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THE APPLICATION OF THRUST VECTORING WITH REGARD TO THE SUPERMANEUVERABILITY OF THE RESEARCH AIRCRAFT X-31A

SAŽETAK

PRIMJENA VEKTORIRANOG POTISKA S OSVRTOM NA SUPERUPRAVLJIVOST ISTRAŽIVAČKOG ZRAKOPLOVA X-31A

Vektorirana propulzija nova je koncepcija upravljanja zrakoplovom pomoću deflekcije mlaza motora.

Istraživanje vektoriranog potiska aktualizirano je u posljednjih desetak godina, uglavnom za primjenu u vojne svrhe.

Realizirani eksperimentalni projekti potvrđuju djelotvornost vektoriranih propulzivnih sustava u općoj upravljivosti, upravljivosti zrakoplova na visokim napadnim kutovima leta, kao i PST-manevarbilnosti nakon prelaska barijere kritičnoga napadnog kuta. Osim za vojno zrakoplovstvo, rezultati istraživanja vektoriranog potiska primjenjivi su u civilnom zrakoplovstvu, poglavito u projektiranju STOL i VTOL zrakoplova.

1. INTRODUCTION

The development of digital control devices for aircraft flight control, namely of digital technologies for controlling the aircraft engine has provided a completely new research methodology for studying the propulsion system design and functional linking of the aircraft with its engine.

In order to improve the flight performance and the aircraft maneuverability, more recent research are aimed at developing a thrust vectoring system i.e. jet-deflection control.

Thrust vectoring is a radical shift in designing of sophisticated high-performance aircraft and in the flight theory a completely new approach compared to the former one which was based on modifications of positions and forms of lift aerobodies i.e. aeroprofiling of the bearing (wing) surfaces and aircraft flight commands.

The application of vectored propulsion on experimental aircraft confirms the fantastic possibilities of aircraft control at high angles of attack, stealth aircraft and aircraft maneuvering.

The results of past research, carried out mainly for military requirements, suffice in order to supplement the traditional knowledge in aerodynamics, thermodynamics, propulsion, and flight mechanics, as well as electromechanics, management, materials and radars, with new knowledge of their interrelations and application in vectored STOL and VTOL aircraft, which fly manned or unmanned.

New knowledge brings also a whole range of unanswered questions that have to be answered by scientists and experts in the field of aeronautics, and they include mainly the following:

- Can the thrust vectoring satisfy the PST (Post Stall Technology) requirements i.e. provide aircraft maneuverability after passing the barrier of the critical angle of attack, and which concept should be applied: the one of a complete or part thrust vectoring, namely the internal or external thrust vectoring?
- Which is the lowest ratio of thrust and aircraft weight at which the advantages of a vectored compared to the conventional aircraft can be accurately determined, and the possibilities for design modifications of the existing conventional aircraft into PST vectored aircraft?
- Does the thrust vectoring for 3D-control (climbing-rolling - turning) of combat aircraft satisfy the basic requirements for survival and victory in the air duel and what physiological indications are needed by the human factor for operation; how to identify the flight regimes and maneuvers in which the vectored aircraft will demonstrate its advantages as compared to the conventional aircraft; which measurable quantity can express this relation (in military aviation the correlation of "factor of lethality" is common)?
- How to modify the geometric design of air inlet ducts and nozzles of the vectored engine in order to meet the specific requirements of various maneuvers i.e. what is the magnitude range of the efficiency of the system engine-nozzle-inlet duct and the limitations related to this new design trend.

The research and application of the thrust vectoring systems in the future impose a need for introduction of measurable quantities for real comparison of maneuverability and control of vectored and conventional aircraft.

Globally, several parallel funded research projects on thrust vectoring are under way.

For instance, Russian scientists are working on a 2D-concept of the SU-27 aircraft, propelled and controlled by jet deflection for climbing and turning, whereas the US designers are elaborating a concept of a climbing and reverse-climbing thrust vectoring for the new F-15 STOL aircraft and the ATF (Advance Tactical Fighter). ATF is also used for studying the advantages of the so-called axi-, that is, 3D-thrust technology (turning - climbing - rolling), and a joint US - German program studies the turning-climbing thrust vectoring on the X-31 aircraft.

2. THRUST VECTORING FOR THE X-31 AIRCRAFT

The concept of aircraft engine thrust vectoring in order to enhance the aircraft maneuverability in close air combat of military aircraft has been present for ages, and the first research started by the application of the patent by von Wolff in 1944 on the AV-8A Harrier aircraft of the US Marine Corps in test flights in 1970.

In the mid-1970s the German engineers of the MBB company (today: DASA), have aimed their research toward the aircraft engine jet deflection for maintaining the maneuverability at greater angles of attack.

The main intention of their research was the need to make the high speed combat aircraft capable for maneuvers which would allow the missiles to stay within the visibility range during frontal attacks.

Some of the first simulations of air combat with the aim to determine the advantages of "post-stall" maneuverability have been performed at IABG (Industrieanlagen-Betriebsgesellschaft) in Ottobrunn in 1977.

The exceptionally positive results of this research on thrust vectoring have encouraged the German MBB company to apply vectored propulsion on a full-size model of a TKF combat aircraft, and the first public appearance followed at the Hannover exhibition in 1980.

Professor Benjamin Gal-Or (Tehnion Israel Institute of Technology, Department of Aeronautical Engineering) in the same year gave first lectures on vectored propulsion and sophisticated performance, and took part in the designing of the first vectored aircraft F-15 and F-16 in RPV-class (Remote Pilot Vehicle), whose test flights were performed in 1987 and 1989.

Although these experimental aircraft showed noted advantages from the point of view of maneuverability, the thrust vectoring concept was still not accepted in the defining of the EuroFighter 2000 project.

The rejection of the thrust vectoring concept for the new generation of combat aircraft did not discourage the German designers, and the MBB company started in 1983 the negotiations with the Rockwell company on construction of a demonstration aircraft of cheap technology, canard-delta configuration with a simple guide for thrust vectoring, similar to those used by F-14 aircraft for spin-maneuver test flights and F/A-18 HARV (High AoA Research Vehicle).

In 1985 Rockwell gets the contract for preliminary research of such an aircraft, and supported by mutual scientific cooperation with the USA and the European NATO countries, starts the X-31 project (as the first in a series of international experimental aircraft), in 1986 approved also by the US Congress.

The X-31A Rockwell/DASA aircraft was displayed at the 1995 Paris Le Bourget international exhibition, demonstrating the capability of outmaneuvering any of the existing combat aircraft.

3. THE CHARACTERISTICS OF X-31

The task of the experimental X-31 program was to improve combat aircraft efficacy in close air combat simulations, by enhancing both the conventional and airborne maneuverability, at and through critical angles of attack, by increasing the deceleration and resistance to negative loads as well as capability of turning the aircraft nose towards the target without changing the flight path.

As the most suitable engine for the research low weight aircraft the General Electric F 404 was chosen, basically with turbofan thrust of 71 kN, which proved tolerant to air flow distorsion.

In order to exceed the unit-based ratio of thrust and weight, normal weight during take-off was limited to approximately 65.2 kN with the allowed amount of fuel of 14.7 kN.

Wing with the thickness to chord ratio of 5.5% provides relatively low resistance and maximum computation speed of about Mach 1.3.

The fuselage has been reinforced for maneuvers within load limitations of +9g and -4g as well as flight at angles of attack of up to 70° at speed of 490 km/h.

In order to reduce the risk of engine stall, an actuator for lowering of inlet guide vane (IGV) by 26° at high angles of attack has been installed, and the inlet duct modified for the surge margin.

Rockwell has designed the fuselage, canard, the vertical fin, and the rudder, whereas MBB (DASA) took over the construction of the carbon fibre wings and metal substructure as well as carbon jet-deflection pedal.

Rockwell assembled the aircraft, and the German team installed the computer control system.

To reduce the costs many assemblies and components have been taken over from the F-16 Lockheed, F/

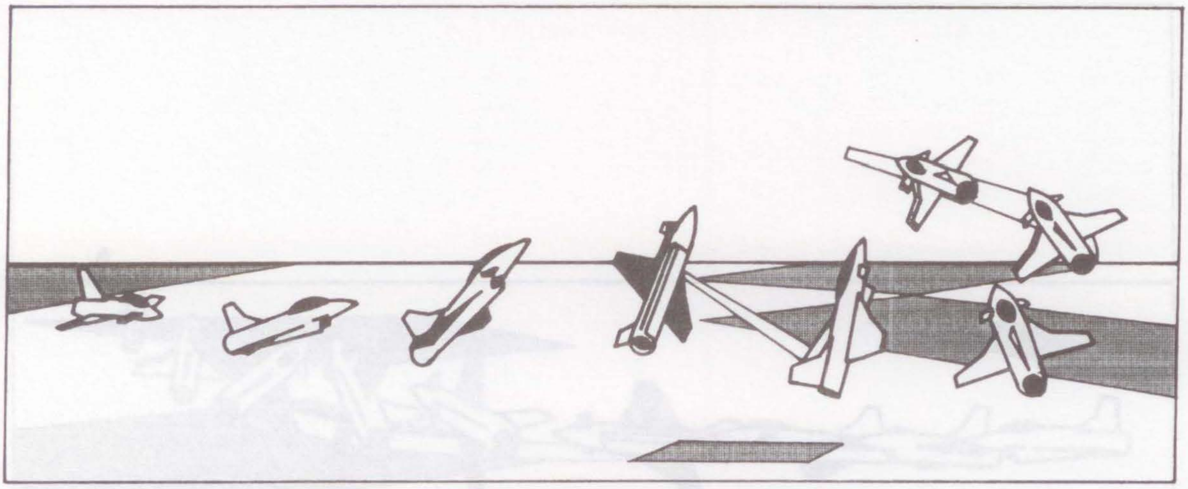

Figure 1 - **Herbst-maneuver**

A-18 Hornet McDonell Douglas and F-20 Tiger Shark aircraft.

The total costs of the program are estimated at 400 mill. Deutschmarks, out of which a quarter is provided by Germany.

4. MAIDEN FLIGHTS OF X-31A

The first test flight of X-31A was performed on 11 October 1990 in Palmadale, California, and already in the following test flight on 19 November 1991 the aircraft achieved the attitude control at 40°.

By the end of the experimental program, on 31 January 1995, X-31A performed more than 520 test flights.

On 18 September 1992, the X-31A aircraft performed for the first time a controlled flight at the angle of attack of 70°, and in the following year it performed the maneuver flight called "Herbst-maneuver".

The "Herbst-maneuver" sequence is marked by the initial lifting of the aircraft nose for climbing with the increase of the angle of attack to 70° resulting in the loss of lift, then by transverse turning of the nose by 180° before starting to dive and return of kinetic energy.

During the whole maneuver the engines run at retarded combustion at the highest available thrust.

Tests have confirmed the efficacy of thrust vectoring for controlling the climbing aircraft, and the results of experiments show the rise of controlability of the negative load by 150%, and turning control by factor 10.

Such significant improvement of control almost entirely eliminates the danger of deep spin and coming out of the rotating dive.

5. AIR COMBAT

In air combat simulations between X-31A and F/A-18 aircraft carried out in 1993, out of 94 simulated duels 78 were won by X-31A (82%), and 8 by F/A-18 (9%), whereas 8 were terminated without victory.

The analysis of simulations shows that the lethality ratio is 1:10 in favor of the vectored X-31A aircraft.

The comparable study of lethality factor, when X-31A did not use thrust vectoring, showed a ratio of 1:2.4 in favor of F/A-18 aircraft.

Experiments have also been carried out simulating the modified flight control system without the vertical fin, so that direction stability, balance and maneuverability were provided exclusively by transverse thrust vectoring.

These tests were based on the idea of the stealth aircraft concept i.e. of reducing the aircraft silhouette which would result in lower radar reflectivity.

The practical realization of this idea has been rejected for the moment, because of the possible adverse effects caused by wind blowing sidewise during landing.

6. POST-STALL MANEUVERS

At the 1995 Paris exhibition Le Bourget, the X-31A aircraft demonstrated, apart from the "Herbst-maneuver" also the "Mongoose-maneuver" which consists of the horizontal turning by 90° at the speed of 315 km/h at the angle of attack of 70° with maximum thrust and engine post-combustion. This maneuver is made possible by the application of the transversal jet-deflection.

Also, the "Helicopter loop" was demonstrated. The aircraft starts the maneuver at the speed of 410 km/h lifting the nose up to loading factor of 2g and maintaining the angle of attack of 20°, then back turning at the height of about 1370 m with the nose passing below the horizon and increasing the angle of attack up to 70°, and then the aircraft is turned by the transversal jet-deflection and pulled out at the height of 900 m.

The Rockwell researchers claim that by applying thrust vectoring in the next generation of combat air-

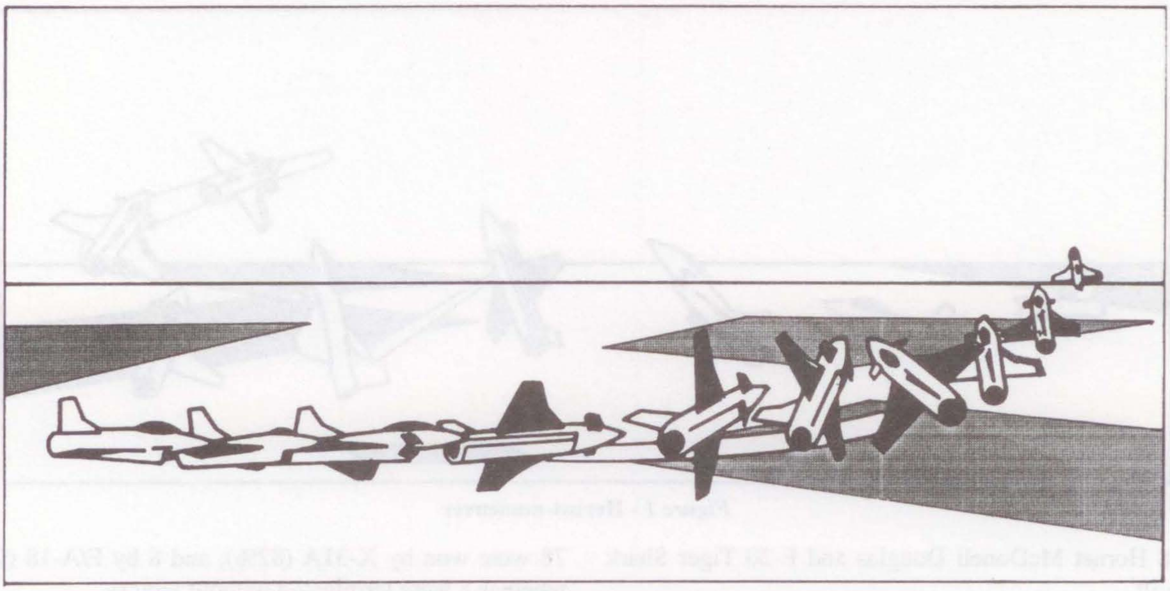

Figure 2 - **Helicopter loop**

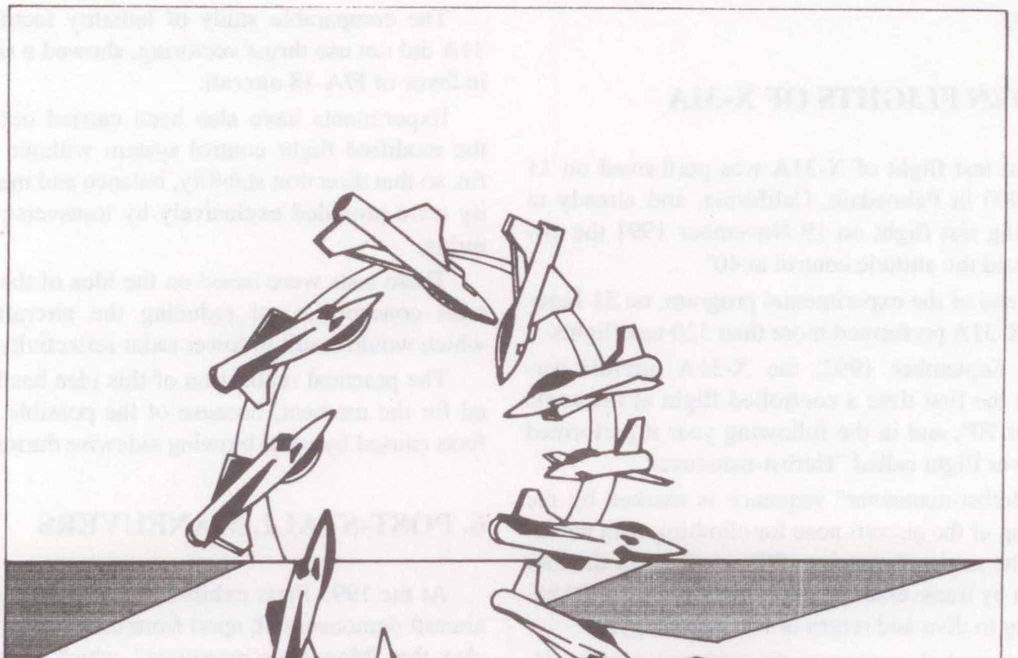

Figure 3 - **Mongoose-maneuver**

craft, the lethality ratio of 1:32 could be achieved in close air combat with conventional aircraft.

The main features of vectored propulsion are the maneuverability after the critical angle of attack, i.e. PST control, enhanced general aircraft attitude control and the possibility to direct the aircraft nose regardless of the flight path.

7. CONCLUSION

In the X-31A research program vectored propulsion has been applied for aircraft attitude control along two axes with no maneuverability along the third one.

Although of relatively cheap technology, the research aircraft X-31A has shown very good maneuverability and significant advantages in close air combat (with the use of conventional missiles) compared to any of the conventionally used combat aircraft.

The concept of vectored propulsion, that is, the concept of aircraft attitude control by engines jet-deflection has been up to now mainly studied for application in military aviation, but doubtless the results obtained by axi-propulsive technology are applicable in civil aviation as well, particularly in advanced take-off and landing flight performances.

Therefore, the expansion of the STOL (Short Take-off and Landing) and VATOL (Vertical Attitude Take-off and Landing) aviation can be expected in the future.

SUMMARY

Vectored propulsion is a new concept of aircraft attitude control by engines jet-deflection. Thrust vectoring research has become actualized during the last ten years, mainly for military application.

The carried out experimental projects confirm the effectiveness of the thrust-vectoring systems in both conventional aircraft attitude control and post-stall maneuverability enhancement.

Apart from military aviation, the results of thrust-vectoring research are applicable in civil aviation, especially in STOL and VTOL aircraft design.

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