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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF AERODYNAMIC CHARACTERISTICS OF SPIN STABILIZED PROJECTILE

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Abstract: *The paper presents the numerical and experimental research and the analysis of the aerodynamic coefficients of the spin stabilized projectile. The numerical prediction method of aerodynamic coefficients is performed with CFD (Computational Fluid Dynamics) steady RANS (Reynolds Averaged Navier Stokes equation) method, four different models of turbulence and three different types of mesh. The semi-empirical methods are performed to predict the values of aerodynamic coefficients and derivatives. Experimental investigation is performed through aerodynamic wind tunnel tests and ballistic proving ground tests. The analyses of static aerodynamic coefficients are performed for subsonic, transonic and supersonic flow for different numerical and experimental research. The experimental proving ground test investigations are done using 3D ballistic radar for transonic and supersonic flight Mach numbers. The comparison of the numerically predicted values of the aerodynamic characteristics is accomplished through the 6-DoF flight model of 40 mm model of projectile in relation to the experimental results. The performed numerical techniques and methods on the structured type of mesh coupled with SST k-ω turbulence model are generated wide and qualitative aerodynamic description for projectile flight dynamic modeling, according to acquired experimental flight test results on the proving ground.*

Keywords: *aerodynamic coefficient, RANS, SST k-ω, experimental aerodynamic measurement, ballistic radar measurement*

1. INTRODUCTION

The accuracy and precision of a flight dynamic system depends on the proper model and the experimental results. The projectile as a flight dynamic system with the specific geometric and dynamic characteristics has to save the initial energy, during the flight through the atmosphere. The optimal aerodynamic shape of the projectile provides stable flight, decreasing drag and preserving velocity.

The classic spin stabilized projectile, observed in the research, as symmetric solid body, is consisted of the front part, nose (ogive shape), the middle cylindrical part (added rotating band) and the rear part, boat-tail (truncated cone shape). The specific dimensions and construction of the projectile determine the specific physical effects of the air flow. The main task is to determine influence of air flow to the projectile with adequate aerodynamic flow model and to verify calculated values in relation to the test values. The significance of the accurate prediction is that the symmetric projectile with initial velocity as the main energy resource, flies to target and the main influence is the air drag, depending on the flow regimes according to geometric parameters and boundary conditions.

The projectile is assumed to be either a body of revolution whose spin axis coincides with a principal axis of inertia, or a finned missile with three or more identical fins spaced symmetrically around the circumference of a body of revolution. In addition to the requirements of configuration and mass symmetry, the projectile is also restricted to small yaw flight along its trajectory. In conventional aircraft aerodynamics, the terms “pitch” or “angle of attack” refer to the aircraft’s nose pointing above or below its flight path; the terms “yaw” or “angle of sideslip” refer to the nose pointing to the left or right of the flight path, [1].

In the paper, the numerical research of the aerodynamic coefficients of axial force is described. The numerical and semi-empirical prediction models of the aerodynamic coefficients are provided by the different techniques and methods, according to the flow regime, and took into account the influence of aerodynamic parameters and their interaction.

2. AERODYNAMIC MODEL OF THE PROJECTILE

The aerodynamic axial force opposes the forward velocity of the projectile and that is the classical aerodynamic force of exterior ballistics as the "air resistance" or "drag". The aerodynamic force acting on projectile in the center of pressure is given by, [1,2],

$$X = q_\infty \cdot S \cdot C_x \quad (1)$$

where are,

$q_\infty = \dfrac{\rho_\infty V_\infty^2}{2}$, Dynamic Pressure,

$S = \dfrac{\pi d^2}{4}$, Reference Area of the Projectile,

C_x, Aerodynamic Coefficient of Axial Force,

ρ_∞, Air Density of the Free Stream and,

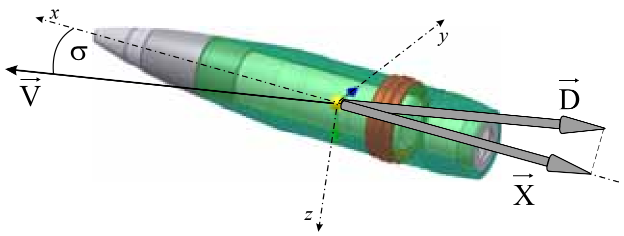
V_∞, Free Stream Velocity.

The axial aerodynamic coefficients, representing aerodynamic force depends on airflow parameters (Mach number, Reynolds number), aerodynamic velocity and the angle of attack.

The component of axial aerodynamic force *X*, and drag force *D*, are presented in Picture 1,

X – Axial Aerodynamic Force,

D – Drag Aerodynamic Force,



Picture 1. The Aerodynamic Force on Projectile

The axial aerodynamic force coefficient is given by (2) and depends on Mach number and the angle of attack σ, [1,2]. The force represents the main component of the total aerodynamic force (Drag),

$$C_x(Ma) = C_{x0}(Ma) + C_{x\sigma^2}(Ma) \quad (2)$$

The aerodynamic axial coefficient $C_x(Ma)$ depends on Mach number (e.g. Reynolds Number), according to the geometry parameters of the projectile, [1,2].

3. THE EXPERIMENTAL RESEARCH

The series of wind tunnel tests of the projectile model of 40 mm are performed in the T-38 wind tunnel [2,3] of the Military Technical Institute in Belgrade (VTI). The series of proving ground ballistic tests are performed in the facility of the Technical Test Center of Serbian Armed Force (TOC).

3.1. The wind tunnel tests

Projectile model of 40 mm mounted in the T-38 test section is shown in Picture 2.

Picture 2. Projectile in the wind tunnel test section, [2]

The T-38 test facility of Military Technical Institute in Belgrade is a blow down type pressurized wind tunnel with a 1.5m x 1.5m square test section [2,3].

The wind tunnel tests of the model are performed in the Mach number range from 0,2 to 3,0. The angle of attack was in the interval from –10 degrees to +10 degrees and roll angle was 0 degrees. The instrumentation and data acquisition system are used within VTI facility. The data reduction is performed after each run, using the standard T38-APS software package in use with the wind-tunnel facility. The reduction is done in several stages, [2,3]:

- Data acquisition system interfacing and signals normalization,
- Determination of flow parameters in the test section of the wind tunnel,
- Determination of model position (orientation) relative to test section and airflow,
- Determination of non-dimensional aerodynamic coefficients of forces and moments.

The stagnation pressure p_0 in the test section is measured by a Mensor quartz bourdon tube absolute pressure transducer pneumatically, connected to a Pitot probe in the settling chamber of the wind tunnel. The range of the used transducer was $7\cdot10^5$ Pa. The difference between the stagnation and static pressure (p_{st} -p_0) in the test section is measured in subsonic/transonic flow regime by a Mensor quartz bourdon tube differential pressure transducer, pneumatically connected to the p_0 Pitot probe and to the orifice on the test section sidewall. In transonic and supersonic flow regimes, the absolute pressure transducer of same type and range are used. The range of the transducers was $1{,}75 \cdot 10^5$ Pa. The atmospheric pressure p_{atm} is measured by a Mensor quartz bourdon tube absolute pressure transducer, pneumatically connected to the pressure port in the wind tunnel exhaust. The range of the transducers was $1{,}75 \cdot 10^5$ Pa. The stagnation temperature T_0 is measured by a custom-made RTD probe in the settling chamber of the wind tunnel. The pitching and rolling angle of the model are measured by NPL resolvers integrated in the model support mechanism. The accuracy of the pitching angle reading was 0,05 degrees and the accuracy of the rolling angle reading was 0,25 degrees, [2,3].

The aerodynamic forces and moments acting on the model are measured by ABLE 1.00 MKXXIIIA internal six-component strain gauge balance. The nominal load range of the balance was 2800 N for normal, 620 N for side force, 134 N for axial force, 145 Nm for pitching, 26 Nm for yawing moment and 17 Nm for rolling moment. The accuracy was approximately 0.25% F.S. for each component. The data acquisition system is consisted of a Teledyne 64 channels “front end” controlled by a PC computer. The front-end channels for flow parameters transducers were set with 30 Hz, fourth-order low pass Butterworth filters and appropriate amplification. The data from all analog channels are digitalized by a 16-bit resolution A/D converter with the overall accuracy of the acquisition system being about 0,05% to 0,1% F.S. of the channel signal range. All channels are sampled with the same 200 samples/s rate, [2,3].

Mach number Ma is calculated using the isentropic relation:

$$Ma = \sqrt{\frac{2}{\kappa - 1}\left(\left(\frac{p_0}{p_{st}}\right)^{\frac{\kappa-1}{\kappa}} - 1\right)} \tag{3}$$

The axial aerodynamic coefficient in the body axis system is calculated from the components of aerodynamic force X, as,

$$C_x = \frac{X}{q_\infty S} \tag{4}$$

3.2. The radar in-flight tests

The experimental in-flight tests are performed in the facility of the TOC, with system of equipment for field ballistic radar measurements and the instrumentation for GPS and atmospheric measurements.

The system of equipment for field radar measurements is consisted of the 3D ballistic radar, the acquisition system and the support system. The radar measurement system is based on Doppler principles, with monopulse phase comparison and range measurements through integrating range, Multi frequency ranging, Frequency modulated ranging and the comparison of principles. The range measurements are done by integrating velocity, according to Multi Frequency Continuous Wave (MF-CW) and Frequency Modulated Continuous Wave (FM-CW).

The performance of the radar system antenna:

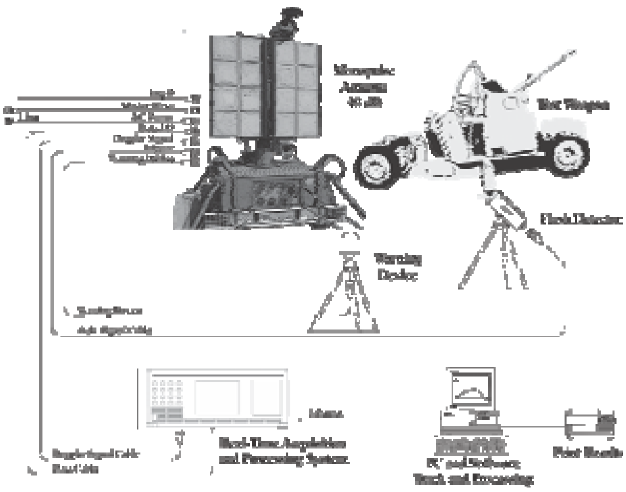
- Monopulse Phased Array Multi Frequency Doppler Radar – MFDR Antenna,
- Output Power: 120 Watts,
- Antenna Gain: 40 dB,
- Maximum Beam: 10°x10°,
- Minimum Beam: 1°x2°,
- Transmitter Type: Continuous Wave, synthesized solid state,
- Frequency: X-band, adjustable between 10400 and 10550 GHz,
- Noise figure: 3dB,
- Transmitter Type: Multiple Frequency CW, solid state PLO, Operation Mode: CW, FM-CW, MF-CW, RF
- Bandwidth: 10 MHz

The measurement is consisted of the set proving ground test of trajectory flight measurements at measured initial conditions of flight and conditions of atmosphere, Picture 3. The results of the measurement are represented as time-dependent values of position of the flight body, in polar coordinates, with time resolution grade of 10^{-3} s.

The values of the aerodynamic axial coefficient is calculated on the basis of the negative acceleration, i.e. retardation of the body in relation to the local coordinate frame, bounded at the initial point of the flight, according to the following equation,

$$C_x\left(Ma_{i,sr}\right) = \frac{V_i - V_{i+1}}{V_i + V_{i+1}} \frac{4 \cdot m}{\rho_{i,sr} \cdot S \cdot \left(x_{i+1} - x_i\right)} \tag{5}$$

where are, m is mass of flight body – projectile, S is cross-section area of projectile, V_i and V_{i+1} are measured flight velocities, x_i and x_{i+1} are horizontal distances, $\rho_{i,sr}$ is average value of air density and $Ma_{i,sr}$ is average value of flight Mach number.



Picture 3. Trajectory Flight Measurement

The ballistic flight experimental test is consisted of ten measurements of 40 mm projectile at five different elevation angles.

4. THE NUMERICAL AND SEMI-EMPIRICAL RESEARCH OF AERODYNAMIC CHARACTERISTICS

The research model is the model of the spin stabilized projectile with following characteristics:

– Reference diameter (caliber) 40 mm,
– Total length ~ 5,2 caliber,
– Nose length, ~ 3 caliber,
– Boat tail length, ~ 0,5 caliber,
– Center of gravity from nose, ~ 3,3 caliber.

On the basis of the geometric and dynamic characteristics of the research model and according to the performed methods, the aerodynamic coefficients are derived. The graphics of the characteristics of the aerodynamic coefficients in relation to Mach number are given in the paper. Mach numbers represents the characteristics of flow field, i.e. the velocity of the projectile in relation to the total atmosphere conditions.

The research deals with numerical simulation of static aerodynamic coefficients. The governing equations are given on the basis of Reynolds Averaged Navier-Stokes equations, of the steady state flow. The derivatives of the aerodynamic coefficients are improved in relation to the measurements and results of the experiments. In this chapter the results of the numerical calculation of the aerodynamic coefficients are described, [4,5].

The research of aerodynamic data, presented in the paper, is consisted of two aerodynamic predictions: the semi-empirical aerodynamic predictions (ADP0), [2,3] and numerical predictions with numerical software of Computational Fluid Dynamics (CFD) incorporated into Ansys Fluent software [4].

The prediction research model of body was 0,04 m referent diameter and 5,2 referent diameter long. The semi-empirical aerodynamic predictions (ADP0) are performed using aerodynamic prediction technique presented at [2]. The results of the aerodynamic prediction technique ADP0 are axial force aerodynamic coefficients at zero yaw. The values of zero-yaw drag coefficient are consisted from the results of the components, according to the body sections and flow characteristics.

The aerodynamic numerical prediction simulations of the research model of projectile are performed using the CFD code. The governing equation is based on Reynolds Averaged Navier Stokes equations (RANS), given by equations for the conservation of mass and momentum, and presented in the following forms [4,5,6,7]:

Continuity,

$$\frac{\partial}{\partial x_i}\left(\bar{\rho}\bar{u}_i\right)=0\,, \qquad (6)$$

Momentum,

$$\frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{u}_i\bar{u}_j\right)= -\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial \bar{u}_i}{\partial x_i}\right)\right]+ \frac{\partial}{\partial x_j}\left(-\bar{\rho}\overline{u_i' u_j'}\right) \qquad (7)$$

where p is mean pressure, ρ is mean density, μ is molecular viscosity, u_i and u_j are mean velocities. Reynolds stresses were given at term,

$$-\bar{\rho}\overline{u_i' u_j'}=\mu_t\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial \bar{u}_i}{\partial x_i}\right)\delta_{ij}\,, \qquad (8)$$

where μ_t is turbulent (eddy) viscosity, k is turbulent kinetic energy. To correctly account for turbulence, Reynolds stresses are modelled in order to achieve closure of (7). The method of modelling employed utilizes the Boussinesq hypothesis to relate the Reynolds stresses to the mean velocity gradients within the flow.

The numerical researches are provided with four numerical results, presented in the paper as CFD1, CFD2, CFD3 and CFD4, and described at Table 1.

Table 1. Numerical predictions

Mark	*Domain*	*Mesh Type*	*Number of Cells*	*Turbulence Model*
CFD1	2D	Quad mapped	$75\cdot10^3$	2 equation k-ε RNG
CFD2	2D	Hybrid/ Tri-Quad	$19\cdot10^4$	2 equations k-ε RNG
CFD3	2D	Hybrid/ Tri-Quad	$21\cdot10^4$	3 equations t-k-kl-ω
CFD4	3D	Hexahedra	$18\cdot10^5$	2 equations SST k-ω

The set of numerical simulations CFD1, with one-equation turbulence model Spalart-Almaras, in 2D numerical domain, consisted of about 75 000 quadrilateral cells, is performed at three flow regimes (Boundary Layer of ~0,025 d size and 1,032 aspect ratio).

The set of numerical simulations CFD2, with two-equations turbulence model RNG *k-ε*, in 2D numerical domain consisted of about $19\cdot10^4$ triangle cells, is performed at three flow regimes (Boundary Layer of ~0,015 *d* size and 1,2 aspect ratio).

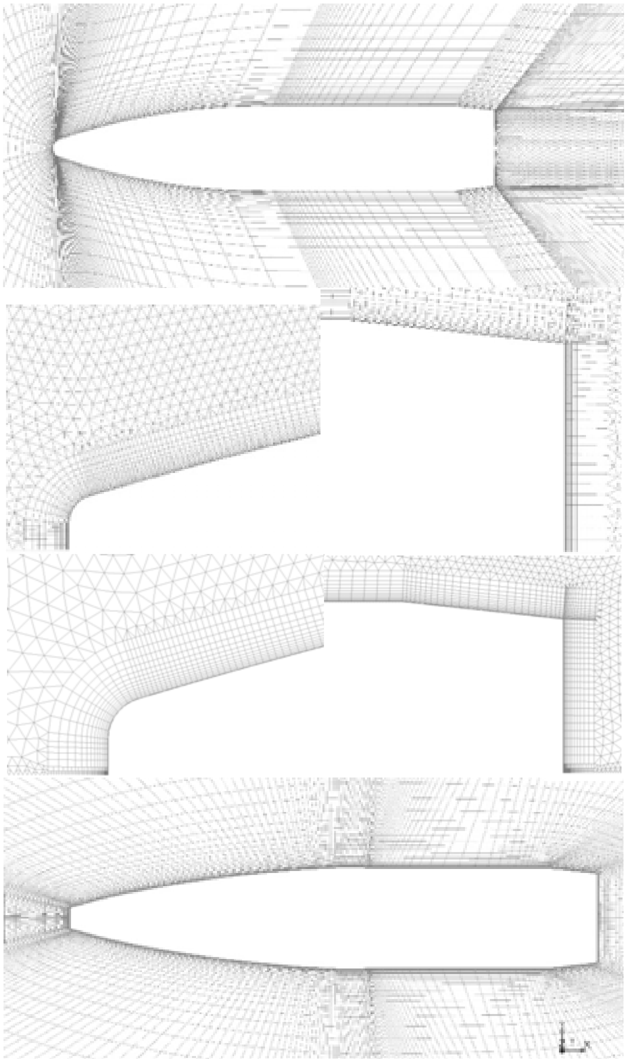
Third set of numerical simulations CFD3 in 2D numerical domain, consisted of about $21\cdot10^4$ triangle cells, is performed at three flow regimes, with three-equations turbulence model *t-k-kl-ω* (Boundary Layer of ~0,001 *d* size and 1,2 aspect ratio).

The fourth set of numerical simulations CFD4 is performed at three sonic regimes, in 3D numerical domain, consisted of about 1.8 million hexahedral cells, with two-equation turbulence model SST *k*- *ω* (Boundary Layer of ~0,0002 *d* size and 1,2 aspect ratio).

The applied turbulence models are, [4,5]:

- Spalart-Almaras, one equation turbulence model (CFD1),
- RNG (Re-Normalization Group) *k-ε*, where additional terms improve accuracy, and *ε* represents turbulence dissipation rate (CFD2),
- Transitional *t-k-kl-ω* model, where kl represents laminar kinetic energy (CFD3),
- SST (shear stress transport) *k-ω*, where the turbulent viscosity is computed through solution of two additional transport equations for the turbulent kinetic energy *k*, and either the turbulence specific dissipation rate, *ω*, (CFD4).

The numerical discretization of the computational domain around the model was designed with mentioned four types of mesh (Table 1). The computational domain for 2D and 3D meshes is created with longitudinal length of 75 to 80 referent diameter of model and lateral width of about 25 - 40 referent diameter of model. The spatial discretization schemes of the equations were second order upwind. The computational domains are presented in Picture 4.



Picture 4. The part of computational domains: a) CFD1, b) CFD2, c) CFD3, d) CFD4

The outer boundaries were set to the free stream conditions at standard atmosphere for the total temperature, $T = 288$ K and the total pressure $p = 100\ 000$ Pa. The inner boundary of the model was modeled as no-slip, isothermal wall boundary.

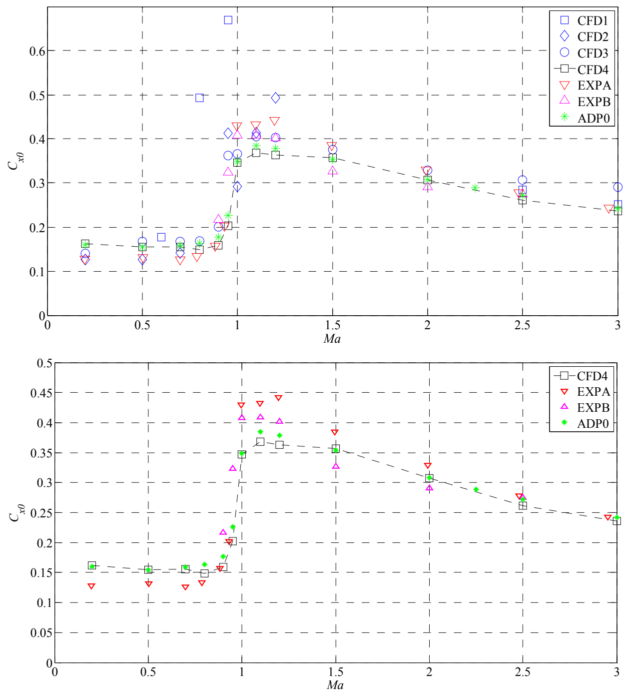
The criteria of convergence were constant values of aerodynamic coefficients of axial force, within last 100 iterations and the residuals below 10^{-6}, for CFD1, CFD2 and CFD3 simulations and bellow 10^{-4} for CFD4 simulations.

The results of computational fluid dynamic simulation was obtained through sets of separated calculations for different Mach numbers of three flow regimes and different values of angle of attack in the range of 0 to 10 degrees.

4. THE ANALYSIS OF RESULTS OF AERODYNAMIC AXIAL COEFFICIENT

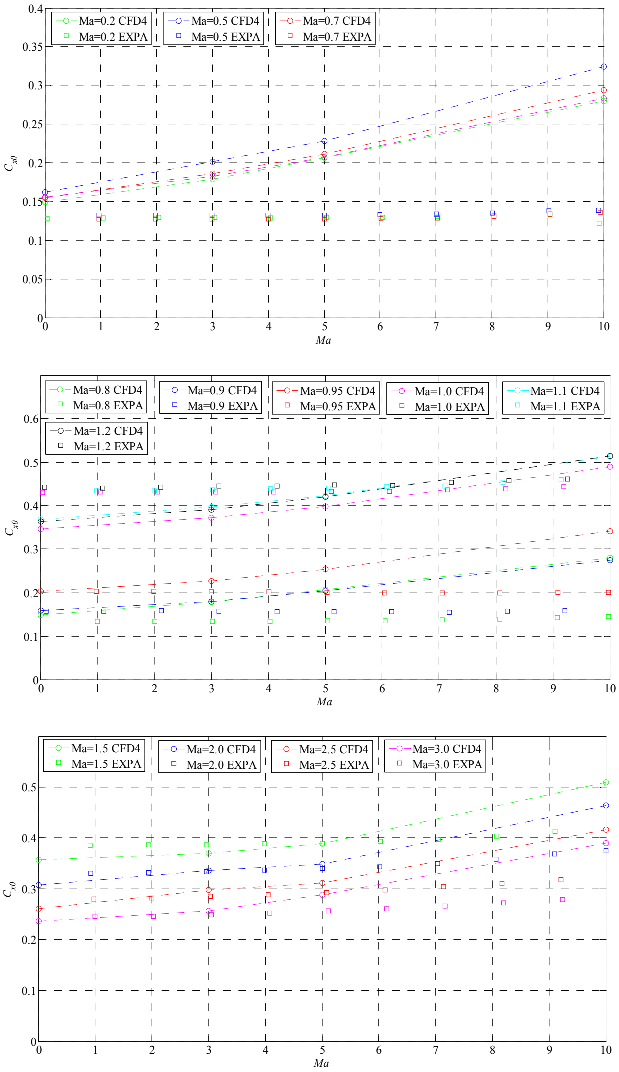
According to the performed research, results are presented as dependencies of flow regimes, i.e. Mach number, and also in relation to the angle of attack.

In Picture 5 was presented the axial aerodynamic coefficient in relation to Mach number. The results of CFD predictions are marked as CFD1 to CFD4. The experimental results are: EXPA for aerodynamic wind tunnel tests and EXPB for ballistic proving ground tests. The semi-empirical aerodynamic prediction results of zero-yaw drag coefficient are marked as ADP0.



Picture 5. Axial AD coefficient vs. Mach number

The CFD3 computational prediction in 2D domain is enable fast and qualitative results through all flow regimes. The CFD4 prediction is shown very good results, in 3D domain, and enabled the analyses of the coefficient in relation to the angle of attack. Further research based on CFD4 prediction is shown good agreement of other static and dynamic coefficients with experimental results.



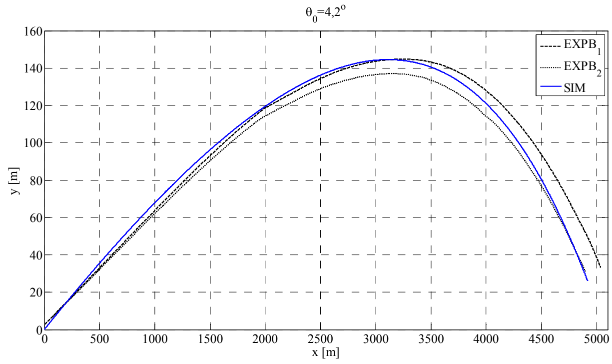
Picture 6. Axial AD coefficient vs. AOA
a) subsonic, b) transonic, c) supersonic regime

In Picture 6 are presented the results of axial aerodynamic coefficient of numerical prediction RANS SST-k-ω in 3D numerical domain (CFD4), and the aerodynamic wind tunnel tests EXPA, in relation to the angle of attack (AOA) for different Mach numbers, of three groups of flow regimes.

The differences between experimental and numerical results are caused by the limitation of the mounting measuring equipment on the model base, Picture 2.

The deviation of the results at the zero AOA are 3,6%, and increases with the values of AOA. The deviations are the smallest in the supersonic flow regime.

The agreement of the experimental field results of the trajectory and calculated aerodynamic coefficient with CFD4, are shown in Picture 7 ($EXPB_1$ and $EXPB_2$). The trajectory of projectile (SIM) is simulated with 6DoF model with the values of aerodynamic coefficient obtained from CFD4.



Picture 7. Trajectory in Vertical plane

5. CONCLUSION

The numerical researches of the aerodynamic coefficient are shown very good agreement with experimental results. The 3D numerical research with three equations SST-k-ω is shown qualitative results and enabled analysis in the relation to the angle of attack. Also, the numerical research in 3D numerical domain is very convenient for further research of the aerodynamic coefficient in relation to the angular velocities (spin) and angle of attack, separately and coupled.

The trajectory in-flight measurements are shown agreement with simulated trajectory based on the CFD aerodynamic results. The trajectory with all its elements, as velocity and angle, are shown same trend and value level.

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