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Methodology for plotting the flight planned route change of the aircraft in flight

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Abstract: A significant number of aviation incidents is related to loss of control in flight and controlled flight into terrain (LOC-I, CFIT, LALT categories). Investigation of these aviation incidents has revealed that these incidents often occur due to the need for rapid changes in flight routes as a result of detecting obstacles, such as thunderstorms, along the aircraft's path. During the determination of alternative routes to circumvent the encountered obstacle, as well as during the implementation process of the chosen rerouted route, the flight crew makes errors due to increased psycho-physiological workload and time constraints. This article presents an approach to the automatic rerouting of the aircraft's flight route to avoid obstacles detected during flight. The algorithm proposed by the authors allows for evaluating the safety of the original route, calculating alternative route options to bypass the obstacles encountered during flight, verifying their feasibility considering the aircraft's flight technical characteristics and control parameter limitations, and selecting the optimal rerouted route based on specific criteria, such as minimizing the increase in the flight route length, reducing additional fuel consumption, time required for implementing the new flight route, etc. Examples of rerouting the flight route of a hypothetical aircraft with detected obstacles along the flight path are provided in the article to demonstrate the algorithm's functionality. It is shown, in particular, that in the considered example, the shortest route for obstacle avoidance is not optimal in terms of time. It is also demonstrated that the safety of flying along the identified alternative rerouted routes depends, among other factors, on the selected flight speed. Therefore, for each calculated rerouted route, the algorithm determines a range of speeds within which the implementation of the obtained rerouted route is possible. This highlights the complexity and non-triviality of the pilot's task of autonomously finding a safe obstacle avoidance route on board the aircraft.

Key words: flight plan, obstacle avoidance, flight safety, control synthesis, restriction on control action, fuel efficiency.

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Методика перестроения маршрута полета воздушного судна в процессе его выполнения

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Аннотация: Большое количество авиационных происшествий связано с потерей управления в полете, а также со столкновением с землей в управляемом полете (категории LOC-I, CFIT, LALT). В результате расследования данных авиационных происшествий выявлено, что часто указанные авиационные происшествия обусловлены необходимостью быстрого изменения маршрута полета вследствие выявления на пути следования воздушного судна препятствий, например грозового фронта. При определении альтернативных маршрутов облета возникшего препятствия, а также в процессе реализации выбранного маршрута облета экипаж совершает ошибки ввиду повышенной психофизиологической нагрузки и дефицита времени. В данной статье представлен подход к автоматическому перестроению маршрута полета воздушного судна для облета обнаруженных в процессе полета препятствий. Предлагаемый авторами алгоритм позволяет оценить безопасность исходного маршрута, рассчитать варианты альтернативных маршрутов облета обнаруженных в процессе полета препятствий, проверить их на реализуемость с учетом летно-технических характеристик воздушного судна, ограничений на управляющие параметры, а также выбрать среди найденных маршрутов облета оптимальный с точки зрения какого-либо критерия, например исходя из минимизации увеличения протяженности маршрута полета, сокращения дополнительных затрат топлива, времени, необходимого на реализацию нового маршрута полета, и т. д. Для демонстрации работоспособности алгоритма в статье представлены примеры перестроения маршрута полета гипотетического воздушного судна с выявленными на пути следования препятствиями. Показано, в частности, что в рассмотренном примере самый короткий маршрут облета препятствий не является оптимальным с точки зрения временных затрат. Также демонстрируется, что безопасность пролета по найденным альтернативным маршрутам облета препятствий зависит в том числе от выбранной скорости полета. Поэтому для каждого рассчитанного маршрута облета препятствий алгоритм определяет диапазон скоростей, в котором возможна реализация полученного маршрута облета препятствий. Последнее указывает на сложность и нетривиальность самостоятельного решения задачи поиска безопасного маршрута облета препятствий пилотом на борту воздушного судна.

Ключевые слова: маршрут полета, облет препятствий, безопасность полета, синтез управления, ограничение на управление, топливная эффективность.

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Introduction

According to flight accident statistics for 2011–2020[1], a significant number of such accidents for civil aircraft is related to such groups of events as loss of control in flight (LOC-I) and controlled flight into terrain (CFIT), and LOC-1, CFIT and LALT for helicopters (fig. 1–4). Analysis of the following accidents has shown that the lack of full crew situational awareness, along with errors due to increased psycho-physiological workload [1, 2] and time constraints for decision-making [3]. In these terms the prior potentially dangerous flight situation identification along with calculating alternative route options in order to choose a route for its performance seems to be relevant. Particularly, automatic rerouting of the aircraft's flight route to avoid obstacles detected during flight, threating the aircraft safety, such as terrestrial natural or artificial object [4], thunderstorm, showers [5], etc. is of undoubtful practical interest.

The crew currently plans flights by means of a flight management computer (FMC). FMC is an airborne computer with relevant air navigation database [6], including air routes, standard departure procedures, arrival and final approach, airfields, and also directory data, for instance, coupling and navigation frequencies [7]. Respectively, the crew plans its flight[2,3] essentially plotting through the given waypoints together: choosing the departure airfield, runway and takeoff heading given by the air traffic controller, standard departure and airway for the following flight. After that the arrival airfield, runway and landing heading are given and the procedures for the following heading and runway are chosen [8]:

- Arrival Route;
- Initial Approach Segment;
- Intermediate Approach Segment;
- Final Approach Segment;
- Missed Approach.

It is clear from above mentioned, that the crew plans the route by the given scenario, provided that there are no unknown obstacles and restricted flight zones. Nevertheless, the aircraft may deviate from the initial plan during the flight due to wide range of reasons. Besides that, the dangerous weather conditions may occur on

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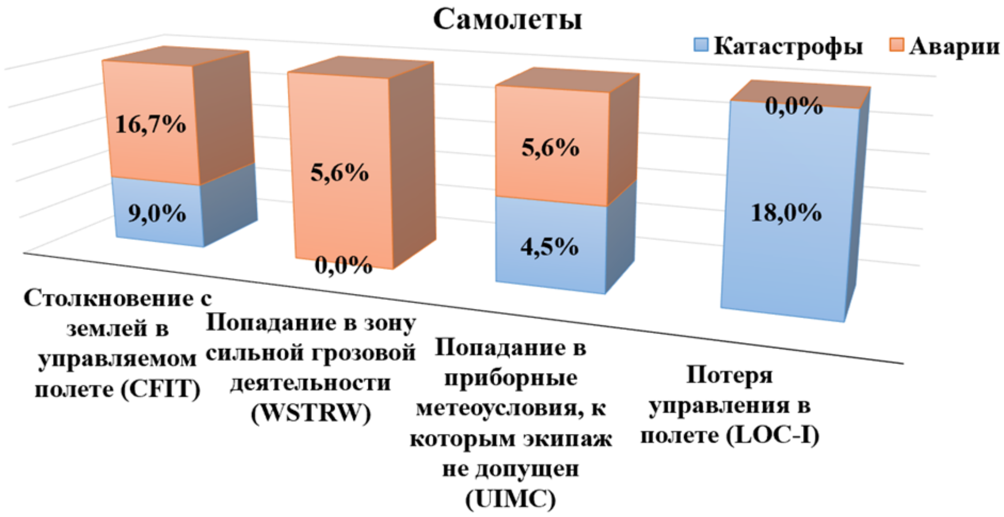

Fig. 1. Types of events that determined aviation accidents with commercial aircraft in 2011–2020

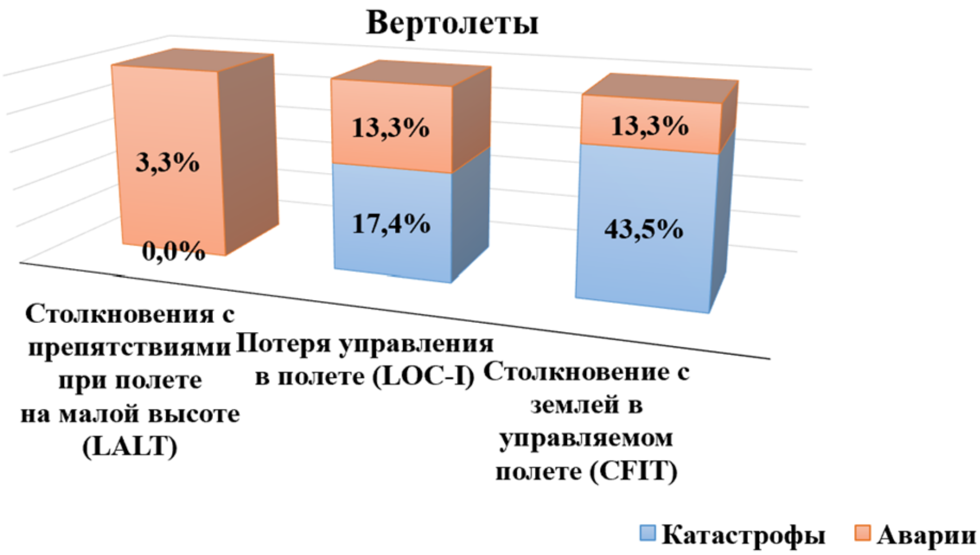

Fig. 2. Types of events that determined aviation accidents with commercial aviation helicopters in 2011–2020

the route. For instance, deviations from the helicopter and general aviation aircraft flight plan may lead to natural or artificial obstacle occurrence along the route. Despite the existence of on-board systems [9, 10] providing the data on obstacles and restrictions along the route and dangerous weather conditions to the crew, the crew has no instrument of automatical rerouting for the obstacle safe avoidance, considering the aircraft limitations and characteristics, which can lead (and leads) to fatal consequences in above mentioned time constraints circumstances. Such an instrument should obviously be integrated into the FMC basic part, be one of its modes and provide:

1) determination of alternative routes majority, providing obstacles avoidance at safe distance in automatical or direct modes considering the aircraft characteristics and limitations;

2) determination of the best routes among the alternative ones by the given criteria, for instance, from a point of view of minimizing the extra time and fuel consumption, lateral deviations, etc. on the initial route.

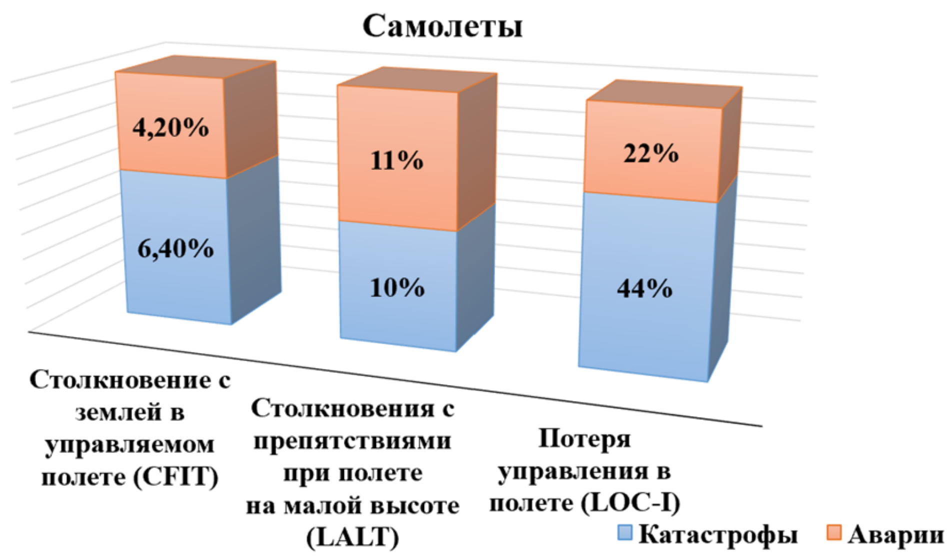

Fig. 3. Types of events that determined aviation accidents with general aviation aircraft in 2011–2020

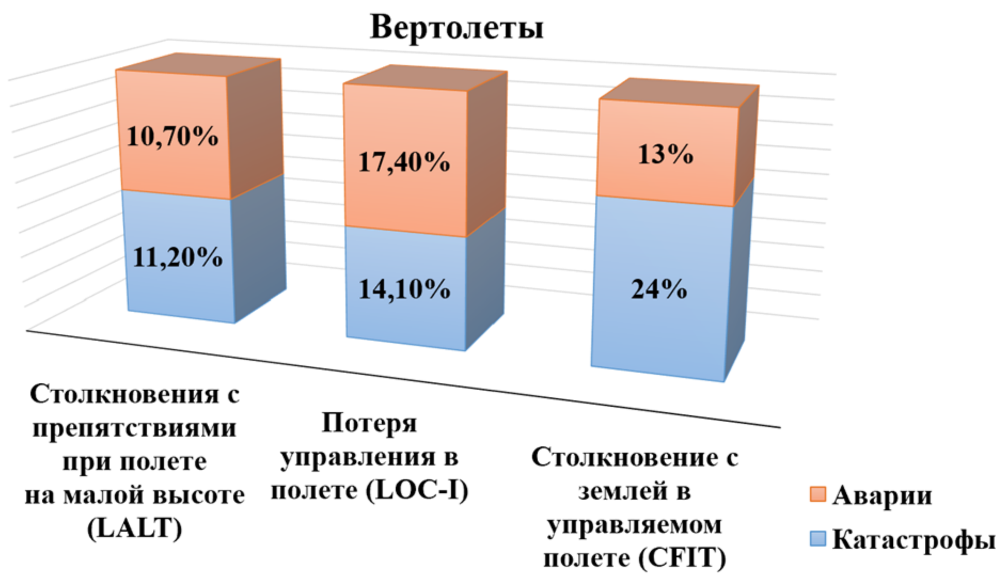

Fig. 4. Types of events that determined aviation accidents with general aviation helicopters in 2011–2020

Setting the problem

Let:

1) flight route be given by the initial route point $\{X_0\}$; pass (turning) route points $\{X_1\},\{X_2\}, \ldots,\{X_{n-1}\}$; final route points $\{X_n\}$, where $X_i = (x_{gi}, y_{gi}, z_{gi})$ are the route points coordinates in normal terrestrial coordinate system [11];

2) obstacles be given by the multitude of points: $\{X_{пр\,1}\}, \ldots, \{X_{пр\,m}\}$;

3) the aircraft flight be described by the system of differential equations [11]

$$\begin{cases} \frac{dV}{dt} = g(n_{xa} - sin\theta), \\ \frac{d\theta}{dt} = \frac{g}{V}\left(n_{ya}cos\gamma_a - cos\theta\right), \\ \frac{d\Psi}{dt} = -\frac{g}{Vcos\theta}n_{ya}sin\gamma_a, \\ \frac{dx_g}{dt} = Vcos\theta cos\Psi, \\ \frac{dy_g}{dt} = Vsin\theta, \\ \frac{dz_g}{dt} = -Vcos\theta sin\Psi, \\ \frac{dm}{dt} = -c_{s,} \end{cases}$$

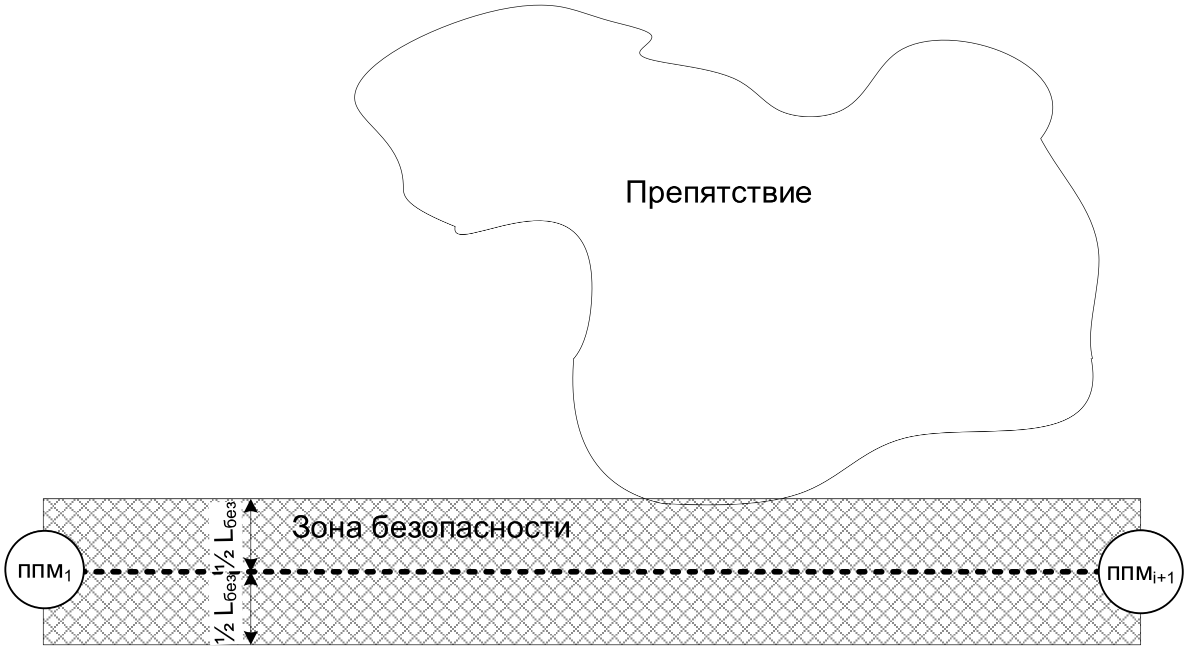

Fig. 5. Safety zone

where V is aircraft speed; θ, Ψ, γ_a are path, route and bank angles; x_g, y_g, z_g are aircraft coordinates in a normal terrestrial coordinate system; g is downward acceleration; n_{ya}, n_{xa} are normal speed and flight path acceleration, calculated as

$$n_{xa} = \frac{P\cos(\propto + \varphi_{\text{дв}}) - c_{xa}\frac{\rho V^2}{2}S}{mg},\ n_{ya} = \frac{c_{ya}\frac{\rho V^2}{2}S + P\sin(\alpha + \varphi_{\text{дв}})}{mg};$$

$\propto$ – angle of attack; $\varphi_{\text{дв}}$ – engine angle of attack; $P = f(V, H, \propto_{\text{руд}})$ – powerplant thrust ; $\propto_{\text{руд}}$ – throttle control lever position, determining the engine mode; $c_{ya} = f(\propto)$ – lift coefficient; $c_{xa} = c_{xa}(c_{ya})$ – drag coefficient; $c_{xa}(c_{ya})$ – aircraft polar curve; ρ – air density; m – aircraft mass; S – wing area; c_s – fuel flow rate. Values $n_{ya}, \gamma_a, \propto_{\text{руд}}$. are used as control functions;

4) limits for flight height and speed, normal speed acceleration and speed bank angle value and rate of change are given:

$$\begin{cases} V_{\text{мин}} \le V(t) \le V_{\text{макс}}, \\ H(t) \ge H_{\text{мин}}, \\ n_{ya\,\text{мин}} \le n_{ya}(t) \le n_{ya\,\text{макс}}, \\ |\dot{n}_{ya}(t)| \le \dot{n}_{ya\,\text{макс}}, \\ |\gamma_a(t)| \le \gamma_{a\,\text{макс}}, \\ |\dot{\gamma}_a(t)| \le \dot{\gamma}_{a\,\text{макс}} \end{cases}$$

5) provided the altitude and speed characteristics of engine unit $P = f(V, y_g, \propto_{\text{руд}})$.

It is necessary to:

1) estimate the route safety by reference to minimum shortest distance between the route and obstacle allowed (fig. 5);

2) determine the alternative safe routes from the initial to final point whether the initial route is dangerous;

3) determine the probable speed of flight via alternative routes;

4) to choose the best possible route by the given criterion.

Research methodology

There is the algorithm for searching a safe obstacle avoidance route in Figure 6.

Fig. 6. Scheme of the main part of the algorithm

The algorithm incoming data are the route initial points $\{X_n\}$ and obstacle profile points $\{X_{m\ пр1}\},\ldots,\ \{X_{m\ прk}\}$, along with aircraft performance.

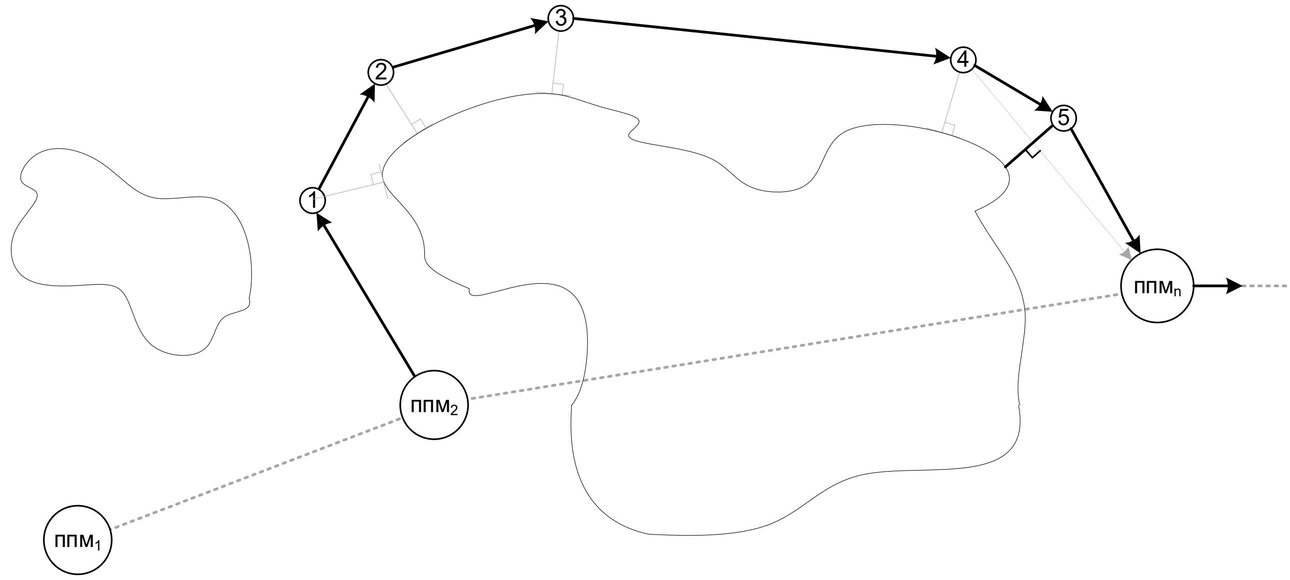

Fig. 7. Route search beam rotation

Let us specify the algorithm key peculiarities.

Route safety estimation is an estimation of an obstacle penetrating cylinder-shaped figure with a given radius. The radius determines the safe distance from the obstacle, which depends, for instance, on the probable aircraft deviation from the route.

Route performability estimation is a multiple aircraft displacement equations integration procedure considering the restrictions mentioned above provided the different aircraft flight speeds. The synthesis control algorithm [12] is used for it, which then allows to estimate the safe avoidance probability with a given speed, deviating from the initial route line not exceeding the given value, considering the aircraft performance and control parameters restrictions. The control parameters, necessary for route performance, exactly acceleration, banking and $\propto_{руд}$ are the algorithm outcoming data.

Alternative routes determination is a procedure, based on a subsequent search of a new route point by rotating the beam from the current route point from the initial flight destination to its collision with an obstacle and then shifting the contact point to the given distance from an obstacle considering the minimum shortest distance between the route and obstacle allowed (fig. 7).

The best possible route choice is made after determining the multitude of alternative route basing on flight operator criteria [13].

After route choice its parameters are coordinated with air traffic control [14] and are proceeded to trajectory autopilot loop for automatic or direct mode implementation.

Results of the research

The present paper introduces the results of a model problem of obstacle avoidance by the hypothetical aircraft in horizontal plane below for two cases:

1) assumption concerning the constant speed along the route;

2) the maximum possible flight speed in every path point by reference to aircraft performance, control parameters restrictions and maintaining safe distance from the obstacle.

The following restrictions are settled while research:

1) g-rating allowed is −1…+2.5;

2) maximum acceleration speed change allowed is 1un/s;

3) bank range allowed is −30º…30º;

4) maximum bank angle rate change allowed is 100º/s.

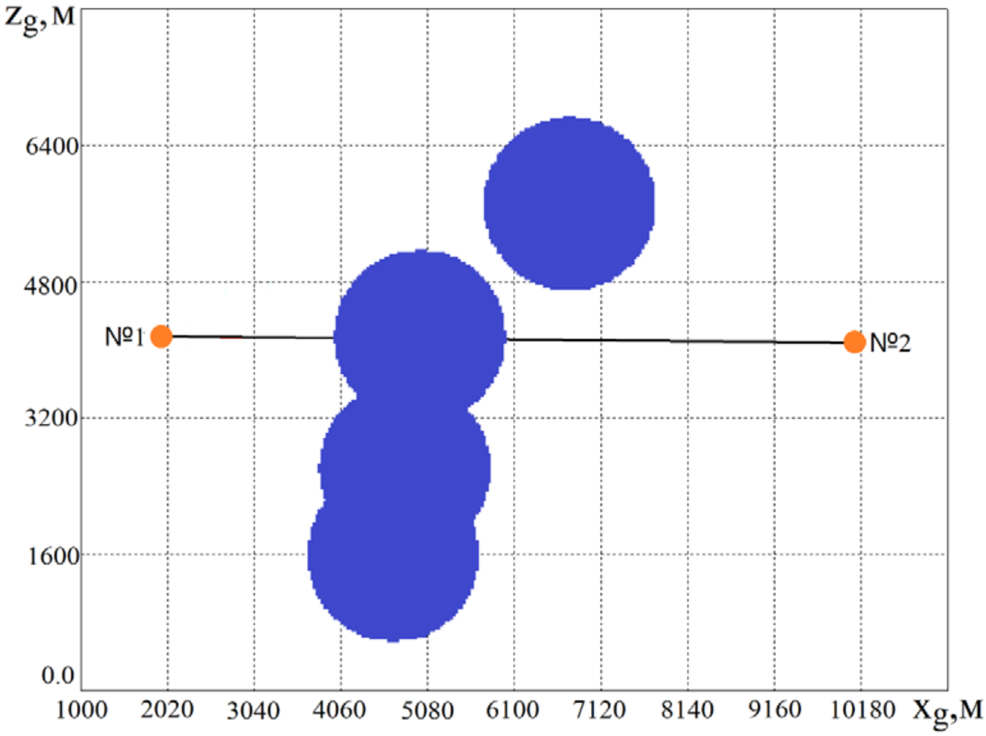

Fig. 8. Starting route and obstacle

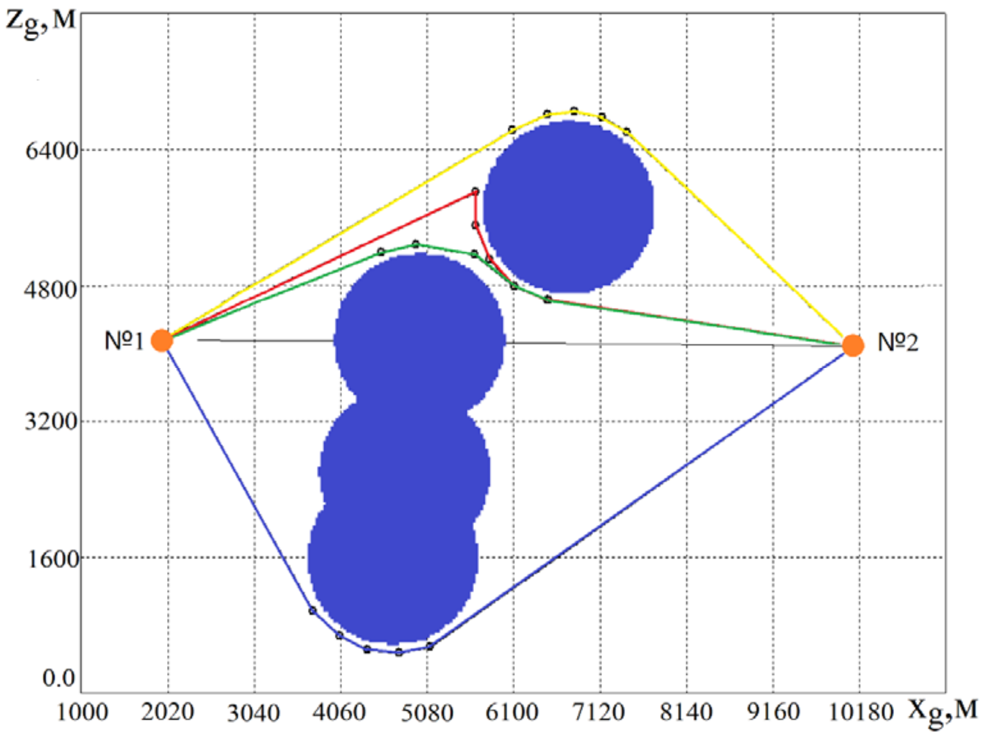

Fig. 9. Obstacle avoidance options at constant speed

The initial flight route in Figure 8 are given by points 1 and 2.

The determined safe obstacle avoidance routes at constant speed along the route are shown in Figure 9.

Discussion of the results

Safe obstacle avoidance route at a constant speed possess the following characteristics:

1) route 1 (marked yellow):
- route length is 9936 m;
- maximum safe speed of flight en-route is 285 km/h;
- g-rating within 0.8…1.4;
- bank angle within 30º…15º;
- estimated time en-route is 126 s;

2) 2 (marked red):
- route length is 9430 m;
- maximum safe speed of flight en-route 70 km/h;
- g-rating within 0.66…1.4;
- bank angle within −26º…3.5º;
- estimated time en-route is is 486 s;

3) 3 (marked green):
- route length 8593 m;
- maximum safe speed of flight en-route is 220 km/h;
- bank angle within 0.6…1.5;
- bank angle within −30º…30º;
- estimated time en-route is 126 s;

4) 4 (marked blue):
- route length is 11327 m;
- maximum safe speed of flight en-route is 295 km/h;
- g-rating within 0.6…1.45;
- bank angle within of −15º…30º;
- estimated time en-route is 139 s;

By reference to above mentioned characteristics, we can make a conclusion that route 3 is the best possible from the minimum length point of view, although route 1 is the one from flight time minimization point of view, as it allows to perform the more flight constant speed due to its more flowing path, which finally gives time advantage.

Safe obstacle avoidance routes with speed[4] changing along the flight path and restricted minimum flight speed of 250 km/h possess the following characteristics:

1) 1 (marked yellow):
- route length is 9936 m;
- maximum/minimum speed en route is 505/284 km/h;
- g-rating within 0.75…1.4;
- estimated time en-route is is 105 s;

2) 2 (marked red):
- route length is 9430 m;
- route performance at a minimum speed restricted to 250 km/h is impossible;

3) 3 (marked green):
- route length is 8593 m;
- route performance at a minimum speed restricted to 250 km/h is impossible;

4) 4 (marked blue):
- route length is 11327 m;
- maximum/minimum speed en route is 485/294 km/h;
- g-rating within 0.4…1.29;
- estimated time en-route at a maximum speed is 123 s.

There is route 3 path at allowed speed at a path of 250 km/h in Figure 10. It is clear that performance impossibility of the route is related to bank limit (fig. 11). In this case aircraft has to quit the given route, which leads to prohibitive obstacle proximity. There are flight results on route 3 at 200 km/h speed in Figure 12. It is clear that reduction of speed provides the given route performance opportunity. There are control parameters for such a case in Figure 13.

[4] The maximum speed allowed is performed in every path point by reference to aircraft performance data, control parameters restrictions and keeping safe distance from the obstacle.

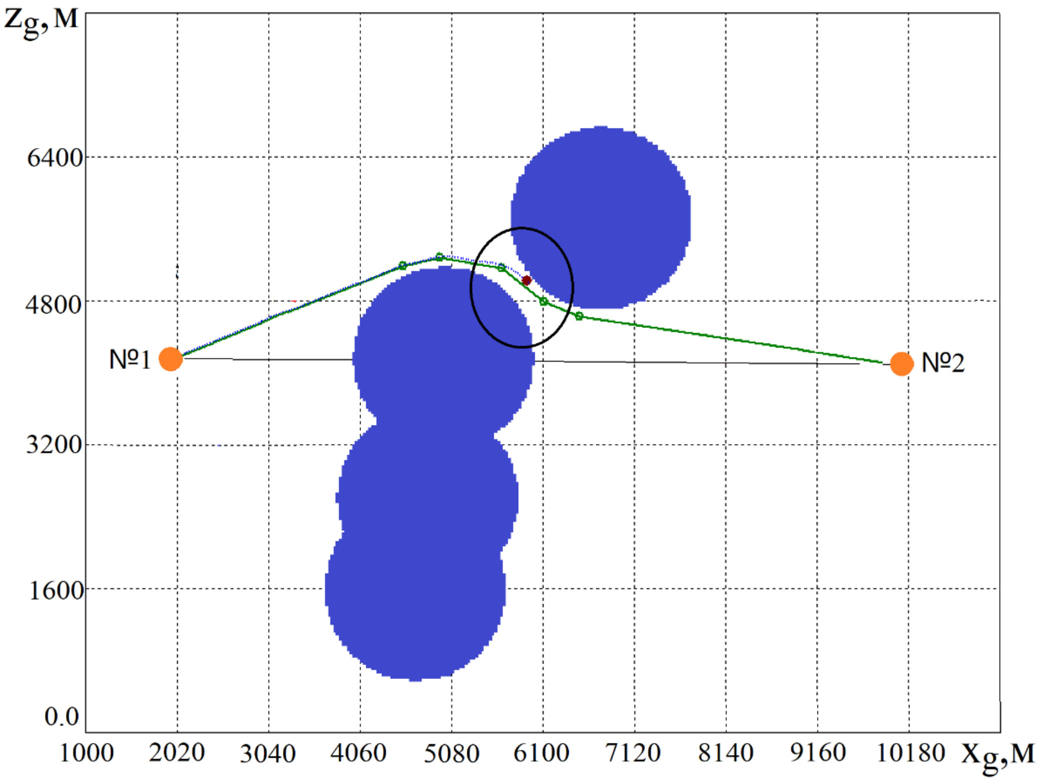

Fig. 10. Checking the route for feasibility at a speed of 250 km/h

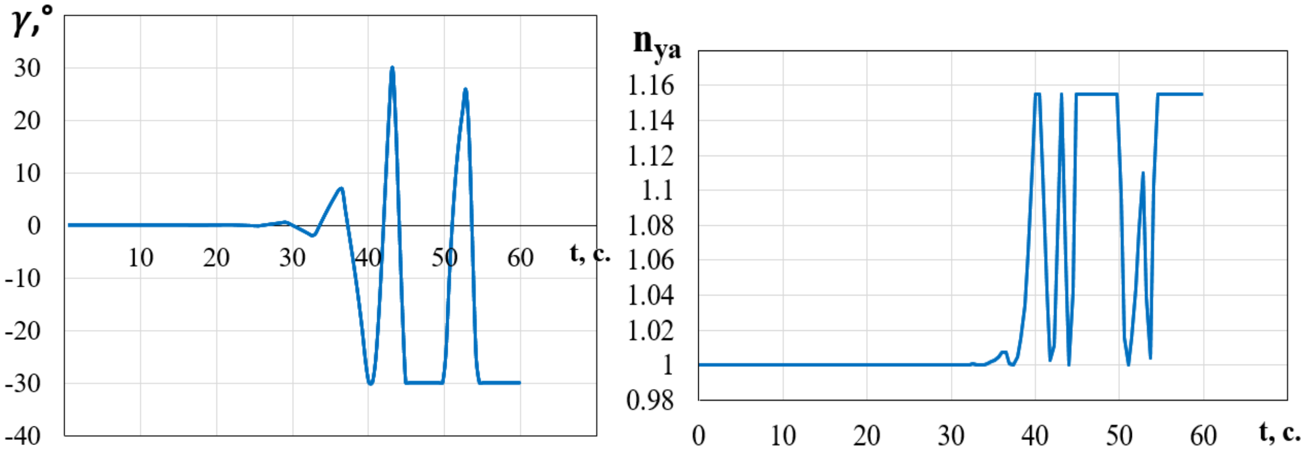

Fig. 11. Graph of change in normal overload when moving along the route at a speed of 250 km/h to the vanishing point

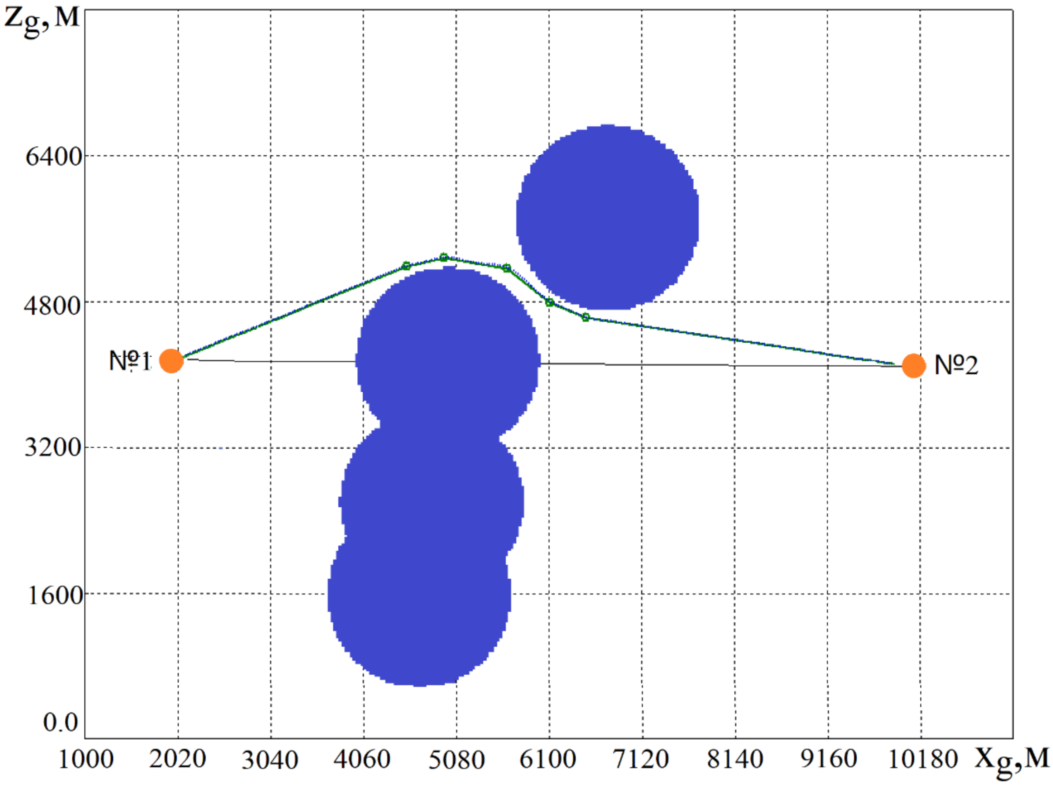

Fig. 12. Checking the route for feasibility at a speed of 200 km/h

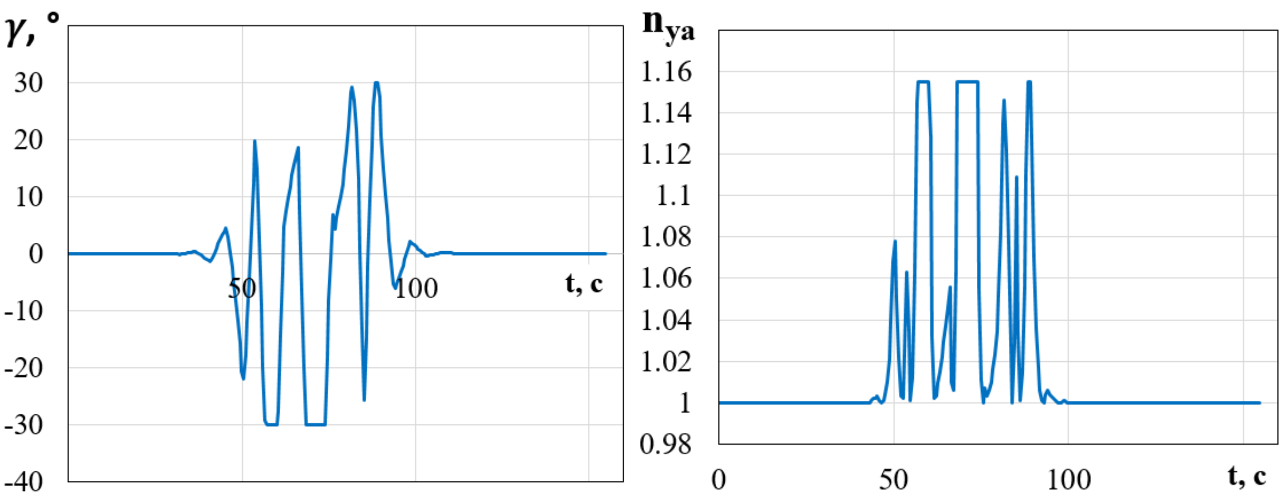

Fig. 13. Graph of changes in normal overload when moving along the route at a speed of 200 km/h

Conclusion

Flight accidents statistics analysis in LOC-I, CFIT, LALT shows their high level of occurrence for civil aircraft. In these terms the prior potentially dangerous flight situation identification along with calculating alternative route options in order to choose a route for its performance seems to be relevant. Automatic rerouting of the aircraft's flight route to safely avoid obstacles detected during flight according to the chosen criteria seems to be relevant in order to decrease the number of such accidents.

There is the algorithm, providing the multitude of alternative safe routes performed by the given aircraft with marking the best possible ones by the chosen obstacle avoidance criteria and route safety estimation basing on current route data and obstacle coordinates, in this article.

The given aircraft flight dynamics modelling numerical numbers confirm the algorithm performance capability, particularly, for obstacle avoidance in horizontal plane or at changing (maximum allowed) speed at flight path.

It is supposed to continue the research in order to estimate the following approach performance capability in terms of making obstacle clearance in vertical plane and in the airspace.

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