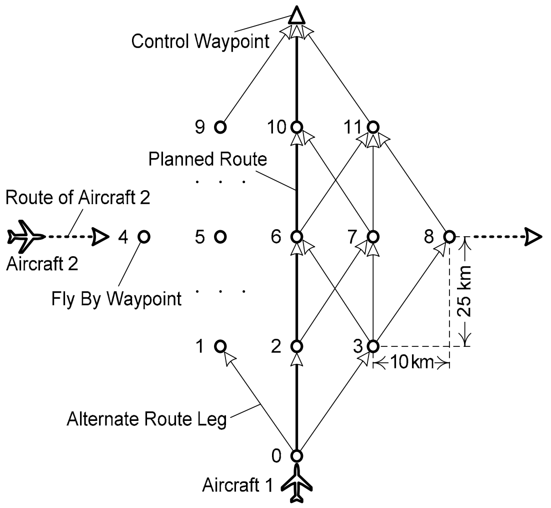


Fig. 1. Formation of the set of admissible trajectories

As a result of the simulation the set **P** of 21 conflict-free Pareto-optimal trajectories was determined (Fig. 2). The set **P** is characterized by the following parameters: minimum and maximum absolute deviation from the planned flight time are 3 s and 34 s respectively; minimum and maximum increase of fuel consumption compared to the flight by planned trajectory are 6,8 % and 13,3 % respectively; minimum and maximum number of flight profile changes are 3 and 7 respectively.

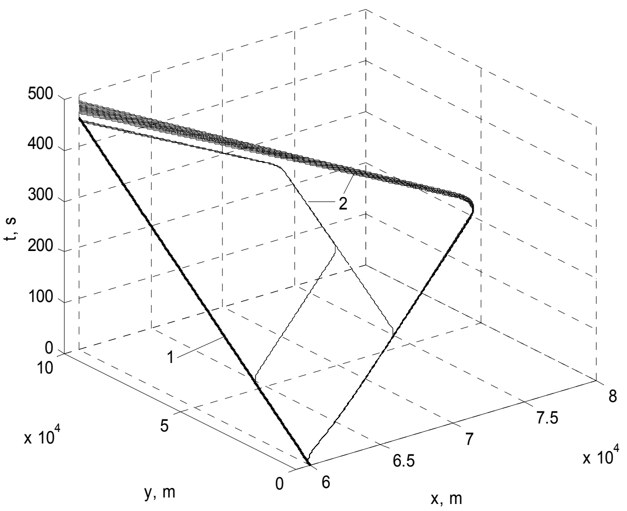


Fig. 2. The set of conflict-free Pareto-optimal trajectories of the first aircraft in the space-time coordinate system: 1 – planed trajectory; 2 – Pareto-optimal trajectories.

The normalized values of estimations $\overline{c}_i$ of Pareto-optimal trajectories are represented in Fig. 3. The values of objective functions F (2)-(4) for Pareto-optimal trajectories are represented in Fig. 4.

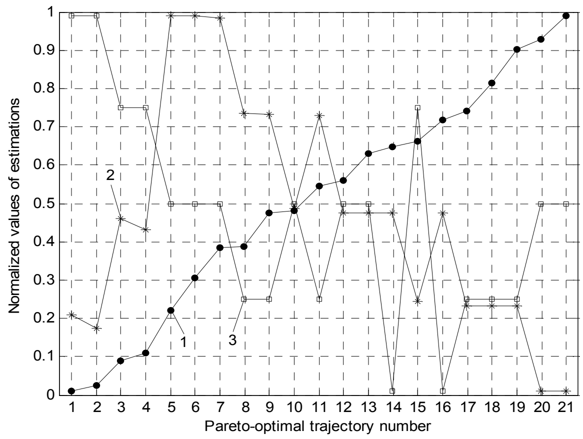


Fig. 3. The normalized values of estimations $\overline{c}_i$ of Pareto-optimal trajectories: 1 – $\overline{c}_1$; 2 – $\overline{c}_2$; 3 – $\overline{c}_3$.

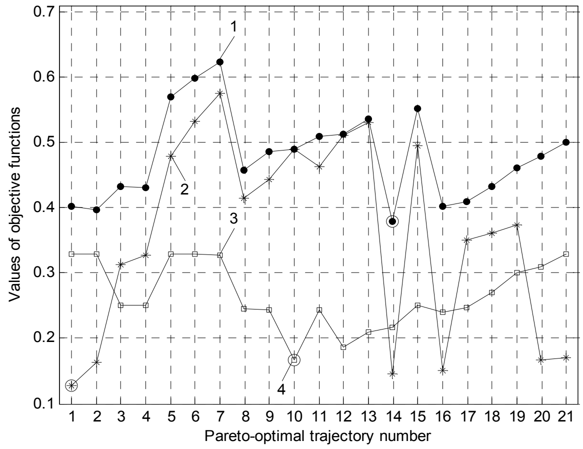
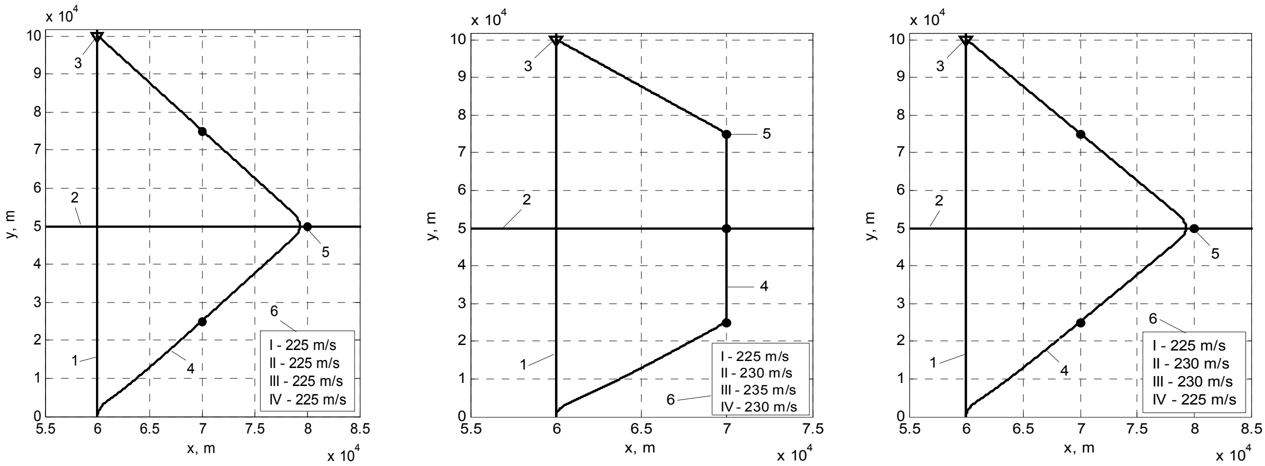


Fig. 4. The values of objective functions F for Pareto-optimal trajectories: 1 – linear convolution; 2 – multiplicative convolution; 3 – Germeier's convolution; 4 – function minimum.

The parameters of selected optimal conflict-free trajectories using different convolutions are represented in Table 2. The graphically optimal conflict-free trajectories are shown in Fig. 5. The dependence of distance d between aircraft from time is shown in Fig. 6.

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

Parameters	Convolution		
	Linear	Multiplicative	Germeier's
Pareto-optimal trajectory number	14	1	10
Deviation from the planned flight time, s	23	3	18
Additional fuel consumption, %	9,9	8,1	10
Number of flight profile changes	3	7	5



a *b* *c*

Fig. 5. The optimal conflict-free trajectory: *a* – selection using linear convolution; *b* – selection using multiplicative convolution; *c* – selection using Germeier's convolution; 1 – planed trajectory of the first aircraft; 2 – planed trajectory of the second aircraft; 3 – control point on the route; 4 – optimal conflict-free trajectory of the first aircraft; 5 – Fly By waypoint; 6 – adjusted speed of the first aircraft at the route legs.

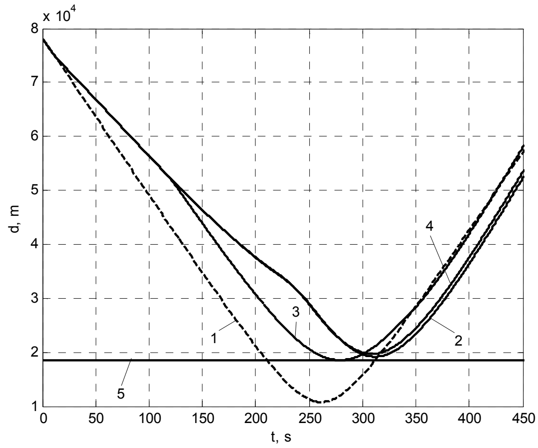


Fig. 6. The dependence of distance d between aircraft from time: 1 – distance at flight by planed trajectories; 2 – distance at conflict resolution by trajectory selected using linear convolution; 3 – distance at conflict resolution by trajectory selected using multiplicative convolution; 4 – distance at conflict resolution by trajectory selected using Germeier's convolution; 5 – separation minimum.

6. Conclusions

The results of computer simulation show that the using of multiplicative convolution and Germeier's convolution provides the most balanced decision, when relative importance of optimality criteria is equal.

The proposed procedure of aircraft conflict-free trajectory selection can be used for developing of modern conflict resolution algorithms and tools.

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Розв'язано задачу багатокритеріального прийняття рішення по вибору безконфліктних траєкторій польоту із застосуванням згортки Гермейера, лінійної та мультиплікативної згортки векторного критерію оптимальності, який складається з критеріїв регулярності, економічності польоту та складності маневрування. Виконано комп'ютерне моделювання багатокритеріального вибору безконфліктних траєкторій для розв'язання типової конфліктної ситуації.

Ключові слова: багатокритеріальний вибір; векторний критерій оптимальності; згортка; повітряний корабель; розв'язання конфліктної ситуації.

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Решена многокритериальная задача принятия решения по выбору бесконфликтных траекторий полета с использованием свертки Гермейера, линейной и мультипликативной свертки векторного критерия оптимальности, состоящего из критериев регулярности, экономичности полета и сложности маневрирования. Выполнено компьютерное моделирование многокритериального выбора бесконфликтных траекторий для разрешения типовой конфликтной ситуации.

Ключевые слова: векторный критерий оптимальности; воздушное судно; многокритериальный выбор; разрешение конфликтной ситуации; свертка.

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