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ALTERNATE CONFLICT AVOIDANCE WITH DESCENT IN FRONT OF THE INTRUDER

ABSTRACT

The relative speeds of aircraft in possible conflict encounter are soaring up to or even above 0.5km/s, meaning that the period of time which includes conflict detection, reaction, and strategical resolution of conflict, etc., before initiation of conflict avoidance maneuvering is short. Therefore, and since current ground based systems for managing, controlling and handling aircraft movements is near its maximum capacity, the existing ground based control has to be enhanced by the autonomous anti-collision and anti-conflict airborne system. Avoidance procedures with descent in front of the intruder are demonstrated as a continuation of autonomous airborne separation research begun with conflict avoidance involving descent behind the intruder. The following continuation is necessary because descending behind the intruder is a safe avoidance only when initial vertical separation exceeds the defined vertical separation minimum.

KEY WORDS

flight safety, descent, conflict resolution, avoidance procedure

1. INTRODUCTION

Problem. In the model of conflict resolution [8] it was demonstrated that conflict encounter in the vicinity of a planned descent of a higher-flying aircarft might be avoided via two main avoidance protocols: by descent behind the intruder flying below avoiding aircraft; and by descent in front of the intruder. From the concept of airborne separation minimums follows the obvious deduction that if initial vertical displacement before initiation of the descent of a higher-flying aircraft does not exceed the required vertical separation minimum, conflict cannot be avoided by descent behind the intruder because an avoiding aircraft must first fly over the intruder [9].

Initial Situation. Two ASAS (Airborne Separation Assurance System) equipped aircraft capable of flying 4D navigation [4] are flying toward each other in the free-flight class airspace with constant speed v_1 and v_2 for intruder A1 and avoiding aircraft A2 respectively. Prior to the top of descent (TOD) both are flying at constant but different flight levels, with a constant relative direction angle between them ψ. The higher flying aircraft A2 will at planned instant $\tau_{TOD/P}$ initiate its descent from cruising altitude FL, at point T/P when the intruder below is at A1-T/P, with planned angle θ_P of direct descent to its destination airport D as shown in Fig. 1 and Fig. 2.

Unless corrected beyond planned TOD at planned rate of descent (ROD) conflict will occur between the aircraft in the initial phase of descent since conflicting descent trajectory from T/P to D of the descending aircraft penetrates the equivalent protected zone (EPZ) around the intruder. Conflict is namely defined as an air traffic situation in which at least two aircraft are on courses which cause, or will cause unless corrected, a simultaneous violation of predefined minimum safe separation requirements in the horizontal plane and vertical plane. Separation minimum in the horizontal plane is defined by r, while minimum vertical separation is defined by h, and with both minimums the disc shaped protected zone around each aircraft is determined. Airborne situation will remain safe if the aircraft trajectories are such that their protected zones never overlap.

Let us consider such an initial situation in the vertical plane, in which the initial vertical displacement between aircraft z before initiation of descent of the higher-flying aircraft A2 does not exceed the vertical separation minimum h.

Anticipated resolution. While the intruder exercises its right of way [1] and does not alter its optimized flight plan, the descending aircraft A2 is obliged to execute an avoidance maneuver. When lateral maneuvering is blocked [7] and when climb is neglected as a solution, this is then the initial situation in the vicinity of the TOD in which conflict can be avoided by descending in front of the intruder [8] as an alternative procedure applicable to prevent the domino effect of avoiding one conflict and getting into another. The crew of the descending aircraft must execute an avoidance maneuver in such a way that the displacement between aircraft in the horizontal plane is greater than the minimum safe longitudinal or lateral separation until safe vertical separation is restored [8], [9].

Avoidance maneuvering in the vertical plane is anticipated on the basis of in-flight conflict situation simulation results [3], [4], [7], [10]. Avoidance procedures, flown by avoiding aircraft in descent in front of the intruder are based on an in-flight conflict resolution model [8] modified from classical works about conflict detection and resolution [2], [5], [6].

2. DESCENDING IN FRONT OF THE INTRUDER

Procedure 1. *Avoidance procedure with descent in front of the intruder from a safely forced TOD* is presented in Fig. 1. In the figure (and in Fig. 2) the conflicting, critical and safe trajectories of a descending aircraft A2 are represented with respect to the intruder's trajectory and EPZ around the latter in the side view on top of the simplest view from above. This avoidance procedure starts when the descending aircraft A2 is at safe instant $\tau_{TOD/FS}$ for the forced initiation of the first phase of avoidance in T/FS from where it will descend with a planned angle of descent θ_P. Note that the trajectory of the descending aircraft will penetrate the EPZ around the intruder if initiation of descent takes place too late, i. e., if initiation of descent is not forced soon enough, which, consequently, leads to conflict. The critical instant of the initial descent is that which leads the trajectory of the descending aircraft to touch the confines of EPZ around the intruder A1. This will be the case if the aircraft initiates descent with a θ_P from T/FC. Its trajectory will then touch the confines of EPZ around the intruder at C1. This critical trajectory is defined with $\Delta\tau$ critical forcing interval of time before scheduled timing of descent $\tau_{TOD/P}$. The position of C1 clearly shows that $\Delta\tau$ can be obtained from boundary conflict conditions for the moment when displacement between aircraft reaches the separation minimum in the vertical plane h simultaneously with the separation minimum in the horizontal plane $2r$. The first phase of the avoidance procedure will be safe if initiation of descent is forced additionaly for the time safety margin $\delta\tau$ prior to the $\Delta\tau$. The forced time safety margin $\delta\tau$ is selected by the flight crew before descent, i. e., execution of an avoidance procedure. The safe instant for the initiation of the forced descent $\tau_{TOD/FS}$ can then be defined as:

$$\tau_{TOD/FS} = \tau_{TOD/P} - \underbrace{\left(\sqrt{B^2 + AC} - B\right)(v_2 A)^{-1}}_{\Delta\tau} - \delta\tau \tag{1}$$

where A, B and C represent the expressions:

$$A = 1 + 2k\cos\psi + k^2$$

$$B = x(k + \cos\psi) + y\sin\psi - \\ -\frac{x+h}{\mathrm{tg}\,\theta_P}\left[1 + k\left(\cos\psi + (k + \cos\psi)\sqrt{1 + tg^2\theta_P}\right)\right]$$

$$C = x^2 + y^2 - 4r^2 - \\ -2\frac{z+h}{\mathrm{tg}\,\theta_P}\left(x\cos\psi + y\sin\psi + kx\sqrt{1 + \mathrm{tg}\,\theta_P}\right) + \\ +\frac{(z+h)^2}{\mathrm{tg}^2\,\theta_P}\left[1 + 2k\cos\psi\sqrt{1 + \mathrm{tg}^2\theta_P} + k^2(1 + \mathrm{tg}^2\theta_P)\right]$$

and additionally $k = v_1 / v_2$.

After clearing the protected zone overlapping in the first phase of the avoidance procedure, the avoiding aircraft would like to alter its descent directly to its destination D. However, the trajectory of the descending aircraft will penetrate the EPZ around the in-

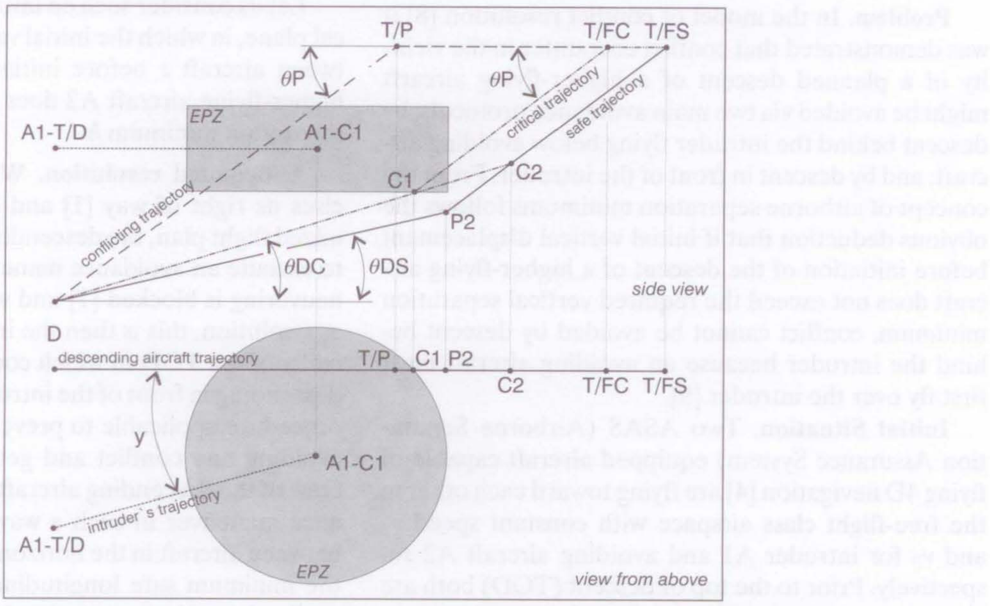

Figure 1 – Avoidance procedure with descent in front of the intruder from forced TOD

truder if the second phase takes place too soon. At the critical instant t_C for the initiation of the second phase the avoiding aircraft will be at C2. Fig. 1 shows that if the aircraft then descends with a critical angle of direct descent θ_{DC}, its descent trajectory touches the EPZ around the intruder at C1 again. The safety of the second phase of the avoidance procedure thus depends upon the timing of its initiation. The second phase of the avoidance procedure will be safe if its initiation is delayed beyond the critical instant t_C for the time safety margin δt which is selected by the flight crew. The safe instant for the initiation of the second phase t_S is then:

$$t_s = \underbrace{\frac{z+h}{v_2 \sin\theta_P} - \delta\tau \frac{1-\cos\theta_{DC}}{\cos\theta_{DC} - \cos\theta_P}}_{t_c} + \delta t \tag{2}$$

where θ_{DC} is the critical angle of direct descent defined as:

$$\operatorname{ctg}\theta_{DC} = \operatorname{ctg}\theta_P + \frac{\sqrt{B^2 + AC} - B}{A(FL - z - h)} \tag{3}$$

At t_S, when it is at P2, the avoiding aircraft will change its angle of descent from the planned θ_P in the first phase to the θ_{DS} safe angle of direct descent of the second phase of the avoidance procedure:

$$\operatorname{tg}\theta_{DS} = \frac{FL - z - h -}{\dfrac{FL - z - h}{\operatorname{tg}\theta_P} + \dfrac{\sqrt{B^2 + AC} - B}{A} +} \cdots$$

$$\cdots \frac{-v_2 \sin\theta_P \left(\delta t - \delta\tau \dfrac{1-\cos\theta_{DC}}{\cos\theta_{DC} - \cos\theta_P}\right)}{+v_2 \left(\delta\tau \dfrac{\cos\theta_{DC}(1-\cos\theta_P}{\cos\theta_{DC} - \cos\theta_P} - \cos\theta_P \delta t\right)} t \tag{4}$$

From Fig. 1 it is obvious that the trajectory of descent in the first phase of the avoidance procedure will be safe and that the avoiding aircraft will descend in front of the EPZ of the intruder for any $\delta\tau > 0$. The comparison between (3) and (4) shows that $\theta_{DS} < \theta_{DC}$ for any $\delta\tau > 0$ and $\delta t > 0$ and therefore in the second phase of the avoidance procedure the avoiding aircraft will fly on a safe trajectory below the EPZ around the intruder.

Procedure 2. *The avoidance procedure with descent in front of the intruder from the planned TOD* starts at the planned instant $\tau_{TOD/P}$, but in the first phase an avoiding aircraft will descend with a safely altered angle of descent θ_S. The avoidance procedure is presented in Fig. 2, where it is shown that an angle of descent θ_S in the first phase of the procedure is safe if it is greater than the critical θ_C. This safety condition is achieved by the safety margin of the increased descent angle $\delta\theta$ which is selected by the flight crew. A safe angle of descent in the first phase θ_S is then:

$$\theta_S = \theta_C + \delta\theta \tag{5}$$

where θ_C can be numerically derived from the boundary conflict conditions between aircraft at C1:

$$x^2 + y^2 + k^2(z+h)^2 - 4r^2 - \\ -2\frac{z+h}{\operatorname{tg}\theta_C}\left(x\cos\psi + y\sin\psi + kx\sqrt{1+\operatorname{tg}^2\theta_C}\right) + \\ + \frac{(z+h)^2}{\operatorname{tg}^2\theta_C}\left(1 + k^2 + 2k\cos\psi\sqrt{1+\operatorname{tg}^2\theta_C}\right) = 0 \tag{6}$$

The safety of the second phase depends on timing. The trajectory of the avoiding aircraft in the direct descent begun before or at C2 will penetrate the EPZ around the intruder. The second phase of the avoidance procedure will be safe if its initiation is delayed

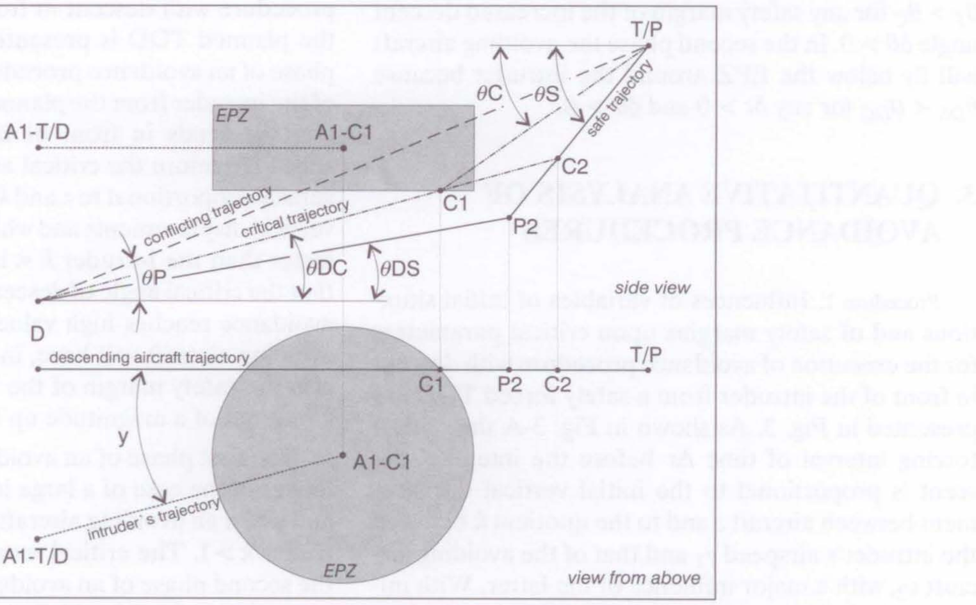

Figure 2 – Avoidance procedure with descent in front of the intruder from the planned TOD with safely altered angle of descent

beyond the critical instant t_C when the avoiding aircraft is at C2 for the time safety margin δt selected by the flight crew. During δt an avoiding aircraft descends with θ_S between C2 and P2 where the second phase starts. The safe instant for the initiation of the second phase t_S is then:

$$t_s = \underbrace{\frac{(z+h)(\cos\theta_{DC}-\cos\theta_C)}{v_2 \sin\theta_C(\cos\theta_{DC}-\cos\theta_C\cos\delta\theta+\sin\theta_C\sin\delta\theta)}}_{t_c} + \delta t \tag{7}$$

where θ_{DC} is the critical angle of direct descent defined as:

$$\operatorname{tg}\theta_{DC} = \frac{(FL-z-h)\operatorname{tg}\theta_P \operatorname{tg}\theta_C}{FL\operatorname{tg}\theta_C-(z+h)\operatorname{tg}\theta_P} \tag{8}$$

At t_S, when it is at P2, an avoiding aircraft will change its safely altered angle of descent in the first phase θ_S to the safe angle of direct descent θ_{DS} of the second phase of the avoidance procedure:

$$\operatorname{tg}\theta_{DS} = \frac{FL-E(\cos\delta\theta+\sin\delta\theta\operatorname{ctg}\theta_C)}{FL\operatorname{ctg}\theta_P-E(\cos\delta\theta\operatorname{ctg}\theta_C-\sin\delta\theta)} \tag{9}$$

where E is:

$$E = v_2\sin\theta_C\delta t + \frac{(z+h)(\cos\theta_{DC}-\cos\theta_C)}{\cos\theta_{DC}-\cos\theta_C\cos\delta\theta+\sin\theta_C\sin\delta\theta}$$

The safety margin $\delta\theta$ of the increased descent angle and the time delay safety margin δt are parameters of safety with which a safe buffer zone between aircraft in a conflict encounter is secured so that their protected zones never overlap during the execution of the avoidance procedure. The avoiding aircraft will descend in front of the EPZ around the intruder, since $\theta_S > \theta_C$ for any safety margin of the increased descent angle $\delta\theta > 0$. In the second phase the avoiding aircraft will fly below the EPZ around the intruder because $\theta_{DS} < \theta_{DC}$ for any $\delta t > 0$ and $\delta\theta > 0$.

3. QUANTITATIVE ANALYSIS OF AVOIDANCE PROCEDURES

Procedure 1. Influences of variables of initial situations and of safety margins upon critical parameters for the execution of avoidance procedure with descent in front of the intruder from a safely forced TOD are presented in Fig. 3. As shown in Fig. 3-A the critical forcing interval of time $\Delta\tau$ before the intended descent is proportional to the initial vertical displacement between aircraft z and to the quotient k between the intruder's airspeed v_1 and that of the avoiding aircraft v_2, with a major influence of the latter. With initial vertical displacement of about $3000m$, and when the intruder is faster than the avoiding aircraft, the critical forcing interval of time with a magnitude of more than a couple of minutes is necessary and the crew of an avoiding aircraft will initiate a safely forced descent even sooner because of the forced time safety margin $\delta\tau$ selected by them.

The critical instant t_C for the initiation of the second phase of avoidance maneuvering is, as shown in Fig. 3-B and Fig. 3-C, proportional to z and k, and according to (2) also to the critical forcing interval of time $\Delta\tau$ and the critical angle of direct descent θ_{DC} to the destination, but inversely proportional to the forced time safety margin $\delta\tau$. This means that the first phase of an avoidance procedure, when an avoiding aircraft will descend in front of the EPZ around the intruder, will last longer in cases of large initial vertical displacements z and when $k>1$ the intruder is faster than an avoiding aircraft; and if the $\delta\tau = 5s$ it will have a magnitude of up to $300s$ (Fig. 3-C). The critical angle of direct descent θ_{DC} to the destination is inversely proportional to the z, k, $\Delta\tau$, and $\delta\tau$ (Fig. 3-D and Fig. 3-E). The same applies for the safe angle of direct descent θ_{DS} in the second phase of the avoidance procedure, which is, according to (4), inversely proportional also to the delay safety margin δt selected by the crew for the initiation of this phase. Fig. 3-F shows that the safe angle of direct descent θ_{DS} will be smaller than the critical θ_{DC} for a small angle of 0.005^o when $\delta\tau = 5s$ is selected. However, Fig. 1 clearly shows that even the slightest difference between θ_{DS} and θ_{DC} assures the safety of avoidance maneuvering since for $\theta_{DS} < \theta_{DC}$ the actual displacement between aircraft during the execution of te second phase of an avoidance, will be greater than the vertical or the horizontal separation minimum.

Procedure 2. Quantitative analysis of avoidance procedure with descent in front of the intruder from the planned TOD is presented in Fig. 4. In the first phase of an avoidance procedure with descent in front of the intruder from the planned TOD an avoiding aircraft descends in front of the intruder's protected zone. Therefore the critical angle of descent θ_C is inversely proportional to z and k. In cases of small initial vertical displacements and when an avoiding aircraft is faster than the intruder $k<1$, Fig. 4-A clearly shows that the critical angle of descent θ_C in the first phase of avoidance reaches high values. A descent rate of an avoiding aircraft will have, in such cases, considering also the safety margin of the increased descent angle $\delta\theta$, values of a magnitude up to $10000ft/min$.

The first phase of an avoidance procedure will last longer in the case of a large initial vertical separation and when an avoiding aircraft flies slower than the intruder $k>1$. The critical moment t_C for initiation of the second phase of an avoidance procedure, in which an avoiding aircraft will fly below the EPZ of the intruder, is therefore proportional to z and k, as shown

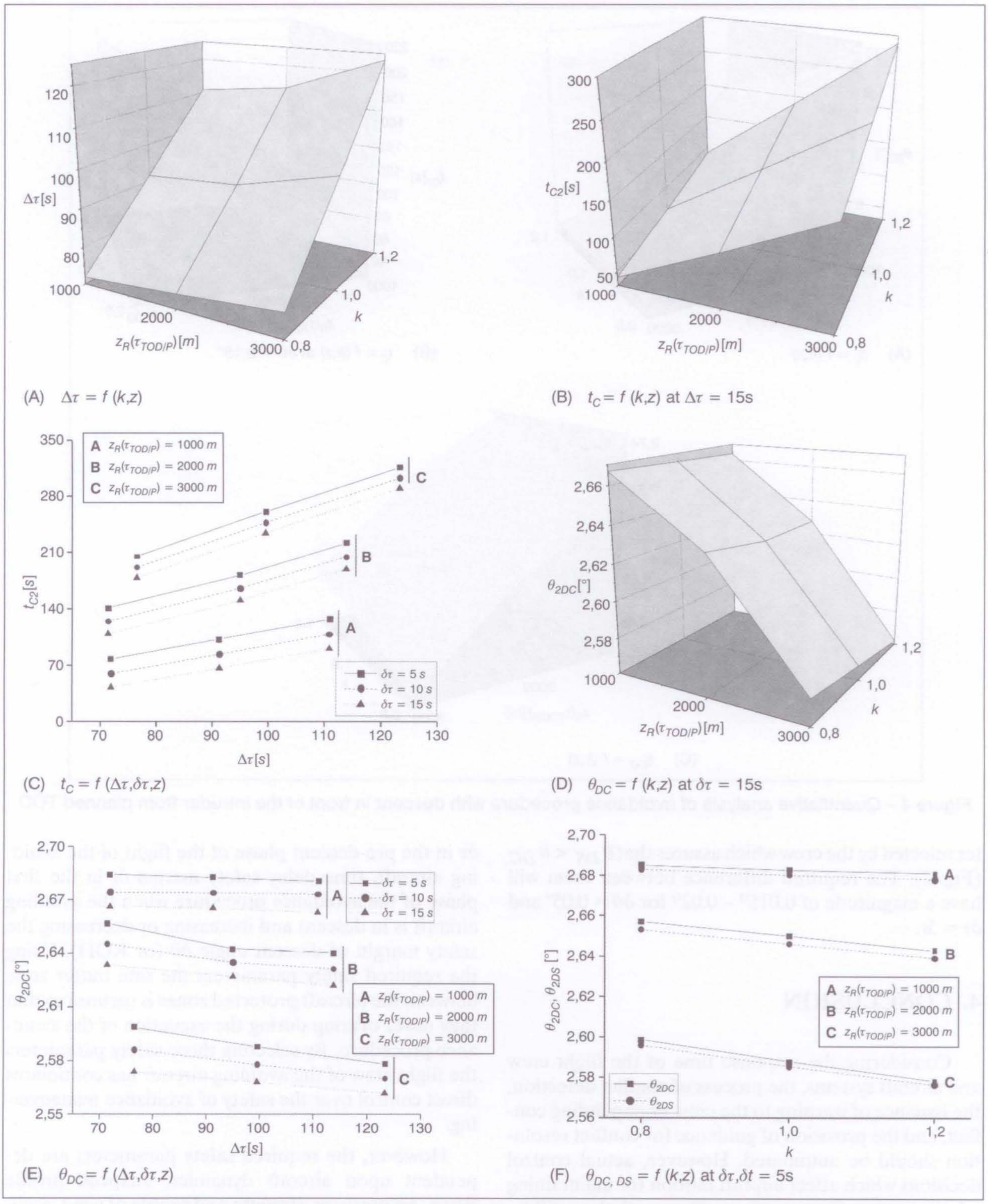

Figure 3 – Quantitative analysis of avoidance procedure with descent in front of the intruder from a safely forced TOD

in Fig. 4-B, but, according to (7) inversely proportional to θ_C and $\delta\theta$. However, no matter how steep a safe angle of descent θ_S is in the first phase of an avoidance, the critical angle of direct descent θ_{DC} in the second phase of avoidance depends proportionaly on k; yet it is inversley proportional to z (Fig. 4-C). The same applies for the safe angle of direct descent θ_{DS} for which (9) shows that it is inversely proportional to the time safety margin δt of a delay of initiation of the second phase of avoidance. This is the safety parame-

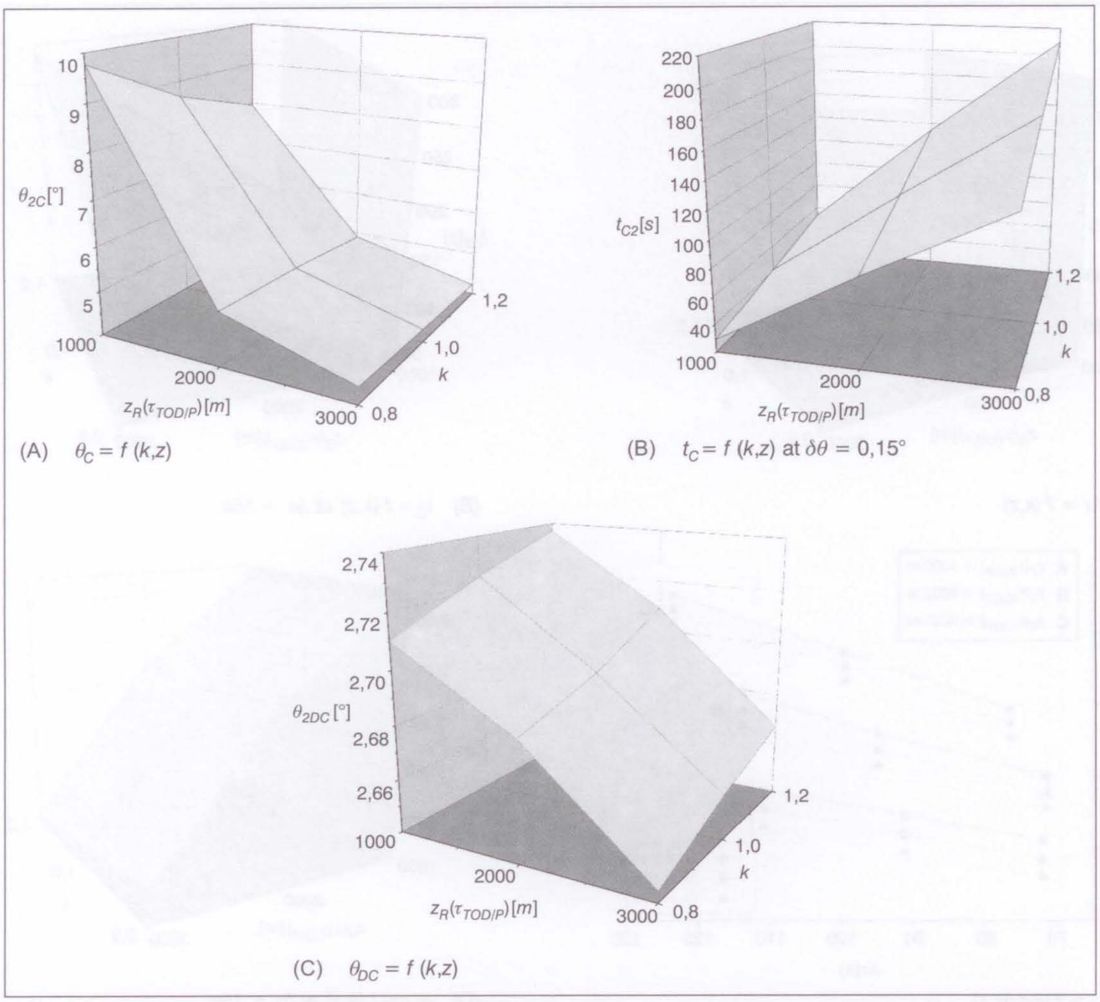

Figure 4 – Quantitative analysis of avoidance procedure with descent in front of the intruder from planned TOD

ter selected by the crew which assures that $\theta_{DS} < \theta_{DC}$ (Fig. 2). The required difference between them will have a magnitude of $0.015° - 0.02°$ for $\delta\theta = 0.05°$ and $\delta\tau = 5s$.

4. CONCLUSION

Considering the response time of the flight crew and aircraft systems, the process of conflict detection, the issuance of warning to the crew of impending conflict, and the provision of guidance for conflict resolution should be automated. However, actual control decisions which affect aircraft motion for maintaining adequate aircraft separation will nevertheless still be based upon the judgment of a human pilot.

While critical parameters are defined by boundary conflict conditions for the moment when relative displacement between aircraft simultaneously reach separation minimums in the vertical and horizontal plane, the essential safety parameters are selected by the flight crew of the avoiding aircraft. Those safety parameters are: time delay or time forced safety margin $\delta\tau$ in the pre-descent phase of the flight of the avoiding aircraft, time delay safety margin δt in the first phase of the avoidance procedure when the avoiding aircraft is in descent and increasing or decreasing the safety margin of descent angle $\delta\theta$ (or ROD). Using the required safety parameters the safe buffer zone between the aircraft protected zones is secured so that they never overlap during the execution of the avoidance procedure. By selecting those safety parameters the flight crew of the avoiding aircraft has continuous direct control over the safety of avoidance maneuvering.

However, the required safety parameters are dependent upon aircraft dynamics, airspeed profile flown, air pressure, strength and profile of wind, accuracy of conflict detection, etc., and further research is necessary for the definition of how large the values of those safety parameters selected by the crew have to be.

For the execution of avoidance procedures with descent in front of the intruder from a safely forced TOD the flight crew has to be warned of a threatening conflict up to two minutes before the planned TOD

($z = 3000m$). Therefore, in case of head on potential encounter, the conflict detection range must be at least $200km$. In comparison, the avoidance procedures with descent in front of the intruder from the planned TOD with safely altered angle of descent requires a shorter conflict detection range of approximately 100 km. The comparatively minor deviation from the original optimised flight path is another advantage of the latter avoidance procedure.

In general, considering the feasibility criteria such as initial vertical displacement for the safety of maneuvering, descent rate requirements for an aircraft flying within a flight envelope for passenger safety and comfort, and deviations from original optimised flight paths, the avoidance procedures with descent in front of the intruder have superior parameters to the avoidance procedures with descent behind the intruder [9].

While unsafe for execution when initial vertical displacement between aircraft does not exceed the vertical separation minimum, the avoidance procedures with descent behind the intruder [9] are in other cases applicable for execution of a *dolphin* descent when descent behind the intruder follows after the descent in front of the intruder (and/or vice versa) for the avoidance of a series of conflicts threatening in the initial phase of descent. With such a descent the penalties due to avoidance maneuvering might be minimized.

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POVZETEK

ALTERNATIVNO IZOGIBANJE NEVARNOSTNEMU STANJU S SPUŠČANJEM PRED VSILJIVCEM

V morebitnem nevarnostnem stanju lahko relativne hitrosti letal presegajo 0,5km/s. Slednje pomeni, da je za zaznavanje, reakcijo in strateško rešitev nevarnostnega stanja, pred samim začetkom izvajanja manevra izogibanja, na voljo sila kratek čas. Zategadelj, in ker zemeljski sistemi za upravljanje, kontrolo in vodenje letel v zraku že dosegajo svoje meje zmogljivosti, so avtonomni sistemi za preprečevanje nevarnostnih stanj na krovu letal neobhodni. Postopki izogibanja nevarnostnim stanjem s spuščanjem pred vsiljivcem so v pričujočem prispevku predstavljeni kot nadaljevanje raziskave avtonomnega ohranjanja varne oddaljenosti med letali v zraku, del te je bil namreč že predstavljen s postopki izogibanja nevarnostnim stanjem z začetkom spuščanja za vsiljivcem. Nadaljevanje je nujno, saj se z začetkom spuščanja za vsiljivcem nevarnostnemu stanju ni moč izogniti, če je začetna navpična razdalja med letaloma manjša od minimialne varne.

KLJUČNE BESEDE

varnost letenja, spuščanje, zaznavanje nevarnostnega stanja, postopek izogibanja

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