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CONFLICT AVOIDANCE BY DESCENT BEHIND THE INTRUDER

ABSTRACT

The paramount priorities for safe implementation of a single pilot manned cockpit concept and the futuristic concept of a single pilot acting as a supervisor for a fully automated aircraft flying on incessantly self-optimised trajectories are eliminations of the risk of mid-air collisions and of conflicts resulting from the lack of safe airborne separations. Avoidance procedures with initiation of descent behind the intruder for conflict resolution between a pair of aircraft where one of them is in the vicinity of the top of its descent represents merely one little piece of this giant puzzle.

KEY WORDS

flight safety, descent, conflict resolution, avoidance procedure

1. INTRODUCTION

Problem. In the crowded skies, air traffic management is a major research challenge. Operational concepts and systems for flight hazard protection that will permit aircraft to fly closer together with greater assurances of safety are necessary.

Scope. The objective of the presented research is the design of conflict avoidance procedures, with simplicity and controllability as the governing design principles.

Focus. Studies conducted for evaluation of Traffic Alert and Collision Avoidance Systems [3] revealed that in 17.3% of conflict events resolution advisories to flight crews were issued in the initial phase of descent. Furthermore we can expect 38.78% of in-flight encounters with at least one aircraft in descent to be among the total number of anticipated conflicts [8], [9] (Table 1).

Table 1 – Relative frequency of conflicts [8], [9].

Encounter Combination	Frequency [%]
Climb + Climb	3.57
Level + Level	47.66
Descent + Descent	10.38
Climb + Level	9.99
Climb + Descent	11.74
Level + Descent	16.66

Conflict avoidance procedures where conflict can be avoided by the vertical plane maneuvers flown by avoiding aircraft in descent behind the intruder are proposed, since literature and existing standard avoidance procedures reveal that avoidance maneuvering procedures for the encounter between a pair of aircraft in the vicinity of the top of the descent are not yet defined. Procedures are based on an in-flight conflict resolution model [7] modified from classical works about conflict detection and resolution [2], [4], [5]. Maneuvering in the vertical plane is anticipated on the basis of in-flight conflict situation simulation results [6] where 63% of the flight crews involved in the simulation executed an avoidance maneuver in the vertical plane either by descending or altering the rate of descent, whereas only 37% of them executed an avoidance maneuver in the horizontal plane.

2. CONFLICT DETECTION AND RESOLUTION

Initial Situation. Conflict is detected while two aircraft are flying toward each other with airspeed v_1 and v_2 for intruder A1 and avoiding aircraft A2, respectively, and with a constant relative direction angle ψ between them. Prior to the top of descent (TOD) both are flying at different flight levels so that the vertical displacement between them is z. Their relative displacement in the horizontal plane is then described by x and y. The higher flying aircraft A2 will at planned instant $\tau_{TOD/P}$ initiate its descent from cruising altitude FL, at point T/P on the following figures when the intruder below is at A1-T/P, with the planned angle θ_P of direct descent to its destination airport D.

Conflict Detection. The principle of maintaining safe airborne separation is based on a virtual protected airspace zone with boundaries defined by separation standards in the particular category of airspace. Radius r of the disc-shaped protected zone is defined by the separation minimum in the horizontal plane (longitudinal, and lateral separation are assumed to be identical), while height h is defined by minimum vertical separation. Conflict is an air traffic situation in which at least two aircraft are on courses that cause, or will cause unless corrected, a simultaneous violation of minimum safe separation requirements in the horizontal plane and in the vertical plane.

$$\{(x^2(\tau_C,t_C)+y^2(\tau_C,t_C))^{-1/2} \le 2r\} \cap \cap \{|z(\tau_C,t_C)| \le h\} \quad (1)$$

Conflict between two aircraft will occur if there exists a conflicting interval of time τ_C before planned TOD, or an interval of conflicting time t_C after planned TOD, for which both equations from (1) are simultaneously satisfied. Displacement between aircraft in the horizontal plane $(x^2+y^2)^{-1/2}$ will then be less than, or equal to, the diameter of protected zone $2r$, and displacement z in the vertical plane will be less than, or equal to, the minimum vertical separation standard h. The solution of equation (1) is a closed interval of total time of conflict t_C in descent after planned TOD, which is a cross-section between the closed interval of conflicting time t_{Ch} of loss of separation in the horizontal plane and the closed interval of conflicting time t_{Cv} of loss of separation in the vertical plane:

$$t_c \in [\underline{t_c},\overline{t_c}] = \{[\underline{t_{Ch}},\overline{t_{Ch}}] \cap [\underline{t_{Cv}},\overline{t_{Cv}}]\} \quad (2)$$

It follows that the cross-section between both the closed interval of conflicting time t_{Ch} of loss of separation in the horizontal plane and t_{Cv} of loss of separation in the vertical plane from equation (2) exists if and only if [7]:

$$\underline{t_{Cv}} < \overline{t_{Ch}} \wedge \overline{t_{Cv}} > \underline{t_{Ch}} \quad (3)$$

Conflict Resolution. Since a conflict between neighboring aircraft occurs when their protected zones overlap, the system of at least two aircraft is defined to be safe if the aircraft trajectories are such that their protected zones never overlap. According to the extended flight rules an aircraft in the pre-descent phase of flight has to give way to the intruder in cruise below and the same applies to the initial to intermediate phase of descent of a descending aircraft [1]. While the intruder exercises its right of way and does not alter its optimized flight plan, the descending aircraft is obliged to execute an avoidance maneuver. Because conflict between aircraft will occur if and only if safe separation minimums in the vertical and in the horizontal plane are violated simultaneously (1), the crew of the descending aircraft must execute a vertical plane avoidance maneuver in such a way that the displacement between aircraft in the horizontal plane will be greater than the minimum safe longitudinal or lateral separation $2r$ for the conflicting time interval of lost vertical separation. On those bases, a general term for conflict resolution can be defined for the altered initiation of descent and the altered angle of descent. From equations (2) and (3) it can be deduced that a descending aircraft can safely avoid threatening conflict with the intruder in the vicinity of the TOD via two main avoidance protocols [7]:

a) descending behind the intruder if $\underline{t_{Cv}} > \overline{t_{Ch}}$

b) descending in front of the intruder if $\overline{t_{Ch}} > \underline{t_{Cv}}$

3. DESCENDING BEHIND THE INTRUDER

Procedure 1. *Avoidance procedure with direct descent behind the intruder from delayed TOD* is presented in Fig. 1. It shows that because of a threatening conflict with the intruder A1 flying below the avoiding aircraft A2 remains, after the planned instant for initiation of descent $\tau_{TOD/P}$ at TOD, in level flight flying above the equivalent protected zone (EPZ) around the intruder until the safely delayed moment $\tau_{TOD/DS}$ of the descent with a safe angle of direct descent θ_{DS}. Initiation of the direct descent will be safe if it is delayed additionally for the time safety margin $\delta\tau$ after the critical moment defined by the critical delaying interval of time $\Delta\tau$. The critical moment for initiation of descent from T/DC is one which leads the trajectory of the descending aircraft to touch the confines of EPZ around the intruder at C1. This is then an example in which an avoiding aircraft descends with a critical angle of direct descent θ_{DC}. Therefore the critical delaying interval of time $\Delta\tau$ and a critical angle of direct descent θ_{DC} can both 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 safe instant $\tau_{TOD/DS}$ for the initiation of the delayed direct descent is then defined as the sum of time during which the initiation of descent was originally planned $\tau_{TOD/P}$, the critical delaying interval of time $\Delta\tau$, and the time safety margin $\delta\tau$:

$$\tau_{TOD/DS} = \tau_{TOD/P} + \underbrace{\left(\sqrt{B^2+AC}-B\right)(v_2 A)^{-1}}_{\Delta\tau} + \delta\tau \quad (4)$$

where A, B and C represent the expressions:

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

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

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

and additionally

$$k = v_1 / v_2.$$

From the same boundary condition but independently of (4) a critical angle of the direct descent θ_{DC} is defined as:

$$\text{tg}\,\theta_{DC} = \frac{FL}{FL\,\text{ctg}\,\theta_P - v_2\Delta\tau} \tag{5}$$

After flying in level flight above EPZ around the intruder, the avoiding aircraft will descend from T/DS with a safe angle of direct descent θ_{DS} behind EPZ around the intruder. For any time delay safety margin $\delta\tau > 0$ selected by the flight crew, a safe angle of direct descent θ_{DS} will be greater than critical θ_{DC}:

$$\text{tg}\,\theta_{DS} = \frac{AFL}{(FL\,\text{ctg}\,\theta_P - v_2\delta\tau)\text{A} + \text{B} - \sqrt{B^2 + AC}} \tag{6}$$

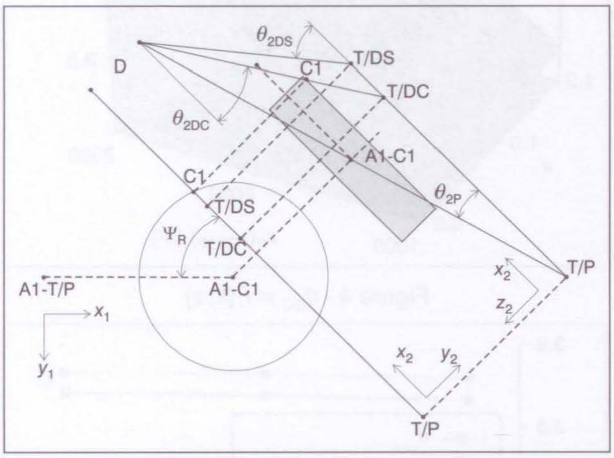

Figure 1 - Avoidance procedure with direct descent behind the intruder from delayed TOD.

Procedure 2. *Avoidance procedure with descent behind the intruder from planned TOD with a safely altered angle of descent* consists of two sequences of separate but interdependent resolution phases and it is presented in Fig. 2. The avoidance procedure starts when the avoiding aircraft A2 initiates its descent at planned instant $\tau_{TOD/P}$ with the safely altered angle of descent θ_S so that it will fly above the EPZ of the intruder A1. That is why θ_S has to be smaller than the critical angle of descent θ_C for the safety margin of the decreased descent angle $\delta\theta$ selected by the flight crew:

$$\theta_s = \theta_c - \delta\theta$$

where the critical angle of descent θ_C in the first phase can be numerically obtained from boundary conflict conditions between aircraft at C1:

$$x^2 + y^2 + k^2(z+h)^2 - 4r^2 -$$
$$-2\frac{z-h}{\text{tg}\,\theta_C}\left(x\cos\psi + y\sin\psi + kx\sqrt{1+\text{tg}^2\theta_C}\right) +$$
$$+\frac{(z-h)^2}{\text{tg}^2\,\theta_C}\left(1 + k^2 + 2k\cos\psi\sqrt{1+\text{tg}^2\theta_C}\right) = 0 \tag{8}$$

If an avoiding aircraft began direct descent too soon, i. e., before or at C2, it would penetrate EPZ around the intruder. Consequently, the second phase of the avoidance procedure starts behind the EPZ around the intruder on the trajectory of descent in the first phase at P2 at the safe instant t_S when the critical instant t_C is delayed further for the time safety margin δt selected by the crew:

$$t_s = \underbrace{\frac{(z-h)(\cos\theta_C - \cos\theta_{DC})}{v_2\sin\theta_C(\cos\theta_C\cos\delta\theta_2 - \sin\theta_C\sin\delta\theta_2 - \cos\theta_{DC})}}_{t_C} + \delta t \tag{9}$$

where θ_{DC} is the critical angle of direct descent defined from boundary conflict conditions as:

$$\text{tg}\,\theta_{DC} = \frac{(FL - z + h)\,\text{tg}\,\theta_P\,\text{tg}\,\theta_C}{FL\,\text{tg}\,\theta_C - (z-h)\,\text{tg}\,\theta_P} \tag{10}$$

Cleared from the protected zone overlapping configuration in the first phase of the avoidance procedure the avoiding aircraft will in the second phase descend with a safe angle of direct descent θ_{DS} behind EPZ around the intruder to the destination airport which is greater than θ_{DC} for any selected $\delta t > 0$:

$$\text{tg}\,\theta_{DS} = \frac{FL - F(\cos\delta\theta - \sin\delta\theta\,\text{ctg}\,\theta_C)}{FL\,\text{ctg}\,\theta_P - F(\cos\delta\theta\,\text{ctg}\,\theta_C + \sin\delta\theta)} \tag{11}$$

where F is:

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

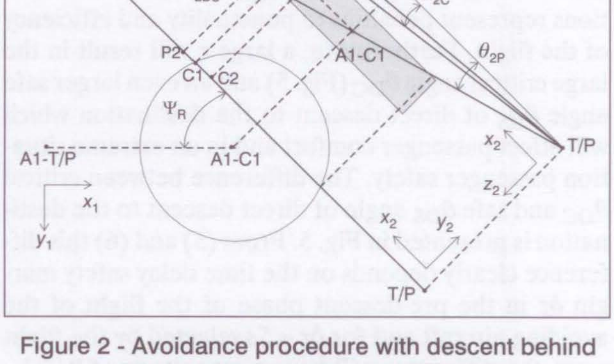

Figure 2 - Avoidance procedure with descent behind the intruder from planned TOD with the safely altered angle of descent.

4. SAFETY OF MANEUVERING

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 in the horizontal plane, essential safety parameters are selected by the flight crew of the avoiding aircraft. Those safety parameters are: time delay 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 the safety margin of the decreased descent angle $\delta\theta$. Using the required safety parameters the safe buffer zone between aircraft protected zones is secured so that they never overlap during execution of the avoidance procedure. By selection of those safety parameters the flight crew of the avoiding aircraft has continuous direct control over the safety of avoidance maneuvering.

5. QUANTITATIVE ANALYSIS OF AVOIDANCE PROCEDURES

Both avoidance procedures were subjected to quantitative analysis with regard to different initial situation parameters: initial vertical displacement between aircraft z and quotient k between intruder's airspeed v_1 and that of the avoiding aircraft v_2.

A major drawback of an avoidance procedure with direct descent behind the intruder from delayed TOD (1st procedure §3) is shown in Fig. 3. The critical delaying interval of time $\Delta\tau$ is proportional to the z and k, and from (4) and (5) also to the critical angle of direct descent θ_{DC}, Fig. 4. Therefore, for a large z and especially for $k > 1$, when the intruder is faster than avoiding aircraft, significant to the magnitude of a couple of minutes the critical delaying interval of time $\Delta\tau$ for critical initiation of descent of a avoiding aircraft is necessary. This means that the avoiding aircraft will in the process of conflict avoidance significantly deviate from its original optimized flight path, where deviations represent penalties to punctuality and efficiency of the flight. Furthermore, a large z will result in the large critical angle θ_{DC} (Fig. 5) and an even larger safe angle θ_{DS} of direct descent to the destination which will affect passenger comfort and in an extreme situation passenger safety. The difference between critical θ_{DC} and safe θ_{DS} angle of direct descent to the destination is presented in Fig. 5. From (5) and (6) this difference clearly depends on the time delay safety margin $\delta\tau$ in the pre-descent phase of the flight of the avoiding aircraft and for $\delta\tau = 5$ s selected by the flight crew, the difference will have a magnitude of 0.02° – 0.04°.

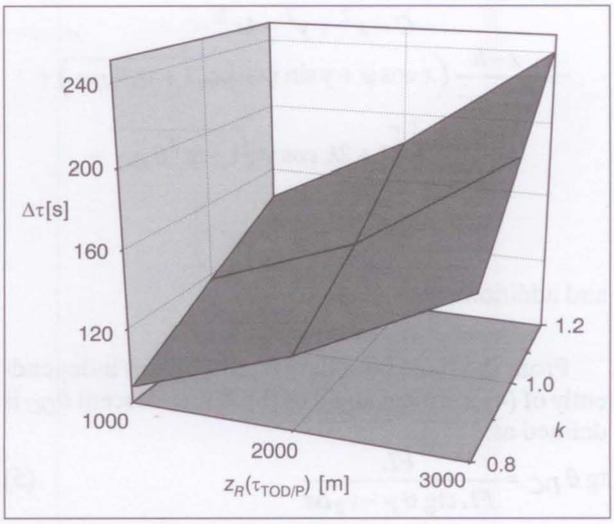

Figure 3 - $\Delta\tau = f(k, z)$

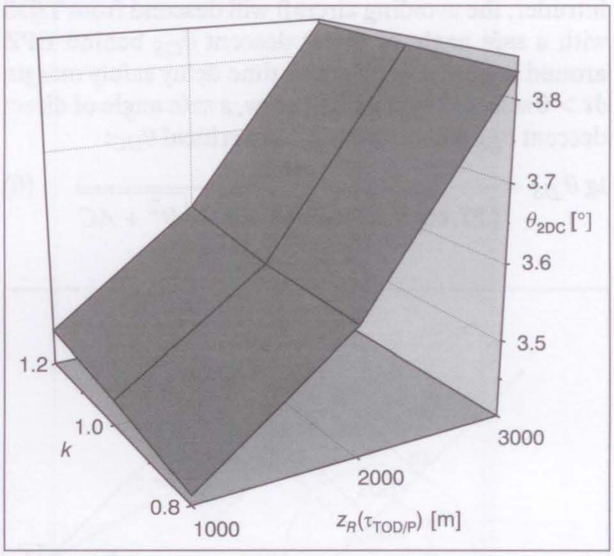

Figure 4 - $\theta_{DC} = f(k, z)$

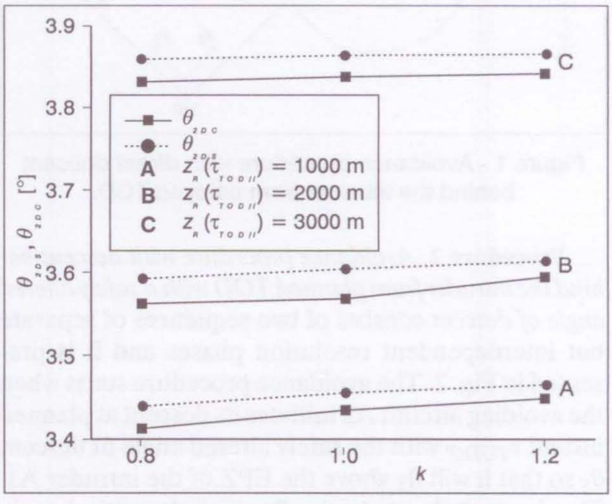

Figure 5 - θ_{DS}, $\theta_{DC} = f(k, z)$ at $\delta\tau = 5$ s

An avoidance procedure with descent behind the intruder from planned TOD with a safely altered angle of descent (2nd procedure §3) requires that the avoiding aircraft descends above the intruder's protected zone. This is why the critical angle θ_C of descent in the first phase of the avoidance procedure will be proportional to the initial vertical separation z between aircraft in a conflict encounter, Fig. 6. The critical angle θ_C of initial descent is proportional also to the airspeed quotient k, but as shown in Fig. 6 its influence is far less than that of z. Fig. 7 shows that the critical moment t_C for execution of the second phase of maneuvering in which an avoiding aircraft will descend behind the intruder is proportional to z and k. According to (9) it is proportional to the critical angle θ_C of descent in the first phase and inversely proportional to the safety margin of the decreased descent angle $\delta\theta$ selected by the flight crew. In any initial situation an avoiding aircraft will in the first phase of maneuvering fly in a descent shallower than planned (Fig. 6); but this first phase of avoidance will last longer for large initial vertical separations z, and when the intruder flies faster than the avoiding aircraft $k > 1$. Because of a shallower descent in the first phase of the avoidance procedure $\theta_S < \theta_P$ an avoiding aircraft will in the second phase descend more steeply than planned $\theta_{DS} > \theta_P$. The critical angle θ_{DC} of direct descent presented in Fig. 8 is proportional to z and inversely proportional to k. For safety of avoidance procedure, the critical angle of direct descent has to be smaller than the safe $\theta_{DC} < \theta_{DS}$ (Fig. 2). The difference between the critical θ_{DC} and the safe θ_{DS} angle of direct descent to the destination is presented in Fig. 9. From (10) and (11) this difference depends proportionally on the safety margin of the decreased descent angle $\delta\theta$ in the first phase of avoidance and on the time delay safety margin δt for initiation of the second phase of the avoidance procedure. For $\delta\theta = 0.05°$ and $\delta t = 5$s selected by the flight crew the difference will have a magnitude of about 0.02°.

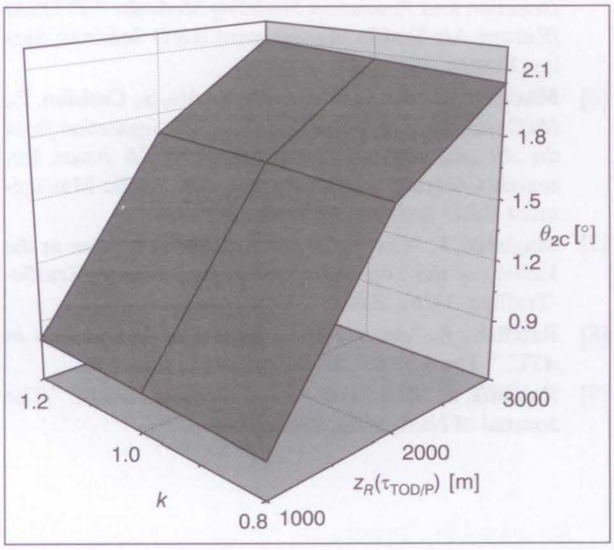

Figure 6 - $\theta_C = f(k, z)$

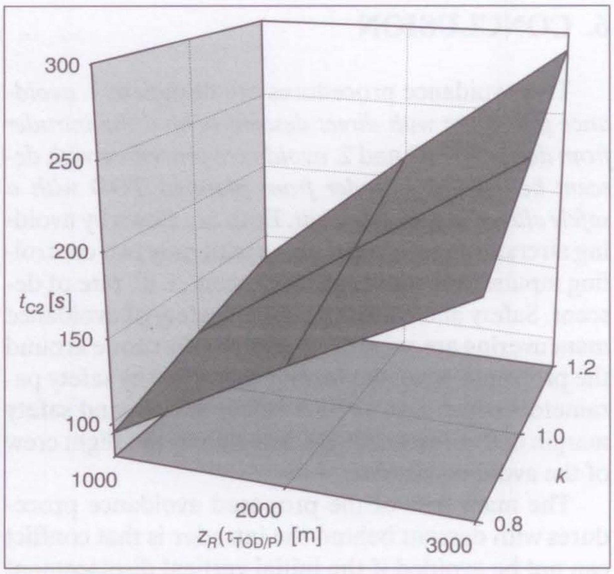

Figure 7 - $t_C = f(k, z)$ at $\delta\theta = 0.15°$

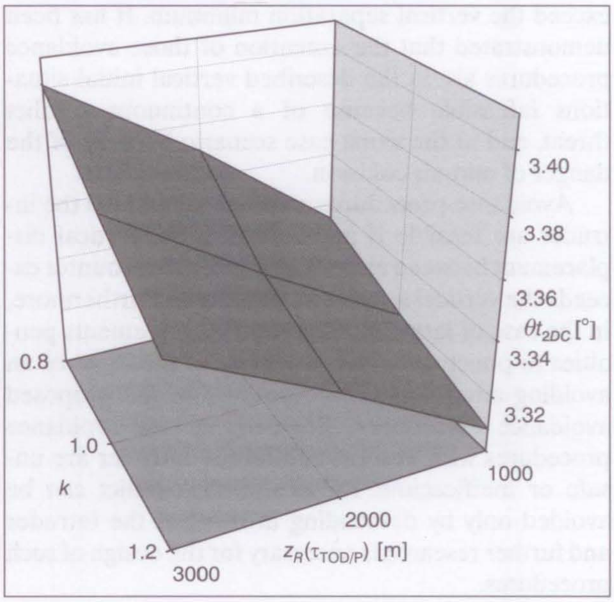

Figure 8 - $\theta_{DC} = f(k, z)$

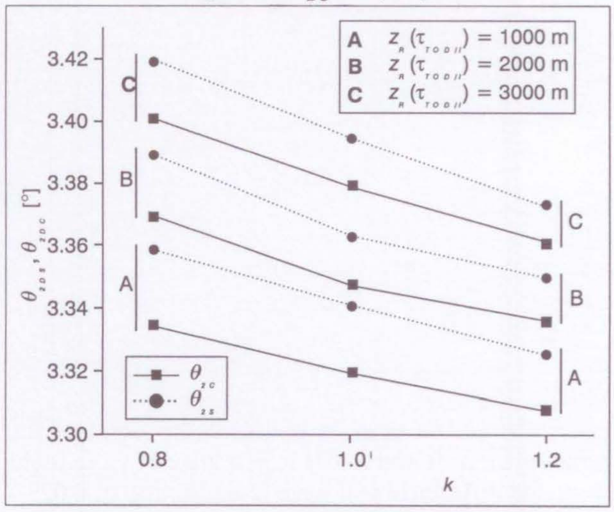

Figure 9 - θ_{DS}, $\theta_{DC} = f(k, z)$ at $\delta\theta = 0.05°$ and $\delta t = 5$ s

6. CONCLUSION

Two avoidance procedures are designed: 1. *avoidance procedure with direct descent behind the intruder from delayed TOD* and 2. *avoidance procedure with descent behind the intruder from planned TOD with a safely altered angle of descent*. Both are flown by avoiding aircraft in the vertical plane with only two controlling inputs: time and angle of descent, i. e., rate of descent. Safety and controllability of safety of avoidance maneuvering are secured by a safe buffer zone around the protected zone; the former is defined by safety parameters which are, as time safety margin and safety margin of the descent angle, selected by the flight crew of the avoiding aircraft.

The main flaw of the proposed avoidance procedures with descent behind the intruder is that conflict can not be avoided if the initial vertical displacement between aircraft before initiation of descent does not exceed the vertical separation minimum. It has been demonstrated that the execution of those avoidance procedures are in the described vertical initial situations infeasible because of a continuous conflict threat, and in the worst case scenario because of the danger of mid-air collision.

Avoidance procedures with descent behind the intruder are feasible if and only if initial vertical displacement between aircraft in a conflict encounter exceeds the vertical separation minimum. Furthermore, in the case of large initial vertical displacements penalties to punctuality and efficiency of the flight of an avoiding aircraft are disadvantages of the proposed avoidance procedures. However, in case avoidance procedures with descent behind the intruder are unsafe or inefficacious for execution, conflict can be avoided only by descending in front of the intruder and further research is necessary for the design of such procedures.

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POVZETEK

IZOGIBANJE NEVARNOSTNEMU STANJU Z ZAČETKOM SPUŠČANJA ZA VSILJIVCEM

Prežemajoča prioriteta za uvajanje koncepta letala z enim samim pilotom in uresničevanje futurističnega koncepta avtonomnega letala, ki bo s pilotom kot nadzornikom avtomatiziranih sistemov letel po nenehno samo-optimiziranih trajektorijah, je odprava tveganj trčenj in nevarnostnih stanj premajhne oddaljenosti med letali v zraku. Konstruirani postopki izogibanja z začetkom spuščanja za vsiljivcem v izogib nevarnostnim stanjem med parom letal v okolici začetka spuščanja predstavljajo zgolj drobcen delček te neizmerne puzle.

KLJUČNE BESEDE

varnost letenja, spuščanje, zaznavanje nevarnostnega stanja, postopek izogibanja

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