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AIRCRAFT INSTRUMENTS AND INSTRUMENTATION COMPUTER COMPLEXES

Continuous Flight Safety Management Information System for a Group of Converging Aircraft

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Abstract—An algorithm for calculating the collision hazard factors for violating aircraft is given. The calculation results of the hazard factors in maneuvering to prevent dangerous approach and in its absence are compared.

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INTRODUCTION

Design of an automatic continuous flight safety management system, including that assuring primarily safety during the approach phase and flying in the vicinity of airports, has become indispensable due to unacceptably great numbers of aviation accidents caused by human factor.

Planning air routes that do not cross is one of the measures to enhance flight safety. The planning problems of multivariable routing of group flights performed in conformance with safety regulations were considered, in particular, by [1, 2]. However, if the crew takes no active steps to avoid collision points, this does not guarantee overall safety, including situations where unmanned aviation is involved.

The structural core disadvantages that come to light during aircraft (AC) approach and landing are as follows [3–11]:

—the inability to range various types of hazard to identify automatically the dominant hazard that requires urgent prevention when multiple hazards emerge;

—the inability to estimate quantitatively and range the degree of each individual hazard; consequently, the inability to select alternatively the best way to prevent them;

—failure to use forecasting properties of safety management in all cases, with the forecast scenarios being both “best-case” and “worst-case”, while taking into account the fact that the degrees of hazard conveyed by traffic advisories (TAs) are not the same as those conveyed by resolution advisories (RAs).

Assuming that an aircraft is technically equipped with a sufficient number of gauges that contain direct measured data and indirect information, one can formulate the requirements to the system that is supposed to do the following principal actions, namely:

—to analyze hazard coefficients for various hazards that emerge simultaneously;

—to select a dominant hazard and to estimate the hazard degree;

—to choose a necessary measure to prevent the hazard;

—to estimate the certainty factor of an alternative choice.

Each of the individual algorithms for the detection and prevention of hazard consists of two blocks, namely, hazardous situation prevention by forecasted control and multialternative choice of ways to prevent them. The forecast, in turn, must be done twice simultaneously: during optimal emergency control and during normal little-active control. This paper proposes a unified approach to forecasted estimation of hazard degrees of various hazards, and their prevention.

APPROACH TO FORMATION OF UNIFIED CONVOLUTIONAL ESTIMATION OF DANGER DEGREE AT HAZARD CAUTION STAGE

Multiple various type hazards have to be taken into account in analyzing safety of flight. The danger degree of any hazard depends on at least three values, namely:

—the penalty function S of a forecasting risk, which corresponds to the maximal anticipated damage cost of an accident;

—the time t available for the prevention of a dangerous flight situation;

—the time τ that it takes to eliminate the dangerous situation.

The contemporary concept of the danger coefficient [3–5] is expressed by the following formula

$$\rho = \frac{S(x,y,z)}{\left(1+\frac{lt}{\tau}\right)^k}. \tag{1}$$

Formula (1) takes into account the following dependences.

1. The danger is in proportion to the penalty function S, where x, y, and z are the coordinates of the relative motion of two ACs within the system of coordinates bound with the principal AC_0.

2. The more relative time t/τ is available, the hazard is lower; vice versa, as the time available t shortens (in particular, due to a belated reaction of the crew), the priority of the hazard is higher, while assuming that the forecasting management properties are such that $\frac{t}{\tau} \geq 1$ in all cases, and the coefficient l is found experimentally.

3. The dimension of the danger coefficients ρ is the same for any hazards, as the coefficients in question become dimensionless numbers through normalizing.

This is why the relative cost of anticipated damage inflicted by a midair collision can be estimated by formula [6–8]

$$S = \frac{MD^2}{r_n^2}, \tag{2}$$

where D is the preset allowable safe distance in the special rules area (SRA), and the value M expertly "fits" the danger coefficients scales so as to make their values S equal in a series of specific equivalent cases.

Formula (2) clearly shows that in case of a terminal miss $r_n >> D$, the value S tends to zero, and when $r_n \approx D$, it tends to one. Moreover, the results of computer simulation suggest that the value of the power $k = 2$ in formula (1) is acceptable. This is why the danger estimation formula used further on is as shown below

$$\rho = \frac{MD^2}{r_n^2\left(1+\frac{lt}{\tau}\right)^2}. \tag{3}$$

Let us consider a modified formula (3) for various cases of aircraft converging. For longitudinal motion of AC in the vertical plane, let us denote the safe distance D as ΔH (which, according to the Civil Aviation Flight Operations Manual, is 300 m), the finite distance r_n in the SRA via h_k, and then find the time τ that it takes to widen the distance at the collision point from the formula

$$\tau = \frac{r_n}{V_v}, \tag{4}$$

where V_v is the preset vertical speed during active avoidance maneuver by means of vertical separation.

Thus, we obtain the first used estimation of the danger coefficient for longitudinal motion of two AC

$$\rho_v = \frac{M_1 \Delta H^2}{\left(h_k + l_1 V_v \frac{r}{\dot{r}}\right)^2}, \tag{5}$$

where $r/\dot{r}$ is the estimation of available flight time to the collision point at a distance r, and the available convergence speed $\dot{r}$, while at $l_1 = 1$, the second term in the denominator is the estimation of the altitude difference in doing vertical maneuver within the time remained to arriving at the collision point.

Further on, let us differentiate between active and passive actions of avoidance by introducing the coefficient l. Let us assume that the vertical speed is apparently lower when the behavior is inactive; this is why we set the value $l_2 = 0.5$. Then, the danger coefficient ρ_v^* of passive altitude control can be estimated by the formula

$$\rho_v^* = \frac{M_1 \Delta H^2}{\left(h_k + l_2 V_v \frac{r}{\dot{r}}\right)^2}. \tag{6}$$

In formulas (5) and (6), the values of the rest of the coefficients are set as $M_1 = 0.05$; $\Delta H = 300$ m; and $V_v = 10$ m/sec.

For two converging AC that follow crossing routes at the same altitude, we obtain the following result. Let us denote the safe distance D via R, and the forecasted terminal miss r_n in the horizontal plane as Z_k. Then, we find that

$$\rho_h = \frac{M_2 R^2}{\left(Z_k + 0.5 l_3 a \left(\frac{r}{\dot{r}}\right)^2\right)^2}, \tag{7}$$

where a is the preset available side acceleration, and at $l_3 = 1$, the second term in the denominator is also the estimation of the route when an active sidestep maneuver to avoid the collision point within the time remained takes place.

For passive control of lateral motion, we obtain a similar formula at $l_4 = 0.5$

$$\rho_h^* = \frac{M_2 R^2}{\left(Z_k + 0.5 l_4 a \left(\frac{r}{\dot{r}}\right)^2\right)^2}. \tag{8}$$

For joint accounting of near miss of two AC in both vertical and horizontal planes, the Flight Operations Manual and other applicable documents state that the generally accepted danger coefficient P_Σ for two converging AC is estimated by the formula

$$P_\Sigma = \min\{\rho_h; \rho_v\}. \tag{9}$$

This paper, whenever necessary, proposes a modified and improved version of the formula in question, which uses the concept of reverse value

$$P_\Sigma = \frac{1}{\frac{1}{\rho_h} + \frac{1}{\rho_v}}. \tag{10}$$

The latter formula can differentiate between dissimilar hazards, thus enhancing the integration of the action from various factors.

This paper contains dual estimation of the risk function in the form of two numbers P_Σ and P_Σ^*—the best-case and the worst-case forecast respectively, which, essentially defines the minimum and the maximum of anticipated risk. The calculation result obtained is then compared with the two danger critical points F_1 and F_2 that determine the three-digit concept of danger, as shown in Fig. 1 [9].

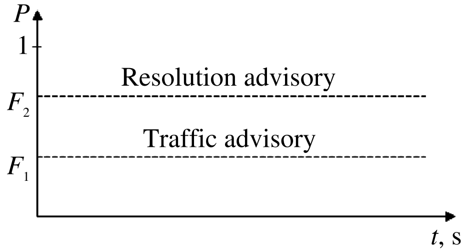

Fig. 1.

Comparing those estimations with boundaries set, one can select the right attempt at timely intervention to avoid a near miss of two AC. Whenever a near miss of more than two AC takes place, the flight is influenced by multiple factors, such that if at least one of the near miss of any *i*th AC presents a serious hazard (its danger coefficient being $P_i = 1$), consequently, the overall coefficient P_0 is also unity. The situation in question is expressed by the integration formula

$$P_0 = 1 - \prod_{i=1}^{m} \left[1 - P_\Sigma(i)\right], \tag{11}$$

where P_0 is the overall danger coefficient for more than two converging AC.

Thus, the proposed unified convolutional approach to quantitative estimation of danger coefficients takes into account the forecast of consequences for both each individual hazard and their simultaneous emergence.

DESCRIPTION OF FLIGHT DANGER ESTIMATION ALGORITHM FOR CONVERGING AC WITH CROSSING PATHS

When the principal AC_0 and another AC_1 converge, three decision-making options are possible:

—a convergence in the vicinity of the SRA (as shown on the surveillance radar) is not dangerous in neither horizontal plane nor in terms of altitude, so no active steps need to be taken;

—a dangerous situation is easily eliminated by changing the flight level of the principal AC_0 within a short time span not exceeding 30 seconds;

—whenever hazard cannot be eliminated by changing the flight level alone for a number of reasons, active course deviation need to be done in the horizontal plane.

For each of the cases listed above, the dual estimation formulas (5)–(8) are used, while more specifically found formulas for calculations of forecasted misses Z_k and h_k are as follows:

1. This is a case when the AC_0 and AC_1 converge at the same altitude, the forecasted miss Z_k in the SRA being

—AC_1 is on the left

$$Z_k = r\frac{\cos(270\text{ deg} + q - \psi) - \sin q}{\cos(\psi - 270\text{ deg})}; \tag{12}$$

—AC_1 is on the right

$$Z_k = r\frac{\cos(\psi + q) - \sin(q - 270\text{ deg})}{\cos(90\text{ deg} - \psi)}, \tag{13}$$

where q is the AC_1 bearing; ψ is the AC_1 heading relative to the heading of the AC_0.

2. A case when the principal AC_0 and another AC_1 converge when changing from one flight level to another, with the forecasted altitude miss h_k in the SRA is

—AC_1 is above

$$h_k = r\frac{\cos(270\ \mathrm{deg} + \varphi - \theta) - \sin\varphi}{\cos(\theta - 270\ \mathrm{deg})}, \tag{14}$$

—AC_1 is below

$$h_k = r\frac{\cos(\theta + \varphi) - \sin(\varphi - 270\ \mathrm{deg})}{\cos(90\ \mathrm{deg} - \theta)}, \tag{15}$$

where φ is the AC_1 elevation; θ is the flight path angle of the AC_1 relative to the flight path angle of the AC_0.

Various cases to avoid collision point for two ACs are estimated as follows:

—without active steps

$$P_\Sigma^* = \frac{2}{\frac{1}{\rho_v^*} + \frac{1}{\rho_h^*}}; \tag{16}$$

—with course deviation

$$P_\Sigma = \frac{2}{\frac{1}{\rho_v^*} + \frac{1}{\rho_h}}; \tag{17}$$

—with changing the flight level

$$P_\Sigma = \frac{2}{\frac{1}{\rho_v} + \frac{1}{\rho_h^*}}; \tag{18}$$

—with both course and altitude maneuver

$$P_\Sigma = \frac{2}{\frac{1}{\rho_v} + \frac{1}{\rho_h}}. \tag{19}$$

The expert estimation formulas obtained suggest that as the AC nears the collision point, the danger coefficients increase, which is equivalent to an increasing feeling of anxiety in the pilot.

The analysis of all the cases listed above allowed formulating an algorithm to caution about and to prevent hazard of collision with another AC; refer to Fig. 2 for the block diagram.

The options possible here, according to the block diagram, are as follows

—options when there is no dangerous collision point whatsoever due to certain combinations of headings;

—options when the intruder AC_1, according to Block 1, is either on the left of or above the principal AC_0;

—position options of the AC_1, according to Block 2 are either on the right of or below the principal AC_0.

Various formulas (12)–(15) should be used to calculate the danger coefficients ρ_h, ρ_h^*, ρ_v, ρ_v^* in each of those cases.

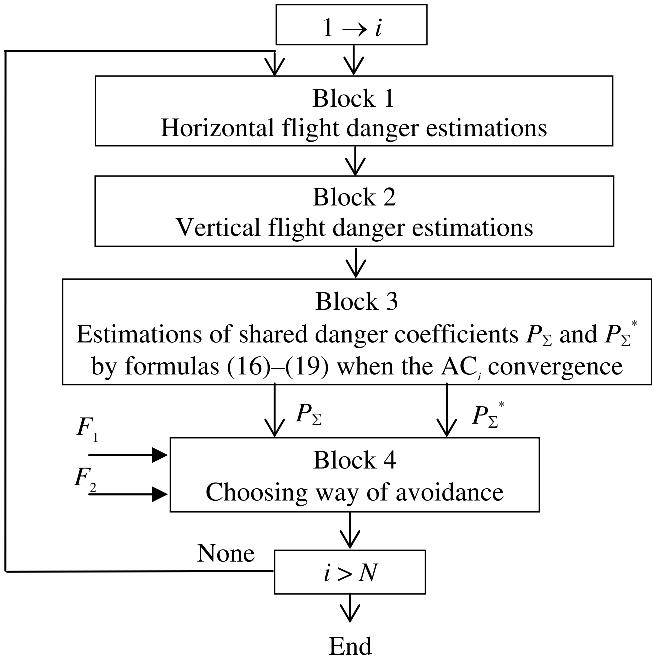

Fig. 2.

In the end, in Block 3, the danger coefficients P_Σ and P_Σ^* are calculated and remembered, and, if the result obtained exceeds the critical points F_1 and F_2, then, in Block 4, necessary steps are taken to select a way of avoidance.

SAFETY CONTROL SYSTEM SIMULATION BY *SIMULINK* GRAPHICAL PROGRAMMING ENVIRONMENT

We have modeled the safety control system performance to consider a case of the principal AC_0 and two intruders AC_1 and AC_2 converging.

In the first case, we initially obtained 3D modeled results for the principal AC_0 and the intruder AC_1 converging, the AC_1 approaching in horizontal plane on the left, with the flight paths crossing at an angle of 45 deg, while descending, with the initial data as follows: the initial distance between the AC is r_0 = 3 000 m; the speed of the AC_0 is 100 m/sec, the speed of the AC_1 is 100 m/sec; the maximum side acceleration was a = 2 m/sec^2; the allowable horizontal separation between the two AC D = 6 000 m; the allowable safe vertical separation of the two AC ΔH = 300 m; the initial azimuth angle φ_0 = 90 deg; the intruder AC_1 approached the principal AC_0 on the left, the heading being 45 deg; the horizontal flight altitude of the AC_0 $Y_1(0)$ = 1 200 m; the initial altitude of the descending intruder AC_1 $Y_2(0)$ = 1 600 m.

Several diagrams were obtained by computer simulation. Figure 3 shows vertical flight danger coefficients found from formulas (5) and (6).

The danger coefficient P_v^* is apparently higher than P_v and is gradually increasing. Figure 4 shows horizontal flight danger coefficients for passive and active behaviors.

The behavior pattern of those coefficients is similar to that of vertical flight danger coefficients. It is worth noting that the respective values of the terminal miss Z_k and h_k were calculated while taking into account relative positions of the both AC, by using formulas (12) and (14), with the AC_1 being above and on the left of the principal AC_0.

The results obtained allow the shared danger coefficients P_{Σ_1} and $P_{\Sigma_1}^*$ to be integrated when the AC_0 and the AC_1 converge, as shown in Fig. 5.

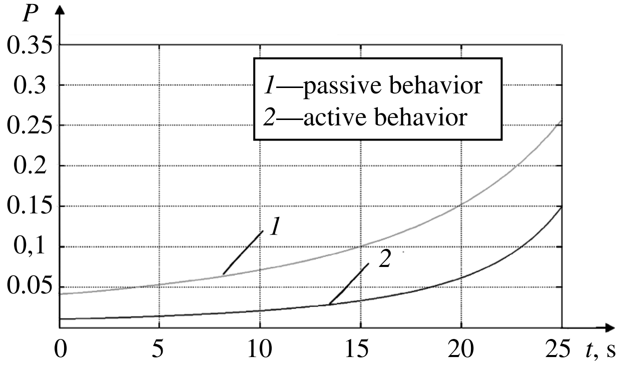

Fig. 3.

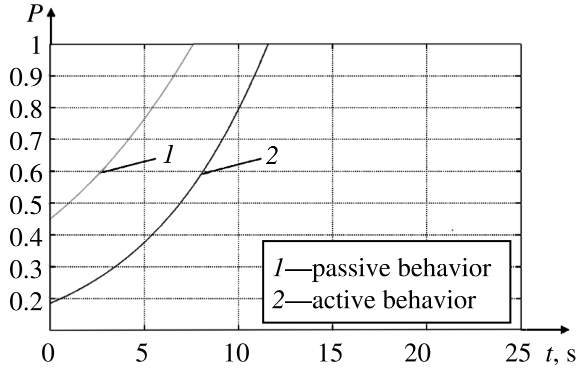

Fig. 4.

Figure 5 also shows the preset critical points $F_1 = 0.01$ and $F_2 = 0.05$ of making decision to avoid the collision point; when those decision critical points are crossed by the functions P_{Σ_1} and $P_{\Sigma_1}^*$ respectively, the time moments are found automatically: $t_1 = 2$ sec for the beginning of normal avoidance, and $t_2 = 5$ sec for the beginning of emergency avoidance of the dangerous collision point by the principal AC_0.

The situation that was considered in the latter case was chronologically as follows: the AC_0 performed a vertical deviation maneuver to avoid the intruder AC_1 (thus decreasing the danger coefficients, which are shown in Fig. 6 by curves *1* and *2*), followed by another intruder AC_2 travelling the path crossing at an angle of 90 deg at the same altitude to the right of the principal AC_0, its initial data being $X_2(0) = 2\ 000$ m, $Y_2(0) = 900$ m, $Z_2(0) = -6\ 000$ m. Figure 6 suggests that respective significant danger coefficients in the shape of curves *3* and *4* appear after an interaction between AC_0 and AC_1.

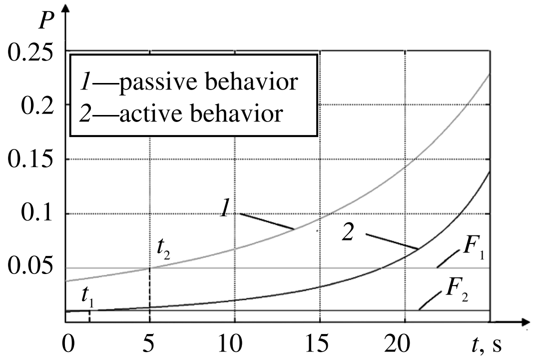

Fig. 5.

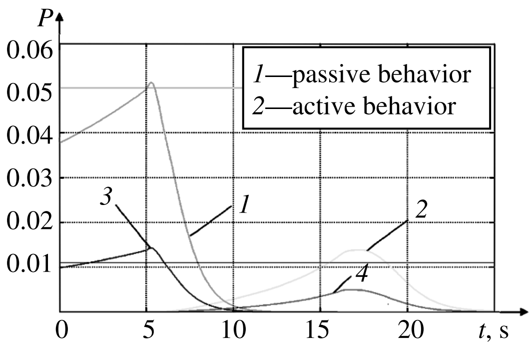

Fig. 6.

Ultimately, the values of the danger coefficients generally do not exceed 0.05, which proves that the TAs and RAs system operates promptly and timely.

CONCLUSIONS

We have proposed a unified convolutional approach to quantitative estimation of flight dangers, while taking into account more than one hazard emerging simultaneously.

We have proposed a rule for the near miss avoidance, when the first critical point should be at first compared with the minimal value of the danger coefficient in order to reduce false alarms, and the second critical point should be compared with the maximum value of the danger coefficient in order to exclude overlooking an emergency, which minimizes type I and type II errors related to making decisions about an avoidance of a near miss.

We have formulated an algorithm to find danger coefficients for each individual hazard for both passive and active behaviors.

The good performance of the safety control information system has been proved by its computer-assisted simulation by *Simulink* graphical programming environment.

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