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Prometna tehnika - Traffic Engineering
Izvorni znanstveni članak - Original scientific paper
U.D.C. 358.4:519.7:681.3
Primljeno - Accepted: 20.02.1996.
Prihvaćeno - Approved: 28.05.1996.

GRAPHIC-ANALYTIC MODELING OF MAXIMAL MANEUVERING CAPABILITIES WITH AIRCRAFT AT HORIZONTAL LEVEL

GRAFIČKO-ANALITIČKO MODELIRANJE MAKSIMALNIH MANEVARSKIH SPOSOBNOSTI ZRAKOPLOVA U HORIZONTALNOJ RAVNINI

Tijekom Domovinskog rata pred oružane snage RH postavljeni su predvidivi i nepredvidivi zahtjevi za uspješno izvršenje bojevih zadaća u zračnom prostoru, uz angažman svih ljudskih i materijalnih resursa Hrvatskog ratnog zrakoplovstva.

Ratno zrakoplovstvo, najsofisticiraniji dio OS-a, pridonijelo je djelovanjem iz zraka po objektima na kopnu (moru) i u zračnom prostoru uspješnom ishodu poduzetih operacija.

Učinkovitost zrakoplova nadzvučnih brzina moguće je povećati pri djelovanju po objektima u zraku poznavanjem graničnih mogućnosti manevriranja, primjenom grafo-analitičke metode modeliranja tijekom pripreme za let, edukacijom pilota i ostalih učesnika za maksimalno iskorištenje mogućnosti letjelice primjenom forsiranog zaokreta. Grafo-analitička metoda pripreme pilota za izvršenje bojeve zadaće jedna je od metoda koja se koristi na višoj razini psihološkog, teorijskog i praktičkog poznavanja uvjeta predstojećeg leta. Primjenjuje se za povećanje učinkovitosti rezultata zračne borbe i smanjenje vlastitih gubitaka.

1. INTRODUCTION

Efficiency of a supersonic aircraft during combat action over airspace targets is considerably influenced by the preparations of pilots and other participants (technicians), as well as the proper functioning of instruments which ensure successful accomplishment of the action.

During pilot's preparations for the task of ground and navy forces protection from the enemy's airplane actions, and support of own forces (air force and anti-aircraft defense units), possible methods of acting in and from airspace are simulated and modeled.

Pilot's preparation is a part of a complicated system of combat security and a part of a subsystem of navigational combat flight security.

It is carried out by applying the measures and tactical procedures of units, pilots (crews), technical stuff and instruments, with the basic objective to increase the effectiveness and efficiency of combat action.

Simulation and modeling of possible ways of acting in and from airspace, form a part of ground measures and tactical procedures in the air. Their positive results include well-timed precise psychological, theoretical and practical abilities of performing the combat task.

Determination of maximal aircraft maneuvering capabilities at horizontal level, using graphic-analytic method and computer simulation, contributes to higher efficiency and to successful performing of combat flight of supersonic aircrafts using afterburner.

In general, the result of air-combat depends on many factors, but this method of modeling results in improvements aimed at the standardization and analysis of influential factors and elimination of negative effects some factors might have on the final results of combat task performing.

2. DEFINITION, CLASSIFICATION AND ORGANIZATION OF THE CROATIAN AIRSPACE

In order to emphasize and realize the sovereignty of Croatia (which includes airspace as well) parallel to combat actions on battle-fields during the Croatian war, many measures have been taken for the integration into the European flight control system.

Croatia has had, and will have an obligation to fulfill all ICAO standard regulations, whether at war, or in peace. The air force, in peace and at war, performs many tasks in the airspace and specific demand of military actions, built in the draft bill on Air Traffic, had to be taken into consideration.

2.1. Definition of Airspace

Croatian airspace consists of the space above the territory and territorial waters of Croatia, as well as the airspace above the Adriatic Sea limited by the borders established by the international agreements (Figure 1). Or-

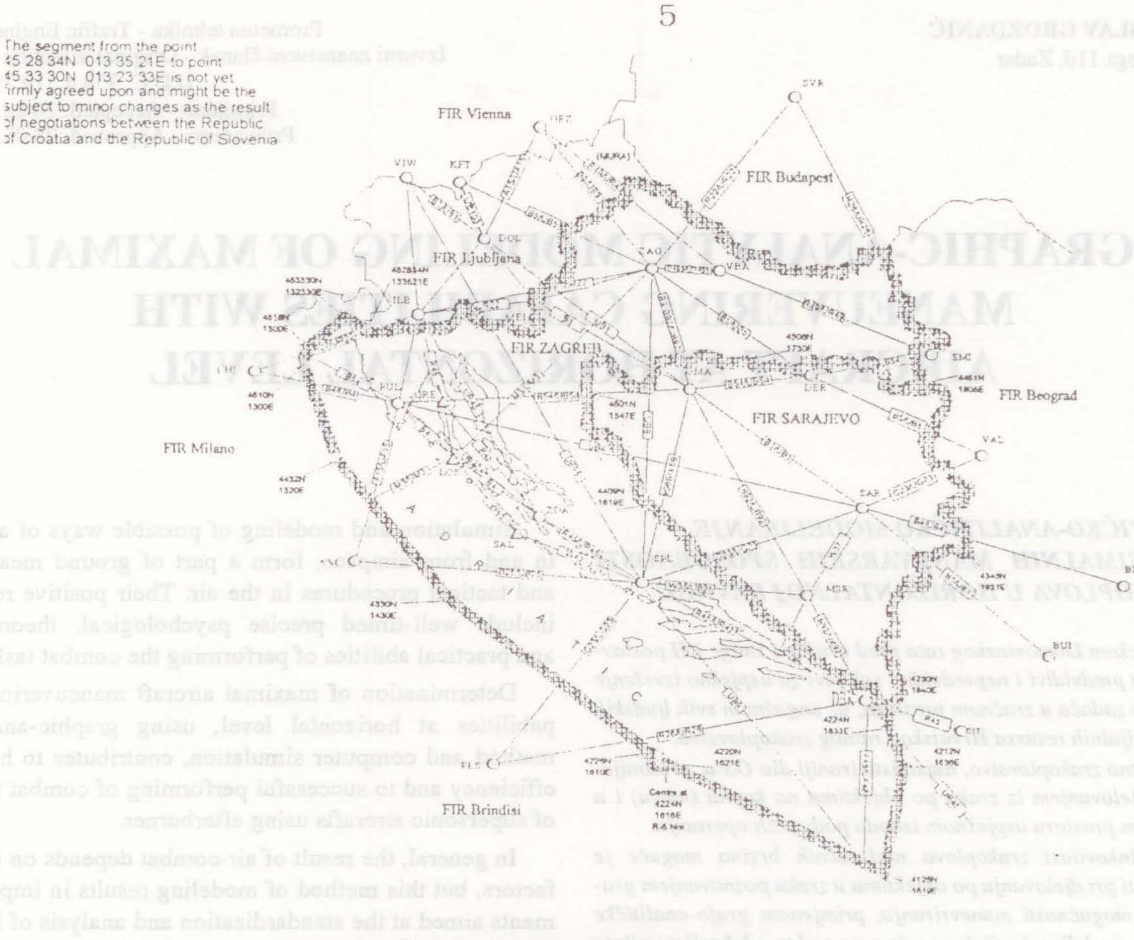

Figure 1 **Croatian airspace borders**

ganization and performing of military flying are completely subordinated to these regulations. [1]

2. 2. Classification of Croatian Airspace

Airspace classification of a certain country is determined according to its needs, working technology, types and intensity of flying, technical support and military flying requirements. Elements of air-traffic classification have been standardized at a world level (Figure 2). Croatian airspace has been classified according to the worldwide acknowledged standards by letters A, B, C, D, G denoting classes according to heights (flight levels) and areas of competence [1].

Defined and classified as described, Croatian airspace sets very strict demand on units and pilots (especially supersonic aircraftpilots), during preparations, organization and performing combat tasks. [2]

Supersonic airplanes, with their airspeeds (GSP) from 0.8-1.5 Mach (900-2000 km/h) pass through zones of responsibilities of individual flight controls (TMA) very fast, and this presents a significant problem during flight monitoring and conducting.

At the same time, they must perform the given task, on call, whether from the zone of expectation or the zone of duty, at all hights ranging from 100 to 1500 m.[3]

3. EVALUATION AND ANALYSIS OF MAXIMAL MANEUVERING CAPABILITIES AT HORIZONTAL LEVEL

Maneuvering at horizontal level (turns) is one of the most used maneuvers during air-combat.

It can be stable (the balance of elements and forces) and unstable, where some of the elements change constantly. [4]

Forced turn is one of the unstable turns, and it is performed with max. engine thrust (afterburner). During this turn it is possible to reduce the airspeed and radius to a certain limit.

That maneuver is most used in air-combat to create good conditions for application of weapons and/or for successful escape from the opponent's reach. [5]

Forced turn is performed at horizontal level with vertical speed indicator at zero, by adjusting the bank for maintaining the relation of forces in balance ($\cos\varphi = 1/12$; $R_z \cos\varphi = G$) with constant change of the airspeed.

Minimal radius (R_{min}), duration of the turn (t_{min}) and max. angle speed (ω_{max}), are achieved at max. overload allowed ($n_{e\,max}$), max. allowed $C_z = C_{z\,all.}$ and max. declined horizontal stabilizer (helm of height).

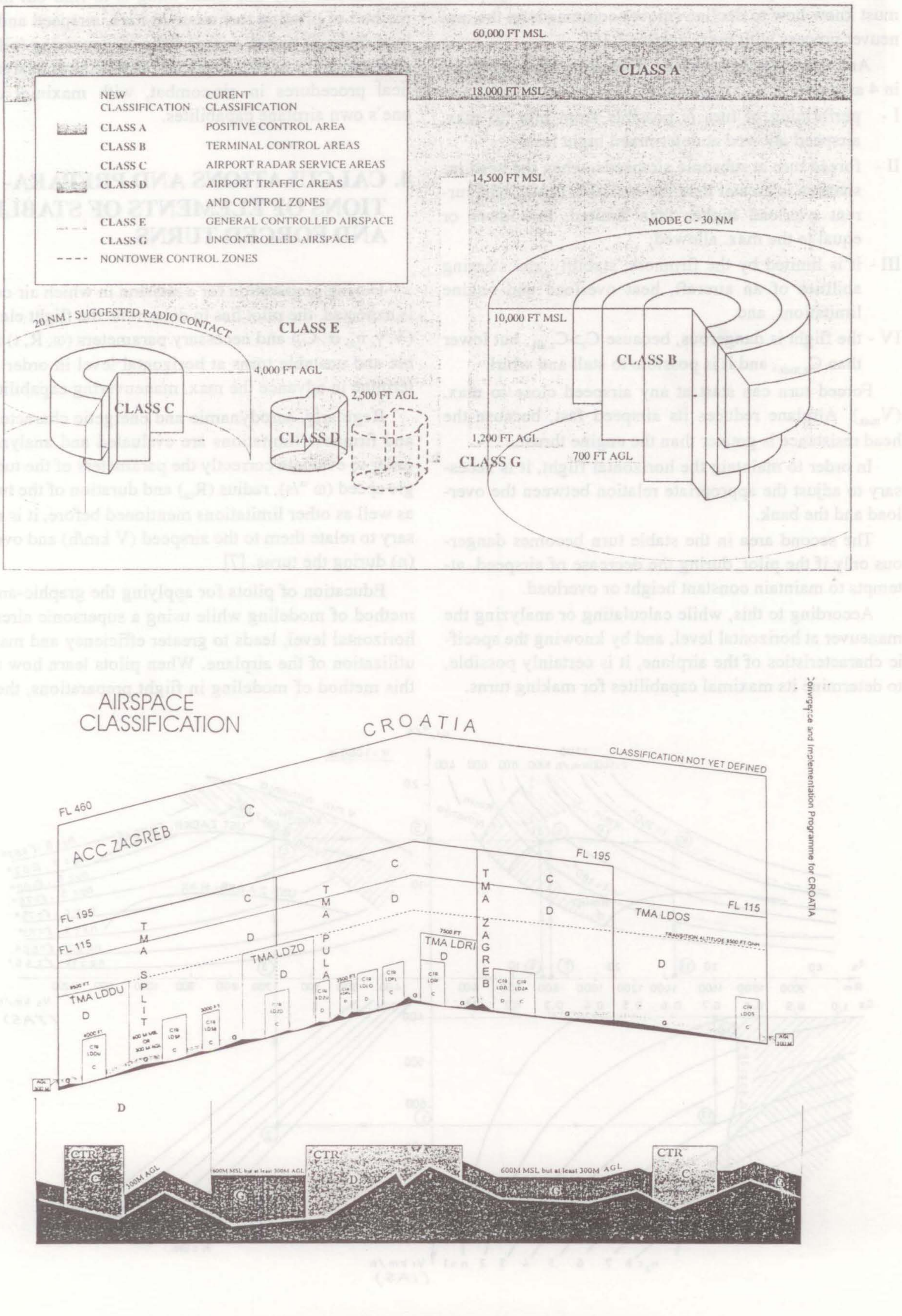

Figure 2 **General classification of the Croatian airspace**

In order to perform the forced turn correctly, pilots must know how to decline (move) commands in the maneuver process with max. overload. [6]

Aerodynamically speaking, forced turn is performed in 4 areas:

I - performing of turn is possible from min. to max. airspeed allowed at determined hight level;

II - forced turn at subsonic airspeeds, when the head resistance is greater than the available thrust, and current overload higher than limited, but lower or equal to the max. allowed;

III - it is limited by the firmness, stability and steering abilities of an aircraft, heat overload and engine limitations, and

IV - the flight is dangerous, because $C_z > C_{z\ all.}$, but lower than $C_{z\ max}$, and it is possible to stall and whirl.

Forced turn can start at any airspeed close to max. (V_{max}). Airplane reduces its airspeed fast, because the head resistance is greater than the engine thrust.

In order to maintain the horizontal flight, it is necessary to adjust the appropriate relation between the overload and the bank.

The second area in the stable turn becomes dangerous only if the pilot, during the decrease of airspeed, attempts to maintain constant height or overload.

According to this, while calculating or analyzing the maneuver at horizontal level, and by knowing the specific characteristics of the airplane, it is certainly possible, to determine its maximal capabilites for making turns.

Another very important thing is to find out the best method of piloting technique in max. airspeed and overload regimes, and to compare the maneuvering (piloting) characteristics of two airplanes, as well as to analyze tactical procedures in air-combat, with maximal use of one's own airplane capabilites.

4. CALCULATIONS AND PREPARATIONS OF ELEMENTS OF STABLE AND FORCED TURNS

During preparation for a mission in which air-combat is expected, the pilot has to determine the flight elements (V, γ, n_z, α, C_z) and necessary parameters (ω, R, t) in stable and unstable turns at horizontal level in order to determine in advance the max. maneuvering capabilities.

Regularly, aerodynamic and energetic characteristics and firmness limitations are evaluated and analyzed. In order to evaluate correctly the parameters of the turn, angle speed (ω °/s), radius (R_m) and duration of the turn (t_s) as well as other limitations mentioned before, it is necessary to relate them to the airspeed (V km/h) and overload (n) during the turns. [7]

Education of pilots for applying the graphic-analytic method of modeling while using a supersonic aircraft at horizontal level, leads to greater efficiency and maximal utilization of the airplane. When pilots learn how to use this method of modeling in flight preparations, they de-

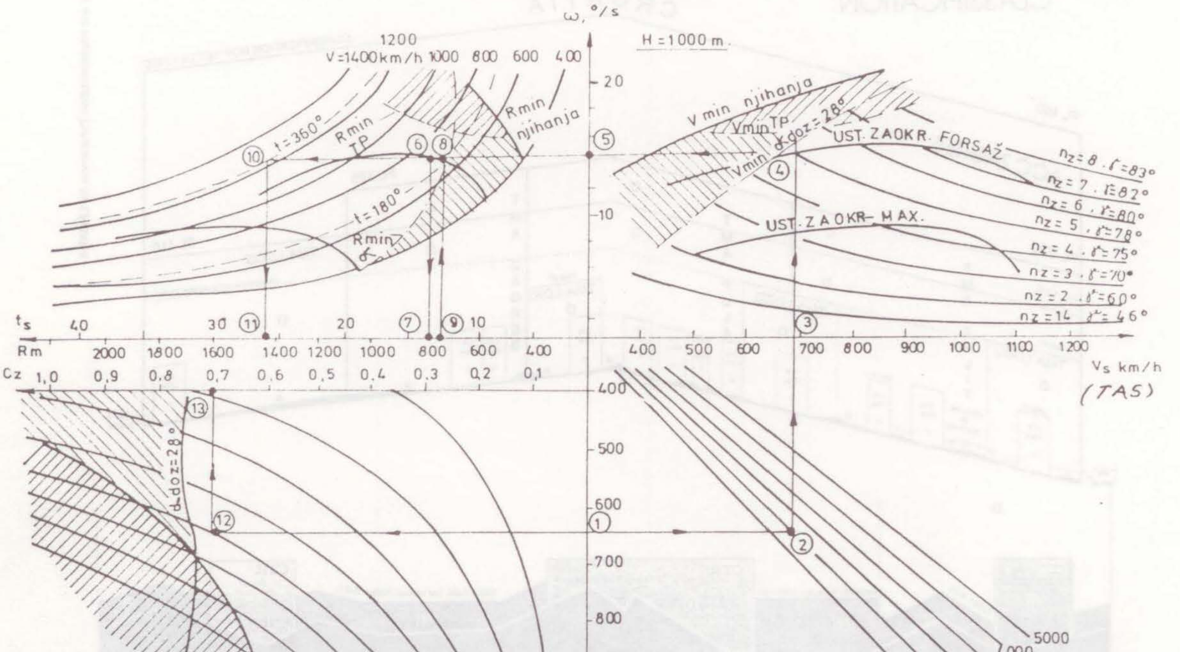

Figure 3 **Nomogram "Determination of maneuvering capabilities at horizontal level"**

velop habits which help them to determine the rational regimes of combat maneuvering all by themselves, which widens greatly the possibilities and capabilities of the aircraft and increases efficiency and security of flying.

To accomplish this goal, it is appropriate to use the nomogram shown in Figure 3, which associates the elements of flight and the parameters of turns at horizontal level.

Symbols in text, figures, nomogrammes and tables are as follows:

V (V_t & V_i) - airspeed (true & instrument), km/h
γ - bank, °
n_z - turn overload, g
α - angle of attack, °
C_z - lifting force (coefficient from 0.1-1)
ω - turn angle speed, °/s
R - turn radius, m
t - turn duration, s
H - height, m

4.1. Explanation and instruction for using the nomogram

The upper left quadrant of the nomogram shows the dependence of the angle speed (ω) in horizontal turn on the airspeed (V), overload (n_z) and bank (γ).

All patterned areas show limitations that would appear after the occurrence of vibrations, max. allowed angle of attack or after reaching the limits of overload. There are also limits of stable turns on max. engine regime and unstable turns on forced regime (afterburner).

Below that limit, there is the area of the stable turn, and above is the area of the unstable (forced) turns.

It is possible to draw the construction firmness limitations, and thus define completely all limitations of maneuvering at horizontal level.

In the upper left quadrant solid lines mark the dependence of changing turn radius (R) on the angle speed (ω), at different airspeeds and dashed lines help to determine the turn duration of the 180° and 360° turns. Parameters R and t are drawn on the horizontal axis - left.

The lower left quadrant shows the dependencies between the change of the lifting force (C_z) and the instrument airspeed (V_i) and overload (n_z), and limitation of vibrations and the angle of attack (α).

It is also possible to draw the limits of allowed angle of attack (α_{all}) shown on the instrument in the cockpit.

Lines in the lower right quadrant help us to transform the instrument airspeed (V_i) into the true one (V_t), depending on the height.

In this way, using the nomogram, it is possible to determine practically all necessary information regarding elements and parameters of flight which do not depend on the type of the airplane and the height, as well as information on limitations during maneuvering. [7]

The nomogram analysis of flight elements and turn parameters

Nomogram in Figure 3 shows points from 1-13, which are basic keys of its usage, and help us read elements and parameters in horizontal stable and unstable turns.

Experimental Flight Conditions

- given instrument airspeed - IAS, V_i = 650 km/h (point 1)
- given height, H = 1000 m (point 2)
- given overload in turn, n_z = 5G (point 4)
- given bank in turn, γ =78° (point 4)

Analysis of the Nomogram Calculated Data (Fig. 3)

Marked line (points 1-2-3-4-5) provide accurate determination of flight elements and necessary parameters during turns, and readings of:

- true airspeed - TAS, V_t = 690 km/h (point 3)
- it is possible to perform the turn under given condition only in forced regime (point 4)
- angle speed, ω = 14°/s (point 5)
- radius, R = 800 m (points 6-7)
- duration, $t_{180°}$ = 13s (points 8-9), $t_{360°}$ = 26s (points 10-11)
- lifting force coefficient, C_z = 0.705 (points 11-12-13)

After analyzing the results, it can be stated that:

1. this turn can be performed only in forced regime,
2. if max. regime was applied, its execution would result in decrease of airspeed, and it would become a forced one because of the head resistance which would be greater than the engine thrust,
3. the limit speed of the allowed angle of attack (α_{all}) and the vibration limits Δn_z = 0.5, can soon reach α_{all} = 28°,
4. crossing the limit of vibrations would cause the airplane to enter the zone of vibrations (C_z = 0.1-0.1),
5. errors in piloting technique, combined with the increase of Δn_z to 1.5 would result in reaching the stalling zone,
6. reducing of airspeed during turn by 25-30 km/h, with constant overload (n_z = 5G) would also bring the airplane to α_{all}, and its further decrease to V_i = 550 km/h - the beginning of stalling.
7. H = 1000 m is the extreme height for performing the stable turn, under given conditions,
8. using the afterburner and in stable turn, the supersonic aircraft can gain considerable advantages when going in or coming out of the air-combat, compared to the capabilites of a potential enemy aircraft, thus creating good conditions for successful ground combat mission, and,

9. theoretical education of pilots and correct implementation of recommendations regarding piloting techniques during combat missions play a crucial role in using maximal manuvering capabilites at horizontal level.

5. THE EFFICIENCY ANALYSIS OF MANEUVERING CAPABILITIES AT DIFFERENT FLIGHT LEVELS

Maximal maneuvering capabilities at horizontal level, even under the same conditions (regime elements) depend greatly on the height.

The efficiency analysis should be performed by comparison of the same experimental conditions for the height of 5000 m and of the changed flight conditions at H=1000 m, thus evaluating the changes in aircraft capabilities.

Experimental Flight Condition

– given instrument airspeed - IAS, V_i = 650 km/h (point 1)
– given height, H = 1000 m (point 2)
– given overload in the turn, n_z = 5G (point 4)
– given bank in the turn, γ = 78° (point 4)

Analysis of the Nomogram Calculated Data (Fig. 4)

Marked lines (points 1-2-3-4-5) provide correct determination of flight regime elements and turn parameters.

– true airspeed (TAS), V_s = 890 km/h (point 3)
– turn under these conditions will be performed at the border of the vibration zone at the angle of attack close to α_{all} (point 4)
– angle speed in the turn, ω = 11 °/s (point 5)
– radius, R = 1000 m (points 6-7)
– duration of the turn, $t_{180°}$ = 17s (points 8-9), $t_{360°}$ = 34s (points 10-11)
– coefficient of the lifting force, C_z = 0.7 (points 11-12-13)

After analyzing the results, it can be stated that:

1. the turn will be unstable (forced)
2. pilot's attempt to maintain constant overload (n = 5G) brings the aircraft, already at V_s = 750 km/h (V_i = 560km/h) to the border of the stalling zone, and then, if no measures are taken, to the stalling itself,
3. it is possible to make a safe maneuver by using certain procedures (piloting technique) while performing the turn,

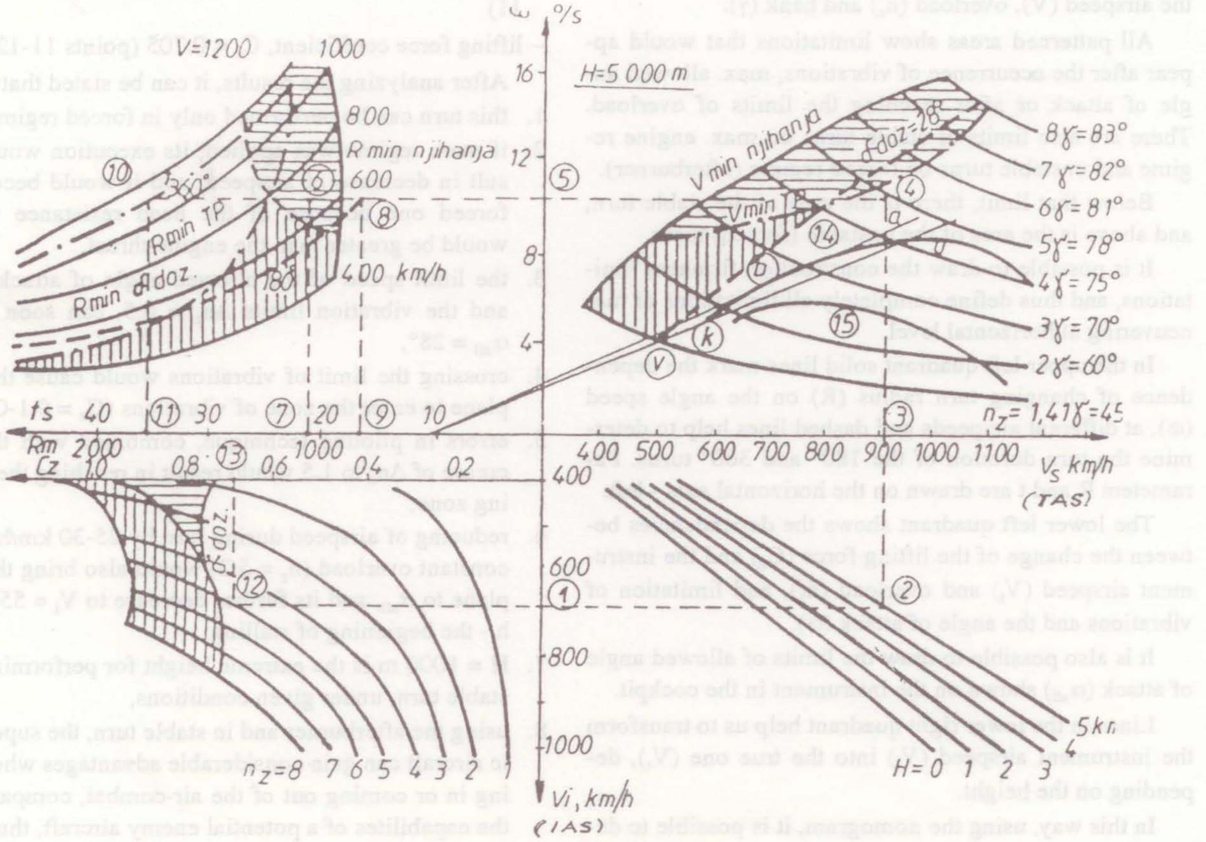

Figure 4 **Determination of the max. maneuvering capabilities in horizontal turn at H=5000 m**

4. it is possible to make a stable turn at V_i = 650 km/h under the given conditions, but with n_z = 3.9G and transverse inclination (γ = 75°), which is marked at point 14, only in the forced engine regime,
5. under the given conditions it is possible to make the turn with n_z = 2.5G and inclination γ = 65° (point 15), but only at maximal engine regime,
6. however, the last two possibilities change some parameters of the turn, which is significant and can affect the air-combat efficiency.

6. DETERMINATION OF THE OPTIMAL CONDITIONS OF MANEUVERING AT HORIZONTAL LEVEL USING GRAPHIC-ANALYTIC METHOD OF MODELING

During combat maneuver of a supersonic airplane at horizontal level (air-combat or combat actions over land targets) at the height of H=1000 m, it is often necessary to make the stable turn with minimal duration (t_{min}).

Which maneuver should be applied:

– with max. overload ($n_{z\,max}$) or
– with max. angle speed (ω_{max})?

Thereby it is necessary to determine other maneuvering conditions:

– engine regime,
– required airspeed (IV),
– required bank (γ)
– required overloading (n_z),
– radius (R_m) and
– duration of the turn (t).

Analysis of the Calculated Data (Fig. 5):

The following may be concluded:

– angle speeds in the turn at the forced regime are significantly greater (points 5 and 5a) than those of max. regime, which means that it is advisable to use the forced regime,

– maneuvering with the max. overload (ω_{max}) and bank angle (γ_{max}) is performed in the regimes determined by the contact points of curves which limit the zones of STABLE turns and the line of constant overload (points (v) and (g)).

– maneuvering regimes with max. angle speed (ω_{max}) are determined in the contact points of zones of stable turns (points 4 and 4a) and straight lines which are parallel with the horizontal axis, and read at points 5a-5,

– comparison of parameters at points (d) and (v) (angle speed and radius), shows that the turn with max. overload and max. transverse inclination is less favorable (desirable) than the turn with max. angle speed (ω_{max}), points 7-7a,

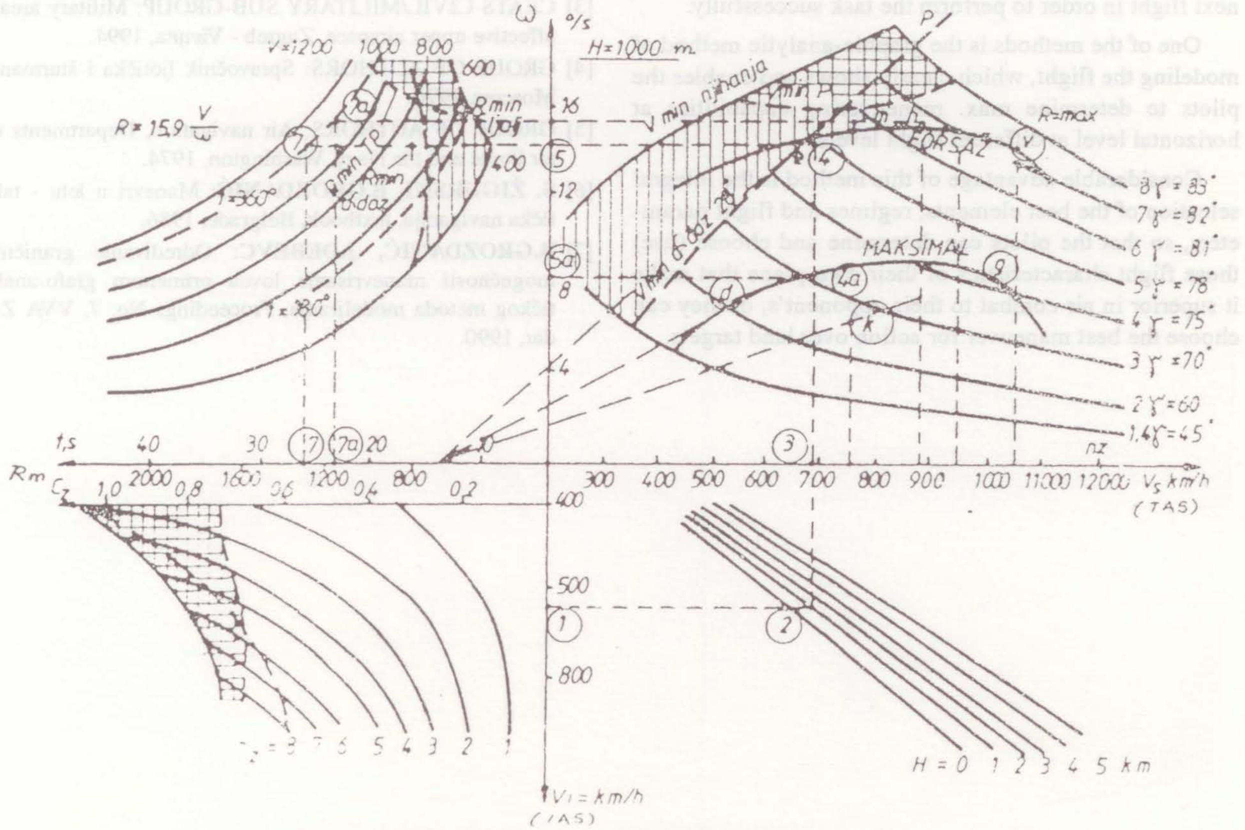

Figure 5 **Selection of the optimal conditions for a more efficient turn**

– parameters of the turn maneuver (ω, R, t) performed with n_{max} and ω_{max} show that the turn with max. angle speed (ω_{max}) is more efficient because of the shorter duration and smaller radius. [7]

The above conclusions regarding the comparison analysis of flight elements and parameters, and aircraft efficiency are clearly shown in Table 1.

Table 1 - Compared parameters of the turn

turn with	ω°/s	n_z	R_m	t_s	V_s km/h	V_i km/h	γ_{max}°	C_z
n_{max}	14.5	7.5	1150	25	1040	980	82.5	0.56
ω_{max}	15.3	7	980	23.5	950	900	82	0.62

**turn with* ω_{max} is more favorable at all elements

CONCLUSION

Flights of military aircrafts in war and in peace are performed in the airspace of a certain country, defined by the ICAO standards and international agreements.

Supersonic aircrafts, using high subsonic airspeeds and afterburner can increase the maneuvering efficiency at horizontal level.

The basic conditions to achieve this are understanding of max. aircraft capabilities, selection of the most suitable usage and excellent piloting technique.

During flight preparation, pilots study and model the next flight in order to perform the task successfully.

One of the methods is the graphic-analytic method of modeling the flight, which clearly shows and enables the pilots to determine max. maneuvering capabilities at horizontal level at different flight levels.

Considerable advantage of this method is the integral selection of the best elements, regimes and flight parameters, so that the pilots can determine and choose (use) those flight characteristics of their own plane that make it superior in air-combat to their opponent's, or they can choose the best maneuver for action over land targets.

SUMMARY

During the Croatian War the military forces of the Republic of Croatia were faced both with foreseen and unforeseen demands regarding successful airspace combat actions, requiring full engagement of all human and physical resources of the Croatian Military Air Force.

Military Air Force, the most sophisticated part of the armed forces, has contributed to the success of the operations by acting in and from airspace against ground and sea targets.

The supersonic aircraft efficiency in combat action over airspace targets can be increased by acquiring knowledge regarding the maximal maneuvering capabilities, application of graphic-analytic modeling during flight preparations, education of pilots and other participants in order to maximally exploit the aricraft capabilites applying the forced turn. Graphic-analytic method of preparing the pilot for combat mission is one of the methods used at a higher level of psychological, theoretical and practical realizations of the next flight conditions. It is applied in order to increase the efficiency of air-combat and to reduce one's own losses.

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