UDK: 623.463.2:533.665
COSATI: 16-04

Aerodynamic Compensation of the Modified Guided Anti-Tank Missile Configuration

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Existing old generation anti-tank missiles with single shaped-charge warheads have limited applications against modern tanks with explosive reactive armor. In order to increase the efficiency, the improved versions of the warheads have been developed. The modification of the missile warhead is related to the front part of the missile, while the rear part with the motor and the missile control system remain the same for all modified missiles. The basic requirement is to use the existing guidance and the control system for both the original and the modified missile. The criteria to determine the required derivatives of the aerodynamic coefficients of the modified missile in order to compensate the change of the missile shape, mass and centre of mass, are defined in the paper. The initial values of the required derivatives of the aerodynamic coefficients are derived from the trimmed flight condition, while final tuning is done by the analysis of the stability of the guidance loop. Based on the required derivatives of the aerodynamic coefficients, the aerodynamic configuration of the missile is redesigned by the semi-empirical method and a CFD simulation. The calculated aerodynamic coefficients of the selected aerodynamic configuration are compared to the wind tunnel experiments. The validity of the design method given in the paper is proved by flight test experiments

Key words: **antitank missile, guided missile, semi-automatic guidance, missile aerodynamics, missile stability, aerodynamic derivatives, aerodynamic coefficients, CFD calculation, stability analysis, numerical analysis.**

Notation and symbols

A – Aerodynamic axial force $[\mathrm{N}]$,
a_z – Missile normal acceleration $[\mathrm{m/s^2}]$.
$C_{\tilde{N}\alpha}$ – Derivative of the normal force coefficient in the aero-ballistic axis system [-],
$C_{\tilde{m}\alpha}$ – Derivative of the pitching moment coefficient in the aero-ballistic axis system [-],
d – Reference length $[\mathrm{m}]$,
F_x – Axial component of the thrust $[\mathrm{N}]$,
F_c – Lateral component of the thrust (thrust vector control force) $[\mathrm{N}]$,
g – Gravity acceleration $[\mathrm{m/s^2}]$,
K_q – Gain of the missile transfer function $[\mathrm{rad/s}]$,
L – Lateral position of the missile relative to the line of sight $[m]$,
l_{TVC} – Distance between the lateral TVC force relative to the centre of mass $[\mathrm{m}]$,
Ma – Mach number [-],
m – Mass of the missile $[\mathrm{kg}]$,
$m_w\, z_w$, m_q, m_η, z_η – Dynamic coefficients.
M_a – Aerodynamic pitching moment $[\mathrm{Nm}]$,
N_a – Aerodynamic normal force $[\mathrm{N}]$,
Q – Dynamic pressure $[\mathrm{N/m^2}]$,
R – Distance from the target tracker to the missile $[\mathrm{m}]$,
S – Reference area $[\mathrm{m^2}]$,
T_{td} – Time delay time constant $[\mathrm{s}]$,
T_d – Time constants of the compensator $[\mathrm{s}]$,
t_{g0} – Time instance which correspond to the begin of the guidance$[\mathrm{s}]$,
t_{tf} – Total time of flight $[\mathrm{s}]$,
V – Missile velocity $[\mathrm{m/s}]$,
W_{td} – Time delay transfer function,
W_c – Transfer function of the compensator,
$W_\eta^{a_z}$ – Transfer function of the missile,
y – Deviation of the missiles trajectories in the horizontal plane [m],
α_{tr} – Trim angle of attack $[rad]$,
γ – Flight path angle $[rad]$,
Δh – Altitude of the missiles trajectories relative to the line of sight [m],
ς_n – Damping factor [-],
η – Equivalent command in the vertical plane $[-]$,
η_F – Angle of thrust vector deflection $[\mathrm{rad}]$,
θ – Pitch angle $[rad]$,
φ – Angular position of the missile line of sight in the inertial space $[\mathrm{rad}]$,

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φ_T – Angular position of the target line of sight in the inertial space [rad],

ω_n – Natural frequency [rad/s],

Introduction

AN anti-tank guided missile (ATGM) is primarily designed to hit and destroy heavily-armored military vehicles.

The first generation of ATGMs is based on a manual command to line of sight (MCLOS) guided system. The operator was required to simultaneously track the tank and the missile and to generate up-down and left-right commands on a joystick for sending them to the missile through the guidance wire. The kill probability of the missile system depends on the operator's skill and training and his capability to perform in the actual battlefield scenario. The guidance wire dispensation from the missile and the operator's response time for guiding the missile limited the missile speed to 100-180 m/s. The operator and the missile system were vulnerable to enemy counter actions during the prolonged flight time due to this low speed [1]. A general description of the MCLOS guidance system and the block diagram of the guidance loop are given in [2, 3].

The advantage of the second generation of ATGMs is semi-automatic command to line of sight (SCLOS). The role of the operator is to track the target. The guidance command is done automatically by the command generation system on the launcher. Based on the displacement of the missile relative to line of sight (LOS), the guidance system generates the commands and transmits guidance signals from the controller to the missile. The missiles are usually equipped with a magnesium flare in the base that automatically ignites upon launch and allows the SCLOS tracking system to estimate the missile displacement from the LOS. The operator's reduced role results, higher missile speed of 150-280 m/s, reduced wing size due to increased speed, tube launching, smaller minimum range and reduced dispersion. Though the missile speed could be increased to 150-280 m/s, still the flight time to the maximum range is 10-15 s and during this time and the target acquisition time, the system and the crew remain vulnerable to enemy counter fire. The exposure time of the system and the operating crew to enemy counter action, though reduced compared to the first generation of ATGM systems, is still unacceptable [1]. Pastrick gave a basic description of the SCLOS guidance system and a comparison relative to the other type of the guidance [2]. Garnel gave a detailed description of the LOS guidance system from the point of demanded lateral acceleration of the missile and design of the phase advance compensator in the guidance loop by classical automatic control [3]. Transfer function parameters of the missile and the transfer function of the kinematic elements are analyzed in detail in [3, 4].

The basic characteristics of the third generation of ATGM systems are fire and forget and top attack capabilities. Besides these basic improvements of the ATGM-3 system, the system requirements and design constraints include also lock-on-before-launch (LOBL) capability, high impact accuracy, tandem shaped charge warhead to defeat all armor including Explosive Reactive Armor (ERA), minimization of the minimum range, need to maximize impact angle for warhead effectiveness, composite airframe to minimize weight and a thermal battery with low activation time and long storage life for electrical power supply [1]. The optimal control theory has been extensively used to achieve the desired impact angle in order to maximize the warhead effect and attack a target's weak spot and to minimize the guidance error [5], [6]. Minimization of the control effort, by the application of the optimal control theory, has been widely considered in order to derive the impact angle control [7-9].

Countermeasures against ATGMs include spaced, perforated, and composite armor, explosive reactive armor (ERA), and active protection systems (APS).

Existing anti-tank missiles with single shaped-charge warheads have limited applications against modern tanks with reactive armor. In order to overcome this problem, a new range of improved warheads is developed. Tandem-charge missiles attempt to defeat ERA protected armor. A small initial charge sets off the ERA while the follow-up main charge attempts to penetrate the main armor.

With technological advances, the operational capabilities of the ATGM systems and their deployment platforms, both vehicle and helicopter-based, have increased considerably. Consequently, their costs have also gone up. The relative cost of the firing platform is typically 30-100 times that of the ATGM [1]. Modernization of both antitank missile guidance systems and missile warheads is very expensive. Partial modernization of existing antitank missiles can be done by replacing existing warheads with new, more effective ones. As a result, the weights, the centre of mass and the shape of modified missiles are not equal to original missiles. The design of a new modified missile has to be done in such a way that the existing guidance and control system can be used for the guidance of the original missiles and the modified ones as well.

The purpose of this paper is to present a new procedure for the design of the aerodynamic configuration of a modified antitank missile in order to obtain the same performance as the original missile. To achieve that, criteria for determining the derivatives of the aerodynamic coefficients of the modified missile are developed, in such a way that the modified missile can be controlled and guided by the existing guidance and control system. Practical importance of this approach is very significant - the same guidance and control system can be used with several missiles with different warheads. The method will be proved by detailed calculations and testing.

Basic requirements

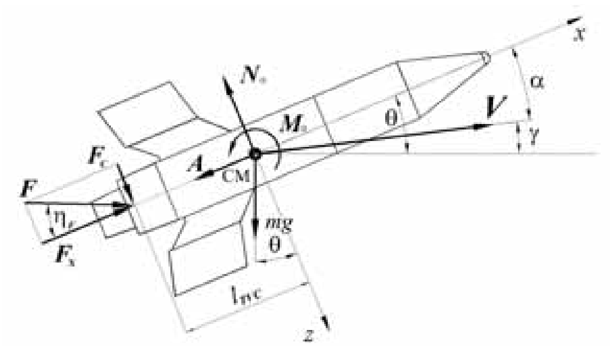
The antitank missile analyzed in this paper is composed of the warhead located in the front section (WH-A) and the rocket motor (M) with thrust vector control systems (TVC) located in the rear section of the missile (Fig.1). The missile dynamics of this type of the missile is analyzed in detail in [10-13].

Improvement of the anti-tank guided missile is related to the guidance system and the warhead. Modernization of both the antitank missile guidance system and the missile warhead is very expensive. Partial modernization of existing antitank missiles can be done by replacing existing warheads with new, more effective ones, while the rear section of the missile with the rocket motor and the missile thrust vector control (TVC) system remains the same. There are two types of the improved warheads (Fig.1). The shape of one improved warhead is equal to the original, while the explosive material is replaced with new, more effective (WH-B) material. The shape and the explosive materials of the second improved warhead (WH-C) are completely different from the original ones. The original missile is named *Model A,* while the modified versions of the missile are named *Model B* and *Model C*.

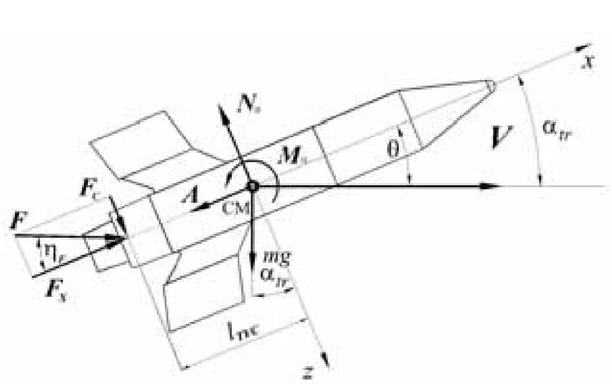
Figure 1: Modernization of the antitank missile with improved warheads

Trimmed flight condition

The flight of the missile in the vertical plane is defined by the flight path angle γ, the inclination angle θ and the angle of attack α (Fig.2a) [4, 14]. The missile analyzed in this paper is controlled by thrust vector control (TVC). The missile flight in the vertical plane is also exposed to the weight mg, the axial component of the thrust F_x and the average lateral thrust control force in the vertical plane F_c [13], the aerodynamic normal force N_a and the pitching moment M_a. One of the basic requirements for the antitank missile with the LOS guidance method is to fly along the LOS from the launching place to the target. The trimmed flight appropriate to the LOS guidance is a flight with zero flight path angle $\gamma = 0$ (Fig.2b).



a) Missile flight in the vertical plane



b) Missile flight in the vertical plane with zero flight path angle

Figure 2.

The condition of the trimmed flight is obtained by the equilibrium of the moments and the forces in the vertical plane. As a result of the trimmed condition, the total pitching moment is equal to zero.

$$QSd\,C_{\tilde{m}\alpha}\,\alpha_{tr} + F_c\,l_{TVC} = 0 \tag{1}$$

If we assume that the axial component of the thrust is equal to the aerodynamic axial force ($F_x = A$), the normal aerodynamic force is equal to the sum of the lateral control force and the missile weight

$$\left(F_c - QSC_{\tilde{N}\alpha}\,\alpha_{tr}\right)\cos\alpha_{tr} + mg = 0 \tag{2}$$

where: $Q = \rho V^2/2$ - dynamic pressure, ρ - air density, V - missile velocity, $S = d^2\pi/4$ - reference area, d - missile caliber, α_{tr} - trimmed angle of attack, $C_{\tilde{N}\alpha}$ - derivative of the normal force coefficient, $C_{\tilde{m}\alpha}$ - derivative of the pitching moment coefficient, F_c - lateral TVC force, l_{TVC} - position of the lateral TVC force relative to the centre of mass, m - missile mass, and g - gravity acceleration.

Since the modernization of the missile is related to the replacement of the warhead with a new, more effective one, the rear part with the motor and the missile control system remains the same. As a result of the modification, there are changes of the missile aerodynamic coefficients, the missile mass and the position of the lateral TVC force relative to the centre of mass. If the trimmed angle of attack is small ($\cos\alpha_{tr} \approx 1$), the trimmed angle of attack can be eliminated by substituting equation (1) into equation (2). As a result, the lateral TVC force can be written as a function of the aerodynamic coefficients, the mass of the missile and the position of the lateral TVC force.

$$F_c = -\frac{\left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)mg}{l_{TVC}/d + \left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)} \tag{3}$$

Since the control system is not changed by the modification, the lateral TVC force is the same for the original and the modified missiles at the analyzed time instance of the missile flight.

If the index "e" is used for the parameters of the existing and "m" for the modified missile configuration, the relation between the aerodynamic coefficients of the modified and the exiting missile configurations can be obtained from equation (3)

$$\begin{aligned}&\frac{\left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)_m m_m\,g}{l_{TVC\,m}/d + \left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)_m} = \\ &= \frac{\left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)_e m_e\,g}{l_{TVC\,e}/d + \left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)_e} = a\,m_e\,g\end{aligned} \tag{4}$$

where $a = \dfrac{\left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)_e}{l_{TVC\,e}/d + \left(C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}\right)_e}$.

The ratio between the derivatives of the pitching moment and the normal force coefficients $l_{cp}/d = -C_{\tilde{m}\alpha}/C_{\tilde{N}\alpha}$ is the distance from the centre of pressure to the centre of gravity (static margin). This ratio of the modified missile configuration can be determined from equation (4).

$$\left(\frac{C_{\tilde{m}\alpha}}{C_{\tilde{N}\alpha}}\right)_m = \left(a\,\frac{m_e}{m_m}\,\frac{l_{TVC\,m}}{d}\right)\bigg/\left(1 - a\,\frac{m_e}{m_m}\right) \tag{5}$$

The derivatives of the normal force and the pitching moment coefficients of the original missile with a known aerodynamic configuration are determined by aerodynamic calculations and wind tunnel experiments. Based on the known configuration of the original missiles *Model A*, the position of the lateral TVC force relative to the centre of the mass and the derivatives, the pitching moment and the normal force coefficients are known (Table 1). These parameters are given for two time instances: one time instance corresponds to the beginning of the guidance (t_{g0}) and the second one to the middle of the total time of flight ($t_{tf}\ /\ 2$).

Table 1 Basic characteristics of *Model A*

t	$\left(\frac{l_{TVC}}{d}\right)_e$	$C_{\tilde{m}\alpha}$	$C_{\tilde{N}\alpha}$
t_{g0}	1.94	-2.65	15.5
$t_{tf}\ /\ 2$	2.05	-4.33	15.5

The ratio between the derivatives of the pitching moment and the normal force coefficients $C_{\tilde{m}\alpha}\ /\ C_{\tilde{N}\alpha}$ of the modified missile are calculated by formula (5). For the centre of the gravity of the modified missiles (Model-B and Model-C), the desired values of $C_{\tilde{m}\alpha}\ /\ C_{\tilde{N}\alpha}$ can be obtained by adding the canards on the modified part of the missile (Fig.3).

Figure 3. Aerodynamic configuration of the antitank missile with improved warheads

In was proved by the analysis that there is a small change of the aerodynamic $C_{\tilde{N}\alpha}$ due to the change of the size and the position of the added canards. For the ratio $C_{\tilde{m}\alpha}\ /\ C_{\tilde{N}\alpha}$ calculated by formula (5) and the assumption that the derivatives of the normal force coefficients $C_{\tilde{N}\alpha}$ are equal to the values of the original missile (*Model A*), the required derivatives of the pitching moment coefficients $C_{\tilde{m}\alpha}$ are calculated for *Model B* and *Model C* (Table 2).

Table 2. Estimated pitching moment derivatives for *Model B* and *Model C*

t		$\frac{m_e}{m_m}$	$\left(\frac{l_{TVC}}{d}\right)_m$	$\frac{C_{\tilde{m}\alpha}}{C_{\tilde{N}\alpha}}$	$C_{\tilde{N}\alpha}$	$C_{\tilde{m}\alpha}$
t_{g0}	*Model B*	0.86	2.350	-0.18	15.5	-2.79
	Model C	0.91	2.345	-0.19	15.5	-2.95
$t_{tf}\ /\ 2$	*Model B*	0.84	2.500	-0.29	15.5	-4.49
	Model C	0.90	2.503	-0.32	15.5	-4.96

Stability of the guidance loop

The block diagram of the semiautomatic command line of sight SCLOS guidance loop is given in Fig.4. The angles φ and φ_T are the angular position of the missile and target line of sight in the inertial space. The position of the missile relative to the line of sight LOS is proportional to the angular misalignment between the missile and the target line of sight $L = R\left(\varphi_T - \varphi\right)$, where R is the distance from the target tracker to the missile [3].

Since the natural frequency of the actuator and the receiver transfer function is more than an order greater than the natural frequency of the missile, the influence of the actuator and the receiver dynamics can be neglected.

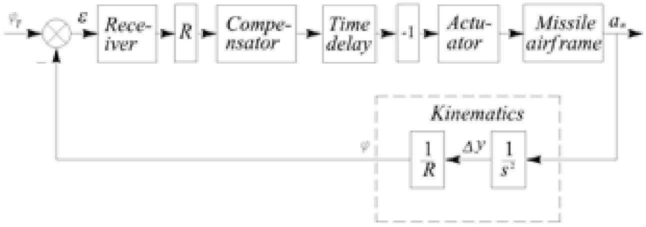


Figure 4. LOS guidance loop

The transfer function of the total time delay, necessary for the stability analysis of the guidance loop, is given in the next form

$$W_{td}(s) = e^{-T_{td}\,s} = e^{-0.1\,s}\,. \tag{6}$$

The transfer function of the guidance loop compensator is given as the first order phase advance element [15].

$$W_c(s) = \frac{T_d s + 1}{T_i s + 1} = \frac{s + 1}{0.28\,s + 1} \tag{7}$$

The primary aim of the analysis of the guidance loop with modified missiles is toachieve that the parameters of the stability of the guidance loop with modified missiles are equal to the parameters of the stability of the guidance loop with the original missile. So, the accuracy of the time constants T_{td}, T_d and T_i is not dominant. It is essential to keep the same values of these time constants for the analysis of the stability of the guidance loop with the original missile (*Model A*) and the modified ones (*Model B* and *Model C*).

The transfer function of the missile can be written as the second order element

$$W_\eta^{a_z}\left(s\right) = -V\,\frac{K_q\omega_n^2}{s^2 + 2\varsigma_n\omega_n s + \omega_n^2} \tag{8}$$

where: $\omega_n^2 = -\left(m_w V - z_w m_q\right)$ - natural frequency, $\varsigma_n = -\left(m_q + z_w\right)\big/2\omega_n$ - damping factor, $K_q = \left(z_\eta m_w - z_w m_\eta\right)\big/\omega_n^2$ - gain.

The dynamic coefficients m_w, z_w, m_q, m_η and z_η are the function of the derivative of the pitching moment coefficient $C_{\tilde{m}\,\alpha}$, the derivatives of the normal force coefficient $C_{\tilde{N}\,\alpha}$, the derivative of the damping pitching moment coefficient $C_{\tilde{m}\,q}$, the dynamic pressure $Q = \rho V^2\big/2$, the air density ρ, the missile velocity V, the reference area $S = d^2\pi/4$, the missile caliber d, the missile mass m and the missile moment of inertia I_y [2].

$$z_w = -\frac{QS}{mV} C_{\tilde{N}\alpha}, \quad z_\eta = \frac{\partial F_c/\partial\eta}{m},$$
$$m_w = \frac{QSd}{I_y V} C_{\tilde{m}\alpha}, \; m_q = \frac{QSd^2}{I_y V} C_{\tilde{m}q}, \; m_\eta = \frac{\partial M^F/\partial\eta}{I_y} \quad (9)$$

Since the product of the dynamic coefficients $z_w m_q$ is much lower than $m_w V$, the natural frequency can be written as the function of the product $m_w V$.

$$\omega_n^2 = -m_w V \quad (10)$$

As a result of the warhead modernization, the shape, the weights and the centre of mass positions of the modified missiles are not equal to those of the original one. Concerning the LOS guidance loop block diagram (Fig.3), there is a change only of the missile airframe.

It was shown that the aerodynamic derivatives $C_{\tilde{m}q}$ and $C_{\tilde{N}\alpha}$ are not significantly influenced by the change of the size and the position of the added canards. The derivative of the pitching moment coefficient $C_{\tilde{m}\alpha}$ can be only controlled by the size and the position of the added canards. The parameters of the missile transfer function are given in Table 4 for two time instances: the beginning of the guidance t_{g0} and the middle of the total time of flight $t_{tf}/2$.

Table 4. Transfer function parameters

	t_{g0}			$t_{tf}/2$		
	K_q	ω_n	ς_n	K_q	ω_n	ς_n
Model A	-0.644	3.13	0.124	-0.379	3.97	0.109
Model B	-0.640	2.95	0.107	-0.318	3.88	0.089
Model C	-0.828	2.46	0.125	-0.372	3.34	0.099

Stability of the guidance loop is verified by the Bode diagram plot of the open loop transfer function for three versions of the missile and the selected time instances of the missile flight. The Bode diagram plots of the open loop, for the selected missile configurations, are given in Fig.5 and Fig.6 for the time instances t_{g0} and $t_{tf}/2$.

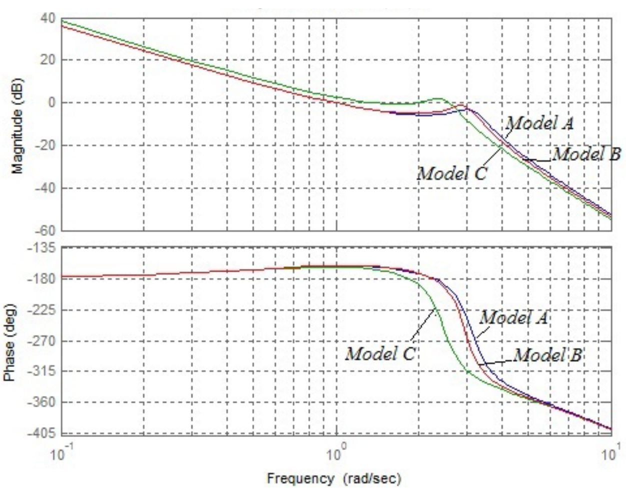


Figure 5. Bode diagram of the open loop transfer function at the beginning of guidance

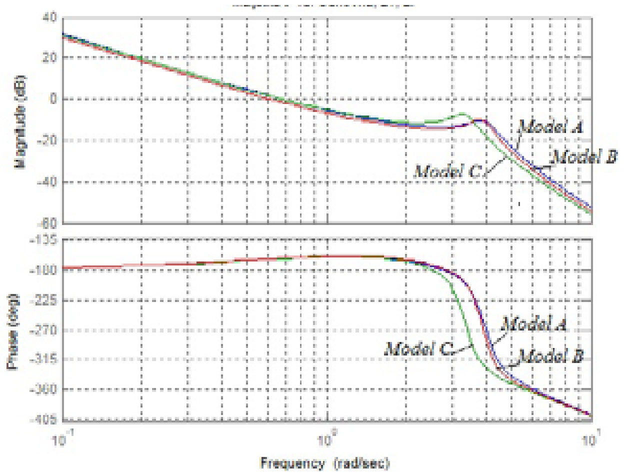


Figure 6. Bode diagram of the open loop transfer function in the middle of the flight

It can be seen from the Bode diagram that the phase margin is lower than 20°. It can be increased by increasing the ratio of the time constants T_d/T_i. Since the same guidance system is used for the original and modified antitank missile, without paying attention to the exact values of the crossover frequencies and phase margins of the open loop, it is necessary to provide that these stability parameters remains the same for the guidance system with analyzed versions of the antitank missiles.

Based on the Bode diagram of the open loop transfer function, it can be seen that the amplitude and the phase diagrams for *Model A* (original missile) and *Model B* are equal. It is also evident that the guidance loop for *Model C* is unstable for the time instance t_{g0} (beginning of guidance).

In order to obtain the stability of the guidance loop for *Model C*, the derivative of the pitching moment coefficient $C_{\tilde{m}\alpha}$ of *Model C* is increased by 30%. The transfer function parameters of the *Model C* missile airframe with the increased $C_{\tilde{m}\alpha}$ are given in Table 5.

Table 5. Transfer function parameters

	t_{g0}			$t_{tf}/2$		
	K_q	ω_n	ς_n	K_q	ω_n	ς_n
Model C	-0.609	2.63	0.144	-0.310	3.46	0.092

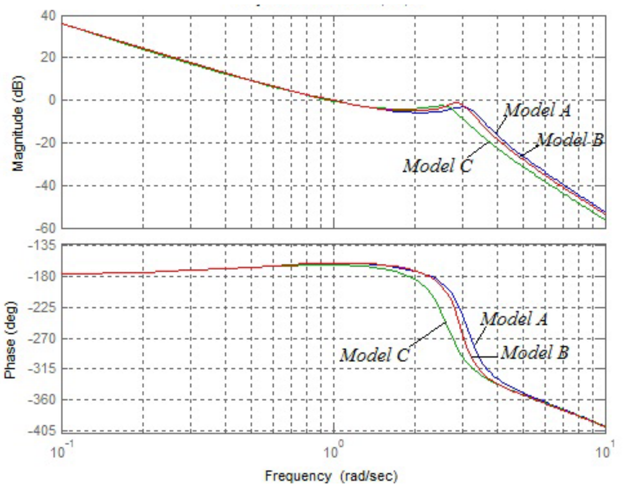


Figure 7. Bode diagram of the open loop transfer function at the beginning of guidance

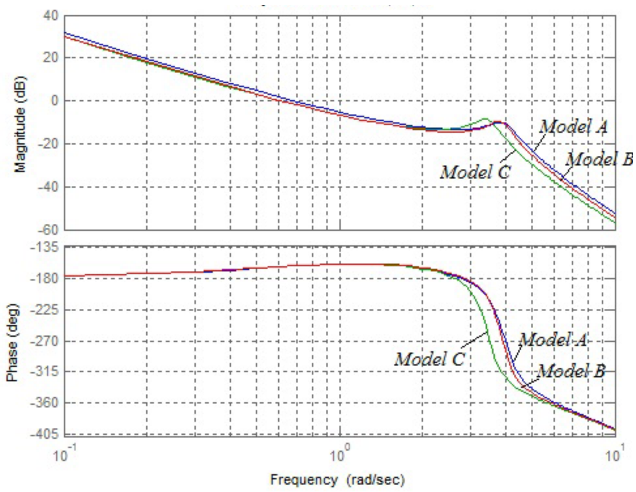


Figure 8. Bode diagram of the open loop transfer function in the middle of the flight

The Bode diagram plots of the open loop transfer function for the analyzed time instance are given in Figures 7 and 8. It can be seen that the stability of the guidance loop at the beginning of guidance is obtained for the increased value of $C_{\tilde{m}\alpha}$.

Aerodynamic configuration of the modified missiles

Design of the aerodynamic configuration

The initial aerodynamic configurations of the modified versions of the missile are determined by the semi-empirical theory [16, 17]. The size and shape of the canards are determined by the try and verify method with DMAC software [18].

Since this semi-empirical method is not appropriate for complicated aerodynamic configurations, the final aerodynamic configurations of the modified versions of the missile are determined by CFD simulation [19] and wind tunnel experiments.

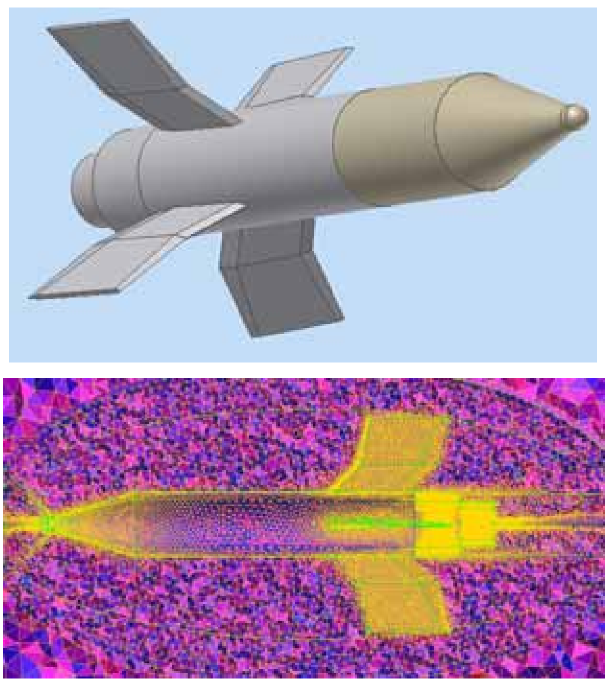


Figure 9. *Model A* - Solid model and Computational Domain Grid

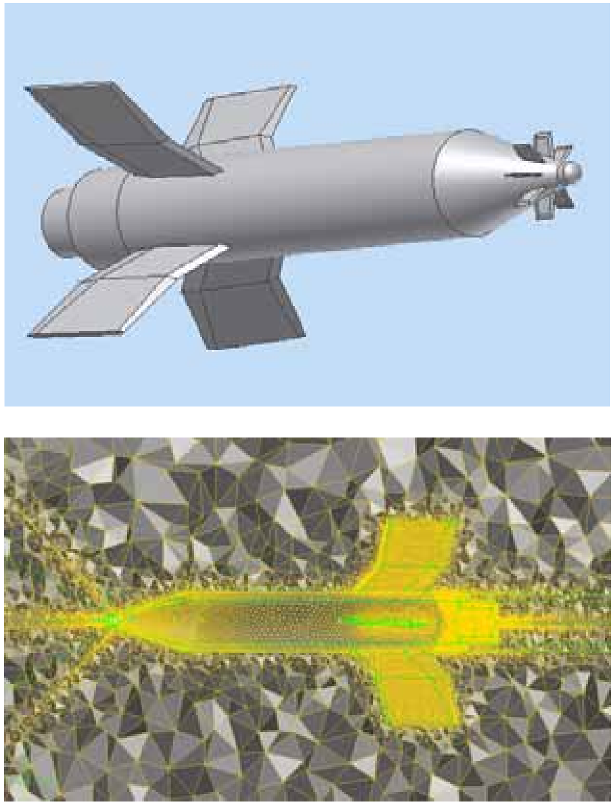


Figure 10. *Model B* - Solid model and Computational Domain Grid

The solid model of the missile is done by INVENTOR software. The control volume in the shape of an ellipsoid with the major axis three times greater than the length of the missile and the minor axis sixteen times greater than the missile diameter is done by GAMBIT software [20]. The unstructured mesh composed of tetrahedral elements is generated in the control volume.

The figure of the solid model and the volume mesh in the cross-sectional view is shown in Figures 9 - 11.

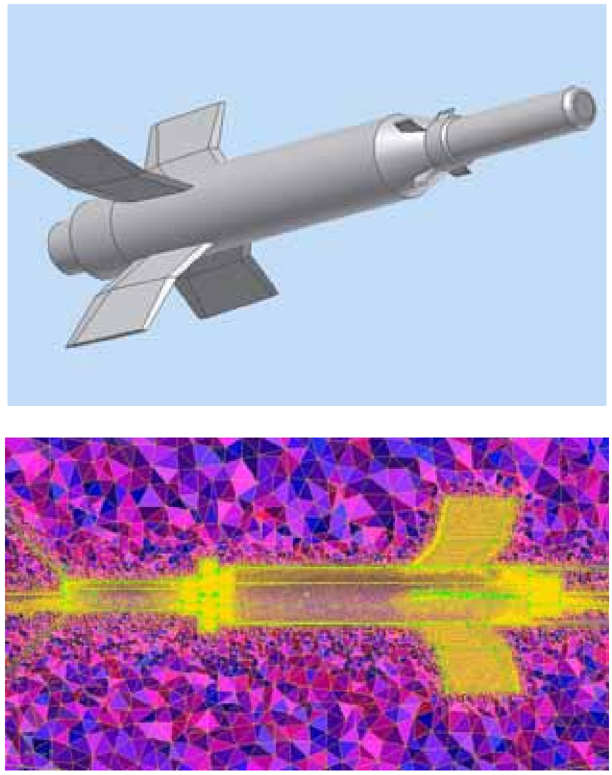


Figure 11. *Model C* - Solid model and Computational Domain Grid

The FLUENT commercial flow solver was used to compute the normal force and the pitching moment coefficients and the flow field around the missile model [20]. The density-based, explicit, compressible, unstructured-mesh solver was used. A modified form of the k- ε two-equation turbulence model (realizable k- ε) was used in this study. This turbulence model solves transport equations for the turbulence kinetic energy, k, and its dissipation rate, ε.

The boundary conditions were as follows. Downstream, upstream, and outer radial boundaries were set as far-field (characteristics-based inflow/outflow), with sea-level temperature and pressure free stream conditions (300 K, 101325 Pa). The Mach number was $\mathrm{Ma} = 0.35$.

Convergence was determined by tracking the change in the flow residuals and the aerodynamic coefficients during the solution. The solution was deemed converged when the flow residuals had been reduced at least 2 orders of magnitude and the aerodynamic coefficients had changed less than about $2\,\%$ over the last 100 iterations.

Wind tunnel measurements

The wind tunnel measurements of all three missile models were done in the continual type T-35 large subsonic wind tunnel of the Military Technical Institute (Fig.12). The test section has an octagonal cross-section. The length, the width and the height of the wind tunnel test section are 5.5 m, 4.4 m and 3.23 m, respectively. The range of the Mach number, which can be achieved with a fan only, is from 0.1 to 0.52, and with a combination of the fan and the injector is from 0.52 to 0.8.

Model A

Model B

Model C

Figure 12. Missile model in T-35 wind tunnel test section

The test program included the measurements of the forces and moments for Mach number $\mathrm{Ma} = 0.35$ and the angles of attack in a range of $-10^{\circ} \le \alpha \le 10^{\circ}$. The wind tunnel models for all three missiles were full scale models with a rear support.

Comparison of CFD calculation and wind tunnel measurements

The normal force and the pitching moment coefficients calculated by FLUENT and measured in the wind tunnel as a function of the angle of attack for all three analyzed models are given in Figures 13 - 15.

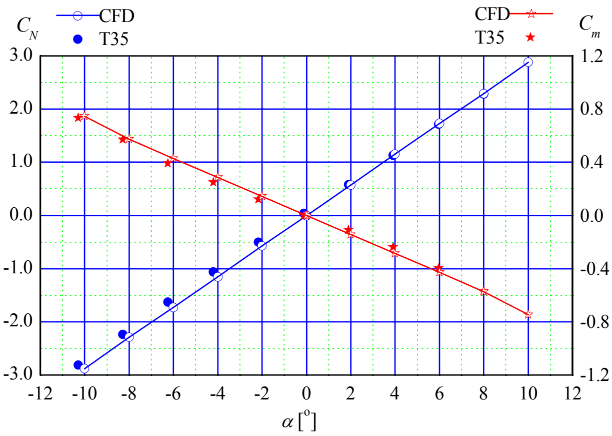


Figure 13. *Model A* - Normal force and pitching moment coefficients

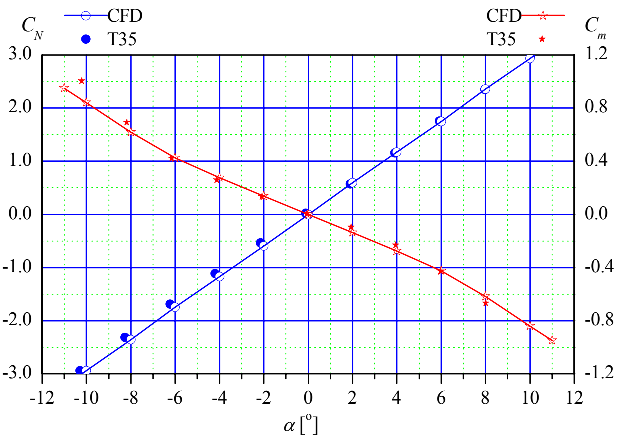


Figure 14. *Model B* - Normal force and pitching moment coefficients

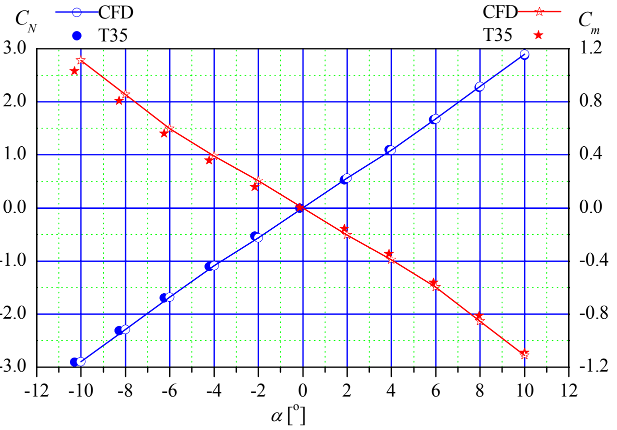


Figure 15. *Model C* - Normal force and pitching moment coefficients

The dispersion of the measured aerodynamic coefficients relative to the ones calculated by CFD FLUENT software is given by the standard deviation.

$$\sigma_{C(\tilde{N},m)} = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}\left(C_{(\tilde{N},\tilde{m})\exp}(i) - C_{(\tilde{N},\tilde{m})cfd}(i)\right)^2} \qquad (11)$$

The standard deviations ($\sigma_{C_{\tilde{N}}}$, $\sigma_{C_{\tilde{m}}}$) and the relative standard deviation for three analyzed models are given in Table 6. The relative standard deviation is obtained by dividing the standard deviation with the absolute values of the maximum measured aerodynamic coefficients. The best agreement between the calculated and the measured normal force coefficients is obtained for Model C $\sigma_{C_{\tilde{N}}} / |C_{\tilde{N}\max}| = 1.78\%$ and the worst for Model A $\sigma_{C_{\tilde{N}}} / |C_{\tilde{N}\max}| = 4.03\%$. The relative standard deviations for the pitching moment coefficients are between 5-6%.

Table 6. $\sigma_{C_{\tilde{N}}}$ and $\sigma_{C_{\tilde{m}}}$ for three analyzed models.

	Model A	Model B	Model C
$\sigma_{C_{\tilde{N}}}$	0.113	0.072	0.052
$\frac{\sigma_{C_{\tilde{N}}}}{\lvert C_{\tilde{N}\max}\rvert}$[%]	4.03	2.26	1.78
$\sigma_{C_{\tilde{m}}}$	0.0368	0.0573	0.0638
$\frac{\sigma_{C_{\tilde{m}}}}{\lvert C_{\tilde{m}\max}\rvert}$[%]	5.02	5.71	5.84

Flight experiments

The validity of the design method, given in the paper, was proved by the flight test. The original and modified missiles were launched from the launching vehicle and guided by the same semi-automatic guidance system to the target. All three missiles were successfully guided to the target.

The projections in the vertical and horizontal planes of the missile lateral displacement relative to the line of sight (LOS) of the original and modified missiles are given in Fig.16. It must be mentioned that the LOS was not fixed for all three experiments, but it was moved during the missiles flight depending on the decision of the operator.

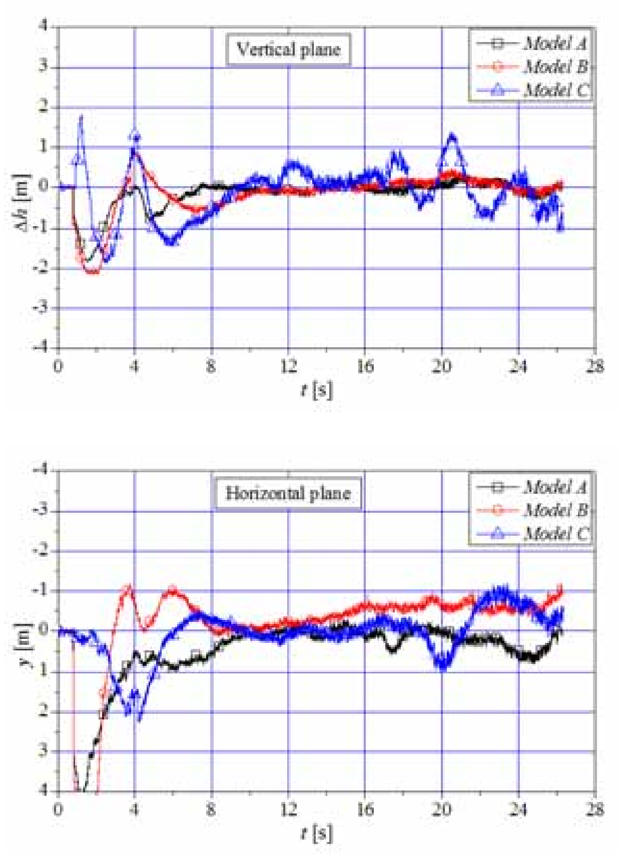


Figure 16. Projections in the vertical and horizontal planes of the missiles trajectories relative to the LOS

Conclusion

Existing old generation anti-tank missiles with single shaped-charge warheads have limited applications against modern tanks with reactive armor. In order to overcome this problem, a new range of improved warheads is developed.

The antitank missile analyzed in this paper is composed of the warhead located in the front section and the rocket motor with the thrust vector control systems (TVC) located in the rear section of the missile.

Based on the request for partial modernization of the guided anti-tank missile, the aerodynamic compensation of the modified missile configuration and the inertial characteristics is analyzed in the paper in such a way that the existing guidance and control system can be used for the guidance of the original and modified missiles as well.

The aerodynamic configurations of the modified missiles are determined in three steps.

In the first step, based on the known inertial and aerodynamic characteristics of the original missiles, the required derivatives of the modified missile are determined by applying the theory of trimmed flight. The trimmed flight of the antitank missile is obtained by the zero flight path angle condition. Having in mind that the lateral thrust control force is not changed by the modification of the missile, the derivatives of the pitching moment of the modified missile are determined as a function of the aerodynamic characteristics of the original missile and the inertial characteristics of the original and modified missiles.

In the second step, the derivatives of the aerodynamic coefficients of the modified missiles previously determined with the analysis of the trimmed flight are used for the stability analysis of the guidance loop. The stability analysis of the guidance loop is done for two characteristic points of the missile trajectory: the beginning of the guidance and the middle of the flight. The amplitude and the phase diagram of the guidance loop of both the modified and original missile are compared in order to ensure the same gain and phase margins. Since the natural frequency of the actuator and receiver transfer functions is more than an order greater than the natural frequency of the missile, the influence of the actuator and receiver dynamics is neglected.

The derivatives of the aerodynamic coefficients determined in the first two steps are the required values for the design of the aerodynamic configuration of the modified missiles.

In the third step, the aerodynamic configurations of the modified missiles are determined by semi-empirical software, CFD simulation and wind tunnel experiments. In order to obtain the required derivatives of the pitching moment and the normal force coefficients, the canards are added on the forward section of the missiles. The results of the CFD calculations show good agreement with the results of the wind tunnel experiments for all three versions of antitank missiles. It is also shown that the normal force coefficients of the modified missiles are equal to the normal force coefficients of the original missile. The size and the shape of the added canards do not influence the normal force coefficients.

The dispersion of the measured aerodynamic coefficients relative to the ones calculated by CFD FLUENT software is given by the standard deviation. The relative standard deviation is obtained by dividing the standard deviation with absolute values of the maximum measured aerodynamic coefficients. The best agreement between the calculated and the measured normal force coefficients is obtained for *Model C* (relative standard deviation is 1.78%) and the worst for *Model A* (relative standard deviation is 4.03%). The relative standard deviations for the pitching moment coefficients are between $5 \div 6\%$ for all three models.

The validity of the design method, given in the paper, was proved by the flight test of the modified versions of the antitank missile. The guidance of the modified missile was done by the guidance system used for the guidance of the original missile.

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Received: 28.01.2014.

Aerdinamička kompenzacija modifikovane konfiguracije protivtenkovske vođene rakete

Protivtekoske rakete sa kumulativnom bojevom glavom starije generacije imaju ograniičenu upotrebu protiv modernih tenkova sa aktivno reaktivnim oklopom. Za povećanje efikasnosti razvijene su poboljšane verzije bojevih glava. Jedan od načina modernizacije postojećih protivtenkovskih raketa se odnosi na zamenu bojeve glave na prednjem delu rakete dok zadnji deo sa sistemom za upravljanje rakete ostaje nepromenjen. U radu su definisani kriterijumi za određivanje potrebnih derivativa aerodinamičkih koeficijenta modifikovane rakete sa ciljem da koristi postojeći sistem za vođenje i upravanje. Početne vrednosti derivativa aerodinamičkih koeficijenata su određeni iz uslova trimovanog leta. Podešavanje zahtevanih vrednosti derivativa aerodinamičkih koeficijenata je ostvareno analizom stabilnosti petlje vođenja. Na osnovu zahtevanih vrednosti derivativa aerodinamičkih koeficienata određena je aerodinamička šema rakete primenom semiempirijskih metoda, numeričke aerodinamike i merenja u aerotunelu. Efikasnost izložene metode za kompezaciju promene mase, centra mase i oblika modifikovane rakete promenom aerodinamičke šeme potvrđena je u realnim letnim ispitivanjima.

Ključne reči: **po raketa, vođena raketa, poluautomatsko vođenje, aerodinamika rakete, stabilnost rakete, aerodinamički derivativi, aerodinamički koeficijenti, analiza stabilnosti, numerička analiza, modifikacija.**

Аэродинамическая компенсация изменённой конфигурации противотанковой управляемой ракеты

Противотанковые ракеты с кумулятивными боеголовками старших поколений уже имеют ограниченное пользование и применение против современных танков с активной реактивной защитой - броней. Для повышения эффективности разработанны усовершенствованные версии боеголовок. Один из способов модернизации существующих противотанковых ракет относится к замене боезарядов на передней части ракеты, пока последняя часть системы управления ракет остается неизменной. Эта статья определяет критерии определения аэродинамических производных коэффициентов модифицированных ракет, чтобы использовать существующую систему управления. Начальные значение производных аэродинамических коэффициентов определяются из условия подстриженного полёта. Установка требуемых значений производных аэродинамических коэффициентов достигается путём анализа стабильности системы петли управления. На основании требуемых значений производных аэродинамических коэффициентов определена аэродинамическая схема ракеты с использованием полуэмпирических методов, численной аэродинамики и измерения в аэродинамической трубе. Эффективность показаного метода компенсации изменений массы, центра массы и формы модифицированных ракет, меняющихся аэродинамической схемой, была подтверждена в реальных лётных испытаниях.

Ключевые слова: **противотанковая ракета, управляемая ракета, полуавтоматическое управление, аэродинамика ракеты, стабильность ракеты, аэродинамические производные, аэродинамические коэффициенты, анализ устойчивости, численный анализ, модификация.**

Compensation aérodynamique de la configuration modifiée du missile antichar guidé

Les missiles antichars à ogive cumulative de vieille génération ont l'emploi limité contre les chars modernes au blindage réactif. Pour augmenter l'efficacité on a développé les versions améliorées des ogives. La modernisation des missiles antichars consiste au remplacement de l'ogive frontale du missile alors que la partie arrière contenant le système de guidage reste inchangée. Dans ce travail on a défini les critères pour la détermination des dérivées nécessaires des coefficients aérodynamiques du missile modifié dans le but d'utiliser le système existant du guidage et du contrôle. Les valeurs initiales des dérivées des coefficients aérodynamiques ont été déterminées à partir des conditions du vol géré. Le réglage des valeurs exigées pour ces dérivées a été obtenu par l'analyse de la stabilité de la boucle de guidage. A la base des valeurs exigées des dérivées des coefficients aérodynamiques on a établi le schéma aérodynamique du missile à l'aide de méthodes semi empiriques, de l'aérodynamique numérique et du mesurage dans la soufflerie. L'efficacité de la méthode présentée pour la compensation du changement de masse, du centre de masse et de la forme du missile modifié par le changement du schéma aérodynamique a été confirmé.

Mots clés: **missile antichar, missile guidé, guidage semi automatique, aérodynamique du missile, stabilité de missile, dérivées aérodynamiques, coefficients aérodynamiques, analyse de stabilité, analyse numérique, modification.**