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Missile aerodynamic coefficients accuracy assessment by semi empirical aerodynamic prediction codes and CFD Code FLUENT®

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Aerodynamic coefficients of the normal force and the pitching moment obtained by three programs (DMAC, NLMAC and FLUENT6) are compared with experimental data from the wind tunnel for three characteristic missile configurations. DMAC program is designed for the calculation of aerodynamic coefficient derivatives and it is based on semiempirical data. NLMAC program is based on the method of the equivalent angle of attack. The program calculates aerodynamic coefficients as a function of the angle of attack for a specified Mach number and control deflections. FLUENT6 is a solver for three-dimensional general transport equations of mass, momentum and energy. It is based on the finite volume method. General transport equations are derived and applied to each cell. There is a good agreement between the calculated value of aerodynamic coefficients and the experimental data.

Key words: **aerodynamics, computational fluid dynamics, derivatives of aerodynamic coefficients, method of the equivalent angle of attack.**

Notation and symbols

AR	– aspect ratio of the wing alone
Φ	– roll angle
C_N	– normal force coefficient
C_m	– pitching moment coefficient
d	– missile diameter
K_B	– body carryover factor for undeflected wing
K_W	– wing interference factor for the body incidence
k_B	– body carryover factor for wing deflection
k_W	– wing deflection factor
K_Φ	– wing interference factor due to roll angle
$\frac{\partial C_N}{\partial \alpha}$	– derivative of normal force coefficient
α	– angle of attack
δ	– wing deflection
Δf_v	– increment of the angle of attack due to vorticity
$\Delta \alpha_q$	– increment of the angle of attack due to the pitch rate
W_{ji}	– vorticity weight function
s_m	– semispan of the wing
V	– control volume
ρ	– density
$\mathbf{V}$	– velocity vector
$\boldsymbol{f}$	– body force per unit mass inside v
p	– pressure
$\boldsymbol{F}_{\text{viscous}}$	– viscous force exerted on the control surface
h	– total energy per unit mass of the moving fluid
$\dot{q}$	– heat addition per unit mass and time
$\dot{\boldsymbol{Q}}_{viscous}$	– viscous-heat addition due to viscous effects
$\dot{\boldsymbol{W}}$	– viscouswork due to the shear stress

Subscripts

BWT	– complete body-wing-tail configuration
B	– body alone
$W(B)$	– wing in the presence of the body
$B(W)$	– body in the presence of the wing
$T(B)$	– tail in the presence of the body
$B(T)$	– body in the presence of the tail
$T(W)$	– tail in the presence of the wing

Introduction

In all phases of a missile design it is necessary to know aerodynamic coefficients as a function of the angle of attack for different Mach numbers and control deflections . In preliminary design, accurate prediction of the aerodynamic coefficients is necessary for the choice of aerodynamic configuration. For the wind tunnel model design, aerodynamic load is required for the balance choice. Design of the missile autopilot, choice of the guidance law and numerical simulation of the flight mechanics require accurate values of the aerodynamic coefficients.

The purpose of this paper is to compare the aerodynamic coefficients of the normal force and the pitching moment obtained by three programs (FLUENT6 [1], DMAC [2] and NLMAC [3]) with the experimental data.

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Three characteristic models are used in this paper for comparing the calculated values of the normal force coefficient and the pitchig moment coefficient with the experimental data (Fig.1). These are:

a) MODEL - A: Canard controlled missile;
b) MODEL - B: Elevon controlled missile or unguided missile;
c) MODEL - C : Airplane configuration missile.

The fin deflection influences on aerodynamic coefficients are not analyzed in this paper. So the aerodynamic coefficients of the normal force and the pitching moment are only the function of the angle of attack.

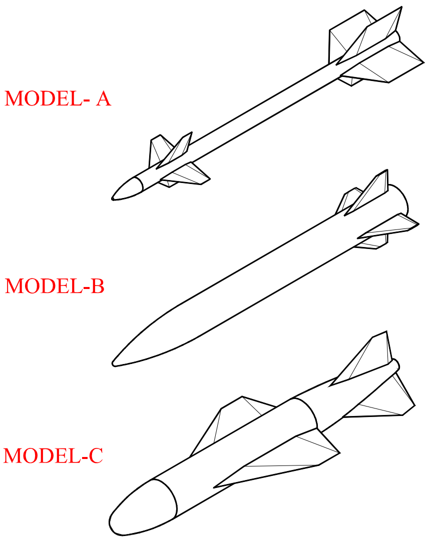

Figure 1. Models of missiles

DMAC program

DMAC (Derivative Missile Aerodynamic Coefficients) program is designed for the calculation of derivatives of missile aerodynamic coefficients. The common approach to the calculation of these derivatives is “component build-up method”. The overall loads are “built up” by summing up the aerodynamic characteristics of the major missile airframe parts (body, wings and tails).

The “build up” method can be illustrated by normal force and pitching moment coefficients [4].

$$C_{N_{BWT}} = C_{N_B} + C_{N_{W(B)}} + C_{N_{B(W)}} + C_{N_{T(B)}} + C_{N_{B(T)}} + C_{N_{T(W)}}$$

$$C_{m_{BWT}} = C_{m_B} + C_{m_{W(B)}} + C_{m_{B(W)}} + C_{m_{T(B)}} + C_{m_{B(T)}} + C_{m_{T(W)}} \qquad (1)$$

Wing-body lift with the linear theory for the wing normal force coefficient C_{N_W} can be written in the following form

$$C_{N_{W(B)}} + C_{N_{B(W)}} = \left(K_W + K_B\right)\frac{\partial C_{N_W}}{\partial \alpha}\alpha \qquad (2)$$

where

$$K_W = \frac{C_{N_{W(B)}}}{C_{N_W}}, \quad K_B = \frac{C_{N_{B(W)}}}{C_{N_W}},$$

for $\alpha \neq 0$ and $\delta = 0$.

The similar expression can be written in case the wing is deflected for an angle δ.

$$C_{N_{W(B)}} + C_{N_{B(W)}} = \left(k_W + k_B\right)\frac{\partial C_{N_W}}{\partial \alpha}\delta \qquad (3)$$

where $k_W = \dfrac{C_{N_{W(B)}}}{C_{N_W}}$, $k_B = \dfrac{C_{N_{B(W)}}}{C_{N_W}}$ for $\alpha = 0$ and $\delta \neq 0$.

The wing influence on the tail is given by effective upwash angle generated by the vortices shed by the wing.

$$C_{N_{T(W)}}{}_{fins} = \frac{\partial C_{N_T}}{\partial \alpha}\Delta\alpha_v \qquad (4)$$

where

$\dfrac{\partial C_{N_T}}{\partial \alpha}$ - derivative of the tail-alone normal force coefficients

$\Delta\alpha_v$ - average downwash angle

Average downwash angle can be equated to the effective fin deflection

$$\Delta\alpha_v = k_W \delta_{eff} \qquad (5)$$

Tail plus body contribution to the normal force due to vortices shed by the wing can be written as

$$C_{N_{T(W)}} = \left(1 + \frac{k_B}{k_W}\right)_{tail} \Delta\alpha_v \frac{\partial C_{N_T}}{\partial \alpha} \qquad (6)$$

As a result, normal force coefficient can be written in the following form

$$C_{N_{BWT}} = C_{N_B} + \left[\left(K_N + K_B\right)\alpha + \left(k_W + k_B\right)\delta\right]_{wing} \cdot \frac{\partial C_{N_W}}{\partial \alpha}$$
$$+ \left[\left(K_N + K_B\right)\alpha + \left(k_W + k_B\right)\delta + \left(1 + \frac{k_B}{k_W}\right)\Delta\alpha_v\right]_{tail} \frac{\partial C_{N_T}}{\partial \alpha} \qquad (7)$$

The derivative of the normal force coefficient can be written as a derivative due to α and a derivative due to δ.

$$\frac{\partial C_{N_{BWT}}}{\partial \alpha} = C_{N_{B\alpha}} + \left(K_N + K_B\right)_{wing}\frac{\partial C_{N_W}}{\partial \alpha} +$$
$$+ \left[\left(K_W + K_B\right) + \left(1 + \frac{k_B}{k_W}\right)\varepsilon_\alpha\right]_{tail}\frac{\partial C_{N_T}}{\partial \alpha} \qquad (8)$$

$$\frac{\partial C_{N_{BWT}}}{\partial \delta} = \left(k_W + k_B\right)_{wing}\frac{\partial C_{N_W}}{\partial \alpha} + \left(k_W + k_B\right)_{tail}\frac{\partial C_{N_T}}{\partial \alpha}$$

The same derivation is valid for the pitching moment coefficient.

Aerodynamic coefficients of both the normal force and the pitch moment can be obtained by multiplying the derivatives of aerodynamic coefficients by the angle of attack and fin deflection angle. Results obtained by the DMAC program can be compared with experimental data in the range of small angle of attack where the aerodynamic coefficient of normal force and pitching moment are linear functions of angle of attack.

NLMAC program

NLMAC (Non Linear Missile Aerodynamic Coefficients) program is based on the method of equivalent angle of attack [5],[6],[7],[8]. It represents an extension of the linear theory to a non-linear range of the angle of attack.

For any finned section of a missile, the linear aerodynamic coefficient of normal force can be written in the following form:

$$C_{NW(B)} = \left(K_W \alpha + k_W \delta + \Delta\alpha_v\right) \frac{\partial C_{NW}}{\partial \alpha} \tag{9}$$

In this formula $\Delta\alpha_v$ represents the effect of any vortex generated upstream of the finned section. The expression in the brackets is defined as the equivalent angle of attack:

$$\alpha_{eq} = K_W \alpha + k_W \delta + \Delta\alpha_v \tag{10}$$

Substituting eq. (10) for eq. (9), the linear aerodynamic coefficient of the wing normal force in the presence of the body can be written in compact form

$$C_{NW(B)} = \frac{\partial C_{NW}}{\partial \alpha} \alpha_{eq} \tag{11}$$

The eq. (11) can be extended to the non-linear term in the sense that the coefficient $C_{NW(B)}$ is equal to the coefficient C_{NW} evaluated at the equivalent angle of attack α_{eq}.

$$C_{NW(B)} = C_{NW}\left(\alpha_{eq}\right) \tag{12}$$

The graphical representation of this method is given in Fig.2

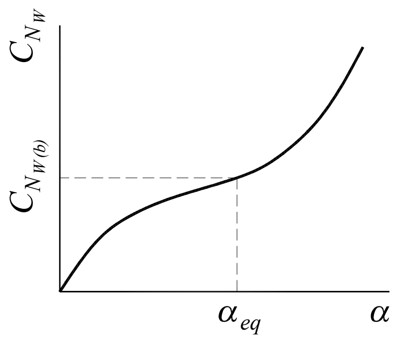

Figure 2. Method of equivalent angle of attack

In order to obtain results, the aerodynamic characteristics of the wing alone have to be known accurateu. Loads of the body in the presence of the fin can be determined by assuming that the load ratio between the body in the presence of the fin and the fin in the presence of the body is linear

$$\frac{C_{NB(W)}}{C_{NW(B)}} = \frac{K_B \alpha + k_B \delta + k_B \Delta\alpha_v / k_W}{K_W \alpha + k_W \delta + \Delta\alpha_v} \tag{13}$$

Substituting relation $\frac{k_B}{k_W} = \frac{K_B}{K_W}$ in the previous expression, the simplified expression is obtained

$$C_{NB(W)} = \frac{K_B}{K_W} C_{NW(B)} \tag{14}$$

In more general case, the calculation of missile aerodynamic coefficients must include roll angle and arbitrary fin deflection.

$$C_{NF(B)} = \left(K_W \alpha \cos\Phi + \frac{2}{AR} K_\Phi \alpha^2 \sin 2\Phi\right) \frac{\partial C_{NW}}{\partial \alpha} \tag{15}$$

where Φ is the roll angle. In this expression, the subscript F is used to denote one fin. The K_Φ coefficient depends on $d/2s_m$.

If fin to fin correlation and the vortex effect are taken into consideration, the equivalent angle of attack for fin i can be expressed in general form,

$$\alpha_{eq_i} = K_W \alpha \cos\Phi_i + \frac{2}{AR} K_\Phi \alpha^2 \sin 2\Phi_i + \sum_{i=1}^{4} \Lambda_{ij} \delta_j + \Delta\alpha_{vi} \tag{16}$$

The vorticity angle $\Delta\alpha_v$, which represents the effect of vorticity, generated upstream of the finned section. The theory of reverse flow is used in this program to calculate $\Delta\alpha_v$

$$\Delta\alpha_{v_i} = \frac{1}{s_m} \sum_{j=1} \int_0^{s_m} \alpha_{v_j}(t) W_{ji}(t)\, dt \tag{17}$$

where W_{ji} - weight function, s_m - semispan of the wings. The weight function is spanwise distribution of the loading for a wing-body combination at the unit angle of attack

FLUENT6 program

FLUENT6 program is a solver for three-dimensional general transport equations of mass, momentum and energy [9], [10] and [11]:

- continuity equation

$$\underbrace{\frac{\partial}{\partial t}\int_v \rho dv}_{\substack{\text{Time rate of the}\\ \text{increase of mass}\\ \text{inside control}\\ \text{volume}}} + \underbrace{\int_{\mathbf{S}} \rho \boldsymbol{V} \cdot \boldsymbol{dS}}_{\substack{\text{Mass flux across}\\ \text{control surface}}} = 0$$

- momentum equation

$$\underbrace{\frac{\partial}{\partial t}\int_v \rho \boldsymbol{V} dv}_{\substack{\text{Time rate of}\\ \text{momentum}\\ \text{inside}\\ \text{control volume}}} + \underbrace{\int_{\mathbf{S}} (\rho \boldsymbol{V} \cdot \boldsymbol{dS}) \boldsymbol{V}}_{\substack{\text{Flow of}\\ \text{momentum}\\ \text{across control}\\ \text{surface}}} = \underbrace{-\int_{\mathbf{S}} p \boldsymbol{dS}}_{\substack{\text{Pressure}\\ \text{force}}} + \underbrace{\int_v \rho \boldsymbol{f} dv}_{\substack{\text{Body}\\ \text{force}}} + \underbrace{\boldsymbol{F}_{\text{viscous}}}_{\substack{\text{Viscous}\\ \text{force}}}$$

- energy equation

$$\underbrace{\frac{\partial}{\partial t}\int_v \rho h dv}_{\substack{\text{Time rate of}\\ \text{total energy}}} + \underbrace{\int_{\mathbf{S}} h(\rho \boldsymbol{V} \cdot \boldsymbol{dS})}_{\substack{\text{Flow of total}\\ \text{energy across}\\ \text{control surface}}} = \underbrace{-\int_{\mathbf{S}} p \boldsymbol{V} \cdot \boldsymbol{dS}}_{\substack{\text{Work due to}\\ \text{pressure force}}} + \underbrace{\int_v \rho \boldsymbol{f} \cdot \boldsymbol{V} dv}_{\substack{\text{Work due}\\ \text{body force}}} +$$

$$+ \underbrace{\int_v \dot{q} \rho dv}_{\substack{\text{Volumetric}\\ \text{heating}}} + \underbrace{\dot{\boldsymbol{Q}}_{\text{viscous}}}_{\substack{\text{Viscous}\\ \text{heat}}} + \underbrace{\dot{\boldsymbol{W}}_{\text{viscous}}}_{\substack{\text{Work of}\\ \text{shear stress}\\ \text{on control}\\ \text{surface}}}$$

FLUENT6 is based on the finite volume method. The control volume is discretized into a finite set of cells and the transport equation (continuity, momentum and energy) is applied to each cell.

For all missile models analyzed in this paper the following options have been chosen in FLUENT6 program:

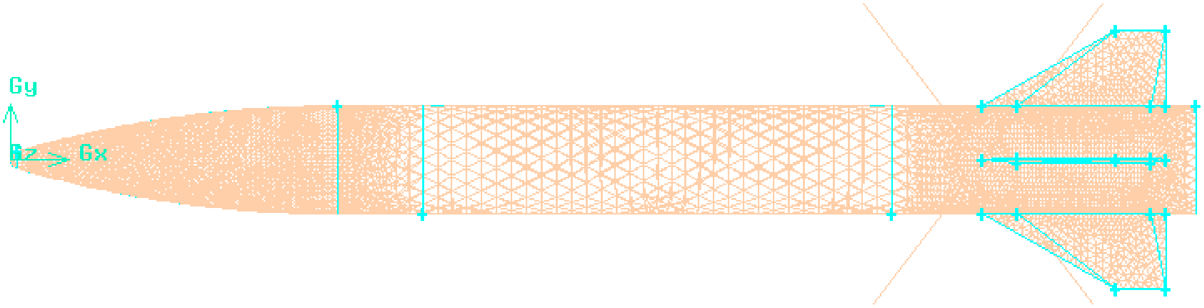

Figure 3. Grid generation on the model B

- three dimensional model (3D),
- implicit coupled solver for stationary flow,
- standard $k-\varepsilon$ turbulence model,
- standard boundary condition for Mach numbers M=0.95, 2.0 and 2.5. The choice of Mach number is dependent on the available experimental data for the analyzed model.

For all models of the missiles analyzed in this paper control volume (domain) for grid generation is obtained when three-dimensional model of the missiles (Fig.3) are subtracted from the sphere. Radius of the sphere is selected to be six hundred times greater than characteristic length of the missiles (diameter). Three-dimensional models of the missiles welle done in AUTOCAD and space unstructured grids were generated in GAMBIT2.

The calculation accuracy of aerodynamic coefficients of the missiles depends on the number of cells in the control domain. On the other hand, computer memory constraints require reduction in number of cells.

In order to reduce the number of cells and to obtain valuable results, two methods of cell reduction are applied for all models:

- Solid models of the missiles are simplified by replacing all round edges with sharp edges,
- Surface of the missile is divided into a few sections. For each of the sections the different surface grid density is applied. Grid density applied for the nose and wing section of the missiles is greater than the one for the body between the nose and the wing section of the missile. (Fig.3 – MODEL B).

Results of calculation

MODEL – A

MODEL-A is canard controlled missile. Geometric characteristics of the missile are given in [12]. The missile sketch with non-dimensional characteristics is given in Fig.4.

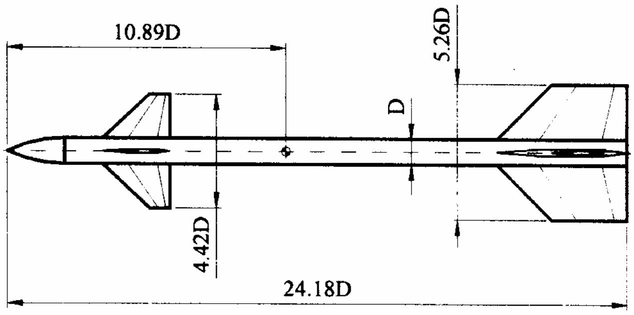

Figure. 4. Geometric characteristics of the Model A

The results of the normal force coefficient, pitching moment calculations and the experimental data are given in Fig.5a and 5b. The experimental data are taken from [5]. It can be seen that the calculation results of the programs NLMAC and FLUENT6 are in good agreement with experimental data in the whole range of the angle of attack ($-18^\circ \le \alpha \le 18^\circ$). Coefficients obtained by DMAC program are in good agreement with the experimental data in linear region ($-4^\circ \le \alpha \le 4^\circ$).

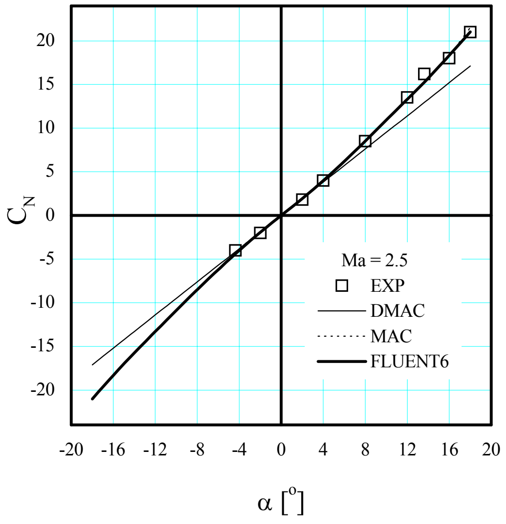

Figure 5a. Normal force coefficient

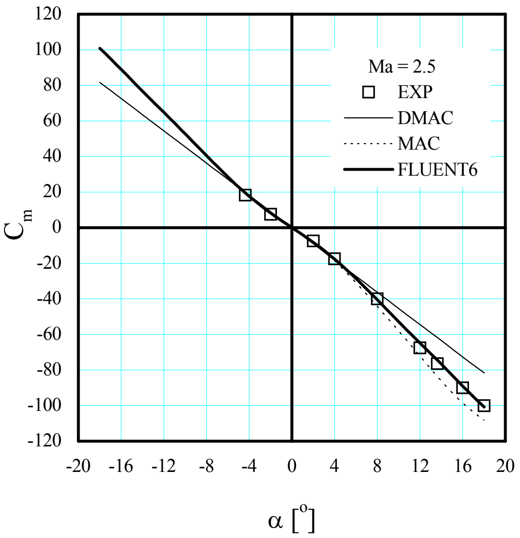

Figure 5b. Pitching moment coefficient

MODEL - B

Basic geometric characteristics of the missile are given in Fig.6. There is one section of the wings.

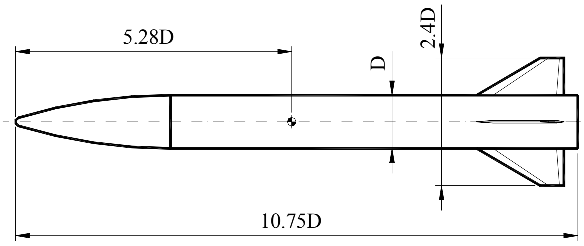

Figure 6. Geometric characteristics of the Model B

Comparison of the aerodynamic coefficients obtained by programs DMAC and NLMAC with experimental data for different angles of attack is given in paper [13]. Results of the calculation obtained by FLUENT6 program for Mach number M=2.0 are added to the comparison in [13].

It can be seen in Fig.7a and 7b that there is slight non-linearity of aerodynamic coefficients for the angle of attack grater that 8°. It is evident that results of calculation obtained by program FLUENT6 and NLMAC match non-linearity of the experiments.

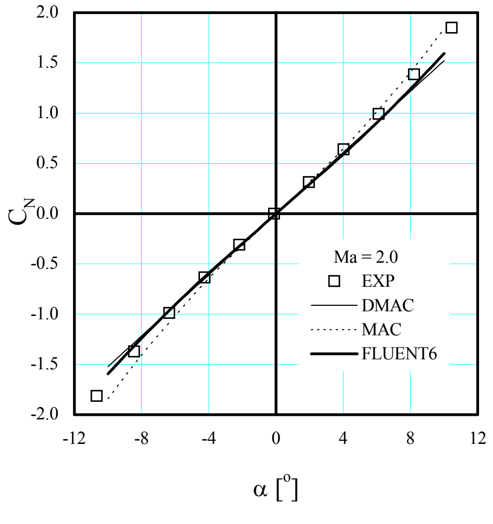

Figure 7a. Normal force coefficient

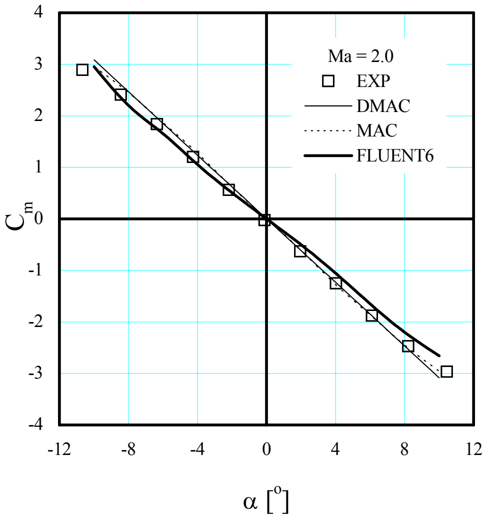

Figure 7b. Pitching moment coefficient

MODEL - C

MODEL-C is a missile with one par of wing and three tail fins [14]. Basic dimensions as a function of the diameter are given in Fig.8.

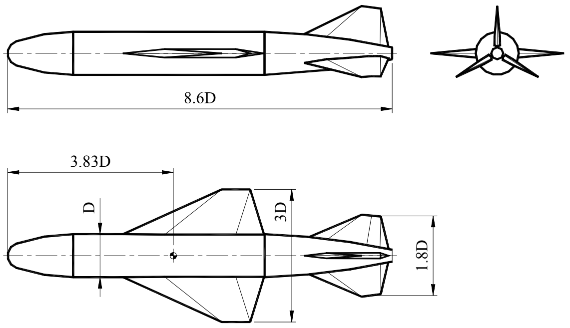

Fig. 8. Geometric characteristics of the Model C

Diagrams of the normal force and pitching moment coefficients as a function of the angle of attack for Mach number M=0.95 are given in Fig.9a and 9b. There are only data calculated by programs FLUENT6 and DMAC because NLMAC program is designed for cruciform missiles.

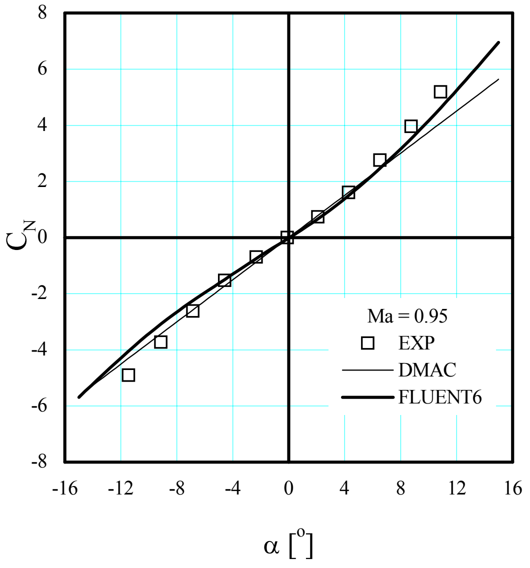

Figure 9a. Normal force coefficient

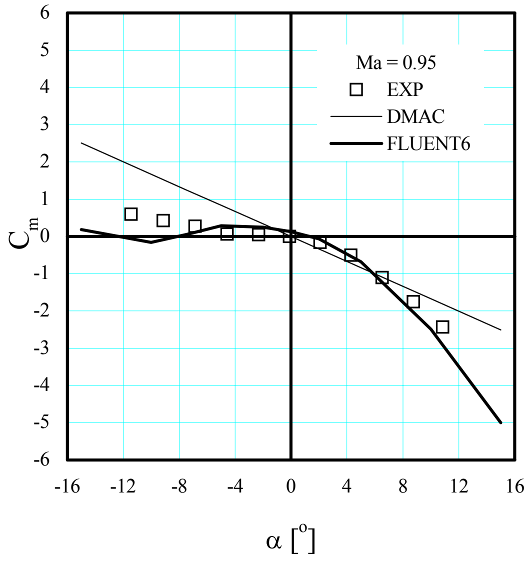

Figure 9b. Pitching moment coefficient

Results obtained by DMAC program are in good agreement with experimental data in the range of small angle of attack where the normal force and pitch moment aerodynamic coefficients are linear with the change of angle of attack ($-4^\circ \le \alpha \le 4^\circ$).

Results obtained by FLUENT6 program agree with experimental data in the region of higher angle of attack where non-linearity is dominant. Deviation from the experimental data at a higher angle of attack is greater than 10%.

Conclusion

The calculation results of aerodynamic coefficients by programs DMAC, NLMAC and FLUENT6 are given for three missiles and compared with the wind tunnel experimental data.

DMAC program is designed to calculate derivatives of aerodynamic coefficients and is based on semiempirical build-up method.

NLMAC program is based on the method of the equivalent angle of attack. As a result of one run there are aerodynamic coefficients for one Mach number. The accuracy of the calculation depends on available aerodynamic characteristics of the wings, fins and body alone. The restriction of the program is that it is applicable for cruciform missiles only.

FLUENT6 program is a general purpose program for numerical solution of three-dimensional general transport equation of mass, momentum and energy. Accuracy of this program depends on the type of grid and number of cells in domain.

It is shown in the paper that there are good agreements between the results of calculation and the experimental data for three different types of the missiles. Results of the DMAC program calculation can be used in the area of small angles of attack ($-4^\circ \le \alpha \le 4^\circ$), where aerodynamic coefficients of the missiles are the linear function of the angle of attack.

Programs NLMAC and FLUENT6 can be used for the calculation of the aerodynamic coefficients at higher angle of attack where aerodynamic coefficients are nonlinear. Deviation of the calculated value from experimental data is less than 10%. Concerning coefficient of the pitching moment, this deviation is greater than 10% for the MODEL-C because the pitching moment is close to zero for the chosen reference point.

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Ocena tačnosti aerodinamičkih koeficijenata rakete pomoću programa DMAC, NLMAC i FLUENT6

Aerodinamički koeficijent normalne sile i koeficijenti momenta propinjanja dobijeni pomoću programa DMAC, NLMAC i FLUENT6 dati su uporedo sa eksperimentalnim vrednostima za tri karakteristične vrste raketa. Program DMAC baziran je na semiempirijskim metodama i koristi se za proračun derivativa aerodinamičkih koeficijenata. Program NLMAC je baziran na metodi ekvivalentnog napadnog ugla i koristi se za proračun aerodinamičkih koeficijenata u funkciji napadnog ugla za jedan Maxov broj i zadati ugao otklona krila. Program FLUENT6 je program za numeričko rešavanje jednačine kontinuiteta, momenta količine kretanja i održanja energije. Program FLUENT6 je baziran na metodi konačnih zapremina pri čemu se diskretizovane jednačine kretanja fluida primenjuju na svaku ćeliju kontrolne zapremine. Rezultati proračuna pomoću ova tri programa pokazali su dosta dobro poklapanje sa eksperimentalnim podacima za testirane modele raketa.

Ključne reči: **aerodinamika, proračunska dinamika fluida, derivativi aerodinamičkih koeficijenata, metoda ekvivalentnog napadnog ugla**

Estimation de la précision des coefficients aérodynamiques chez les missiles à l'aide des programmes DMAC, NLMAC et FLUENT6

Les coefficients aérodynamiques de la force normale et les coefficients du moment de tangage, obtenus à l'aide des programmes DMAC, NLMAC et FLUENT6, sont comparés aux résultats expérimentaux pour les trois configurations caractéristiques des missiles. Le programme DMAC est basé sur les méthodes sémi-empiriques et il est conçu pour calculer les dérivées des coefficients aérodynamiques. Le programme NLMAC est basé sur la méthode de l'angle d'attaque équivalent. Il calcule les coefficients aérodynamiques en fonction de l'angle d'attaque pour un nombre de Mach et la déflexion des ailletes. Le programme FLUENT6 est utilisé pour resoudre les équations de continuIté, de vitesse et d'énergie. Il est basé sur la méthode des volumes finites. Les équations de transport des fluides dérivées sont appliquées à chaque cellule. Il y à un bon accord entre les coefficients aérodynamiques calculés et les données expérimentales.

Mots-clés: **aérodynamique, dynamique des fluides quantificative, dérivées des coefficients aérodynamiques, méthode de l'angle d'attaque équivalent.**