Aerodynamic assessment of axisymmetric launchers in the context of multidisciplinary optimisation

Alexandru-Iulian ONEL*,[1,2], Teodor-Viorel CHELARU[2]

*Corresponding author
*,[1]INCAS – National Institute for Aerospace Research "Elie Carafoli",
B-dul Iuliu Maniu 220, 061126, Bucharest, Romania,
onel.alexandru@incas.ro
[2]"POLITEHNICA" University of Bucharest, Faculty of Aerospace Engineering,
Str. Gheorghe Polizu 1-7, 011061, Bucharest, Romania,
teodor.chelaru@upb.ro

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***Abstract**: The paper presents a fast mathematical model that can be used to quickly assess the aerodynamic force coefficients of axisymmetric launchers as functions of Mach number and angle of attack. The tool developed based on the proposed mathematical model can be used separately or it can be integrated in a multidisciplinary optimisation algorithm for a preliminary small launcher design.*

***Key Words:** mathematical model, aerodynamic force coefficients, axisymmetric launcher, multidisciplinary optimisation*

1. INTRODUCTION

Due to the increase in the number of nano- and micro-satellites planned to be inserted into Low Earth Orbit (LEO), the need for small dedicated launchers has emerged in the last years. Thus, a preliminary design of such a small launcher, which is often realised with the use of a multidisciplinary design optimisation (MDO) tool is of great interest.

Various MDO algorithm schemes can be employed, Figure 1 presenting the block scheme used in this paper and in [1], [2], [3], [4]. The tool developed employs a genetic algorithm function in order to obtain the global optimum of the small launcher design problem.

The MDO tool developed consists of four main disciplines that are assessed in a cascade order: Weights & Sizing, Propulsion, Aerodynamics and Trajectory and secondary modules such as: Optimisation variables, Inputs, Objection function. The objective of this paper is to present the mathematical model that can be used in the assessment of the small launchers aerodynamic performance, which takes place in the Aerodynamics block of the MDO scheme presented in Figure 1. It can take up to several hundred thousand iterations [2] to reach solution convergence, therefore it is desirable to reduce the complexity of the mathematical models.

The usual approach to reduce MDO complexity is to use a 3DOF dynamic model. Many 3DOF problem formulations can be used ([5], [6]), accurate results being obtained with the aid of a null bank angle model, as the one detailed in [7].

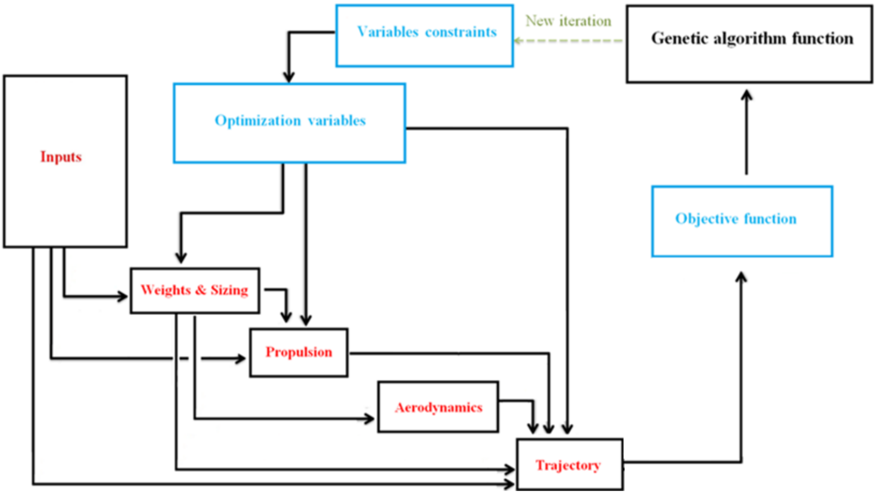

Figure 1 – MDO tool block scheme

For an axisymmetric launcher, the following aerodynamic coefficients are needed as outputs from the Aerodynamics module, later to be used in the MDO tool:

- $C_A = f(\alpha, M)$;
- $C_N = f(\alpha, M)$;
- $C_D = f(\alpha, M)$;
- $C_L = f(\alpha, M)$.

where: C_A represents the axial force coefficient; C_N represents the normal force coefficient; C_D represents the drag coefficient; C_L represents the lift coefficient; α represents the angle of attack and M is the flow Mach number.

2. MATHEMATICAL MODEL

It is practical to breakdown the complex geometry of an axisymmetric launcher into simple geometric components. The aerodynamic force coefficients of the launcher are considered to be the sum of all individual components contribution, normalised by the reference area.

A generic small launcher can be approximated by using the following simple geometric components, as seen in Figure 2:

- Fairings: conical, ogive, Haack series, ellipsoid, etc. (component 1);
- Cylindrical stage (component 2, 4, 5, 7);
- Positive transitions (component 6);
- Negative transitions (component 3).

The mathematical model proposed in this paper is an extension of the model detailed in [3], where only the drag coefficient at zero-angle of attack was computed, using:

$$C_{d_{0_{launcher}}} = \sum_{i}^{N} \left(\frac{A_i}{A_{ref}} \cdot C_{d_{0_i}} \right) \tag{1}$$

where: N represents the number of simple geometric components; A_i is the local reference area; A_{ref} is the launcher reference are and $C_{d_{0_i}}$ represents the individual component zero-angle of attack drag coefficient.

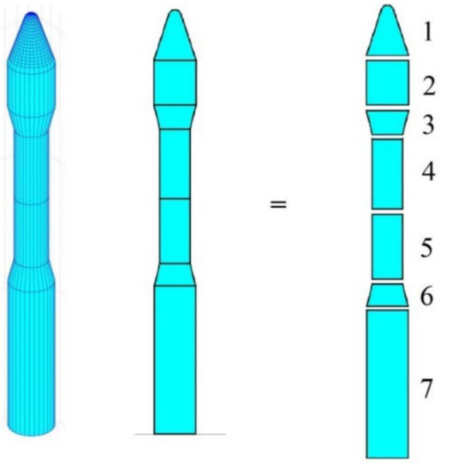

Figure 2 – Small launcher breakdown [3]

In this proposed model, similar to the one in [3], the reference area used for the launcher is its maximum frontal area. Considering the zero-angle of attack launcher drag coefficient $C_{d_{0_{launcher}}}$ (which is a function of Mach number) known, the following step is to estimate the alpha drag of the small launcher.

The alpha drag coefficient (which is a function of angle of attack in rad.) is estimated from [8] and [9] by using:

$$C_{d_{alpha_{launcher}}} = 2\delta\alpha^2 + \frac{3.6\eta\left(1.36l_l - 0.55l_f\right)}{\pi d_b}\alpha^3 \tag{2}$$

where: δ, η are empirical derived parameters, l_l is the launcher length, l_f is the fairing length and d_b is the maximum launcher diameter.

The total drag coefficient of the launcher can now be obtained using:

$$C_{D_{launcher}}(\alpha, M) = C_{d_{0_{launcher}}}(M) + C_{d_{alpha_{launcher}}}(\alpha) \tag{3}$$

Next, the normal force coefficient is modelled, using:

$$C_{N_{launcher}} = \sum_i^N \left(C_{N_i}\right) \tag{4}$$

where the normal force coefficient of the individual component is computed by:

$$C_{N_i} = C_{N_{i_\alpha}}\alpha \tag{5}$$

The normal force coefficient derivative $C_{N_{i_\alpha}}$ of each individual component is calculated using:

$$C_{N_{i_\alpha}}(\alpha, M) = C_{N_{incomp_{i_\alpha}}}(\alpha) \cdot F_{comp}(\alpha, M) \tag{6}$$

where: $C_{N_{incomp_{i_\alpha}}}$ is the incompressible normal force coefficient derivative and F_{comp} is the proposed compressibility factor.

For the modelling of the $C_{N_{incomp_{i_\alpha}}}$ term, the Barrowman model [10] is used together with the Galejs extension [11]. Thus, the following expression is used:

$$C_{N_{incomp_{i_\alpha}}} = \frac{2}{A_{ref}}[A(l) - A(0)]\frac{\sin\alpha}{\alpha} + K\frac{A_p}{A_{ref}}\alpha \tag{7}$$

where: $A(l)$ is the aft area of the i^{th} component, $A(0)$ is the fore area of i^{th} component, K is the Galejs constant ($K = 1$) and A_p is the component planform area.

The compressibility factor F_{comp} is computed with the following proposed mathematical model, based on in-house results of axisymmetric configurations, CFD data [12] and experimental data [13], [14].

For *cylindrical stages* and *non-conical fairings*, the following two variable polynomial approximation is used:

$$F_{comp} = p_1 + p_2M_c + p_3\alpha + p_4{M_c}^2 + p_5M_c\alpha + p_6\alpha^2 \tag{8}$$

where: α is the launcher angle of attack [°], $M_c = Msin(\alpha)$ is the crosswind Mach number and $P = (p_1, \ldots, p_6)$ are the polynomial coefficients of the approximation function, given by:

$$P = \begin{cases} (1,\ 0.6973,\ 0.0155,\ 24.9025,\ -0.3652,\ -0.0056) & \text{if } M \le 0.8 \\ (1,\ -0.0596,\ 0.0821,\ -1.0376,\ 0.2040,\ -0.0143) & \text{if } M > 0.8 \end{cases} \tag{9}$$

For *transitions* (positive and negative), the following hybrid model is proposed:

$$F_{comp} = \begin{cases} p_1 + p_2M_c + p_3\alpha + p_4{M_c}^2 + p_5M_c\alpha + p_6\alpha^2 & \text{if } M \le 0.8 \\ \text{linear model between } \Updownarrow & \text{if } 0.8 < M < 1.5 \\ 0.886M^{-0.295} & \text{if } M \ge 1.5 \end{cases} \tag{10}$$

with $P = (p_1, \ldots, p_6)$ defined in equation (9).

For *conical fairings* the following hybrid model is proposed:

$$F_{comp} = \begin{cases} p_1 + p_2M_c + p_3\alpha + p_4{M_c}^2 + p_5M_c\alpha + p_6\alpha^2 & \text{if } M \le 0.8 \\ \text{linear model between } \Updownarrow & \text{if } 0.8 < M < 1.5 \\ 0.0422M^3 - 0.4777M^2 + 1.6279M - 0.4941 & \text{if } 5 \ge M \ge 1.5 \\ 0.0033M^3 - 0.0665M^2 + 0.3776M + 0.3333 & \text{if } M > 5 \end{cases} \tag{11}$$

with $P = (p_1, \ldots, p_6)$ defined in equation (9).

The proposed model used to compute the compressibility factor F_{comp} is valid for Mach numbers ≤ 10 and angles of attack ≤ 8° and is suitable for small launchers assessment.

Having now defined the aerodynamic force coefficients pair$\left(C_{D_{launcher}}, C_{N_{launcher}}\right)$, one can estimate the axial force coefficient of the launcher $C_{A_{launcher}}$ by using [9]:

$$C_{A_{launcher}} = \frac{C_{D_{launcher}}\cos\alpha - \frac{1}{2}C_{N_{launcher}}\sin 2\alpha}{1 - \sin^2\alpha} \tag{12}$$

Finally, the lift coefficient can be computed:

$$C_{L_{launcher}} = C_{N_{launcher}} \cos\alpha - C_{A_{launcher}} \sin\alpha \tag{13}$$

3. RESULTS

The capabilities of the previous developed Matlab tool [3] has been extended to include the computation of all four aerodynamic force coefficients of interest by implementing the proposed mathematical model presented in this paper. The average run time for a three-stage small launcher configuration is approximately 0.05s. The atmospheric conditions used in the computations are those of sea level.

To validate the proposed mathematical model, a comparison with CFD results obtained with the aid of commercial software Ansys Fluent version 19 is made. The small launcher test geometry is the one from [3] and shown in Figure 3 with its respective dimensions given in Table 1. The total length of the small launcher is 16.25m with a maximum diameter of 1.6m, corresponding to a reference area of 2.0106m^2. The influence of the exhaust jet will not be considered in this paper, the studied configuration being that of the engine power-off state.

Table 1 – Test configuration dimensions [3]

Test configuration	
Component	Dimensions
Fairing	Length: 2.4m/1.65m/0.9m
	Diameter: 1.6m/1.15m
	LD Haack nose cone
Third stage	Length: 2.6m
	Diameter: 1.15m
Second stage	Length: 2.4m
	Diameter: 1.15m
Interstage 1-2	Length: 0.8m
	Fore diameter: 1.15m
	Aft diameter: 1.55m
First stage	Length: 5.5m
	Diameter: 1.55m

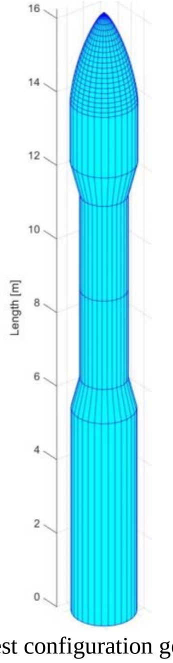

Figure 3 – Test configuration geometry [3]

For the CFD computations two set of runs were performed:

- The first set extends the test matrix in [3] from 13 cases to a total of 54 cases (ranging from Mach=0.01 to Mach=10 and the angle of attack from 0° to 8°), without species model;
- The second set consists of 18 cases (ranging from M=5 to Mach=10 and the angle of attack from 0° to 8°) performed with a species transport model. The Park model for dissociated air, presented in [15] has been used with the reaction mechanism from [16]. A finite rate/eddy dissipation model (FR/ED) turbulence-chemistry interaction has been implemented.

All of the CFD cases were performed using a k-ω SST turbulence model, with the following options enabled: Low-Reynolds number correction, Curvature correction, Compressibility effects and Production limiter. The convective flux was computed with Roe flux-difference splitting (Roe-FDS) scheme. A second-order upwind scheme was selected due to its reduced numerical diffusion. If convergence problems occurred, then a first-order upwind scheme was first used and later switched to a higher order.

During the CFD simulations, the Courant number was varied between 0.5 and 15, depending on each case particularities, in order to accelerate the solution convergence. The convergence criteria usually consist in the residuals decreasing below 10^{-5} and/or the monitor of aerodynamic force coefficients C_A, C_N, C_D and C_L should remain constant for at least 1000 iterations. Approximately 10.000 iterations were needed to reach convergence.

The drag coefficient computed with the model described in [3] and extended in this paper is shown in Figure 4, Figure 5 and Figure 6 for angles of attack of 0°, 4° and 8°, together with the results obtained from the CFD analysis. No noticeable differences have been obtained between the CFD cases with and without species model. A good correlation between the proposed model and the high fidelity CFD results is observed, the time needed for the former being only a small fraction of the latter.

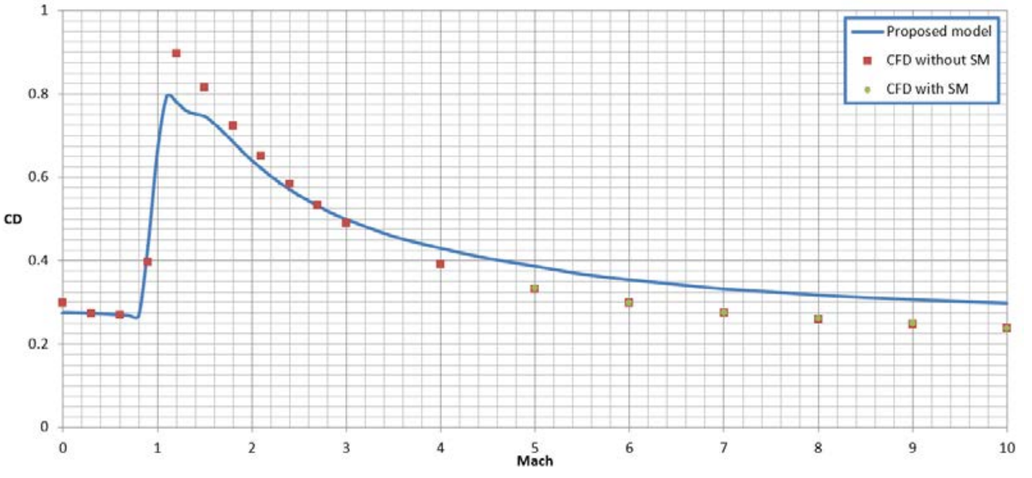

Figure 4 – Drag coefficient, 0° angle of attack

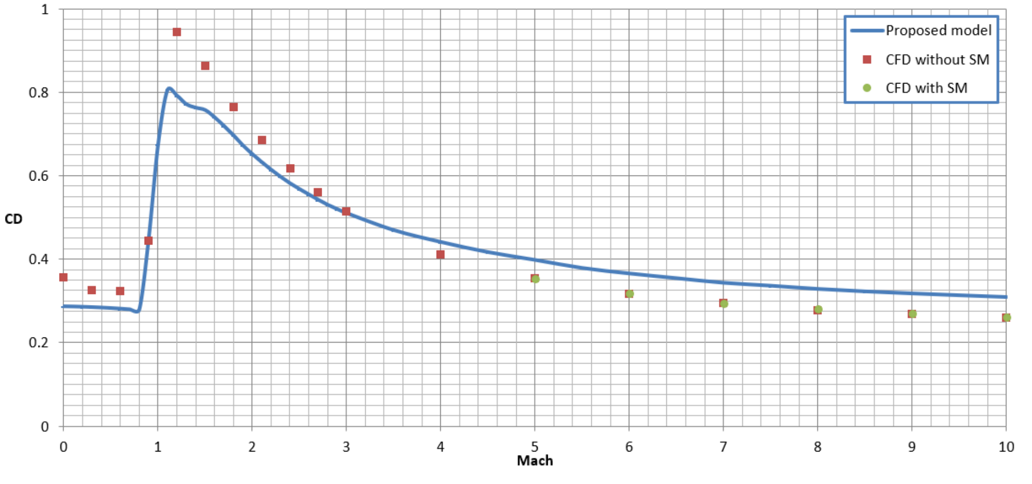

Figure 5 – Drag coefficient, 4° angle of attack

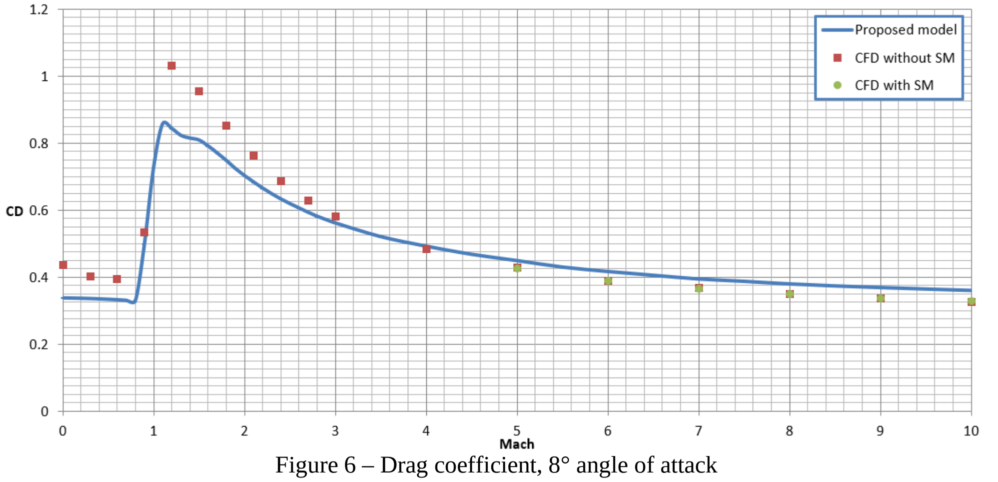

Figure 6 – Drag coefficient, 8° angle of attack

Because of the axisymmetric geometry of the small launcher, a null normal force (and coefficient) is obtained at 0° angle of attack. For angles of attack of 4° and 8°, the results comparison can be seen in Figure 7 and Figure 8. Again, the results provided by the proposed model are in close correlation with the ones provided from the CFD campaign.

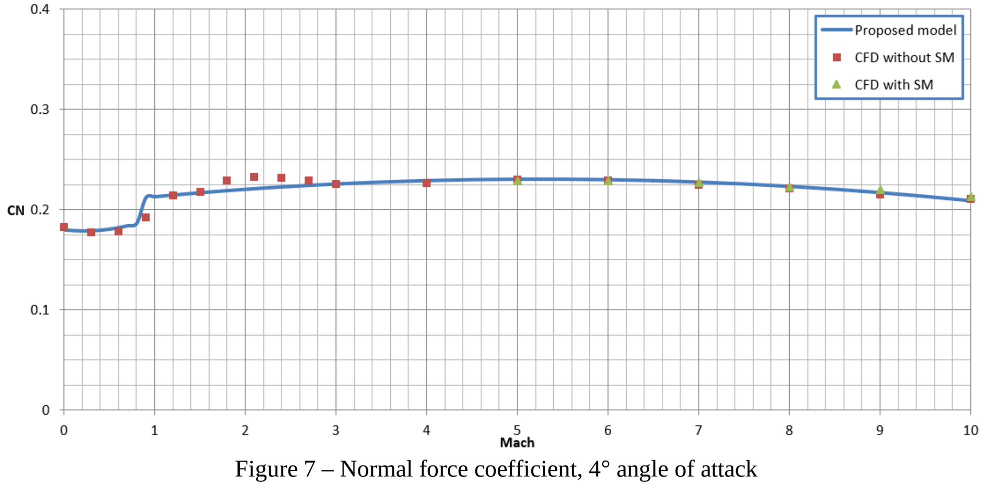

Figure 7 – Normal force coefficient, 4° angle of attack

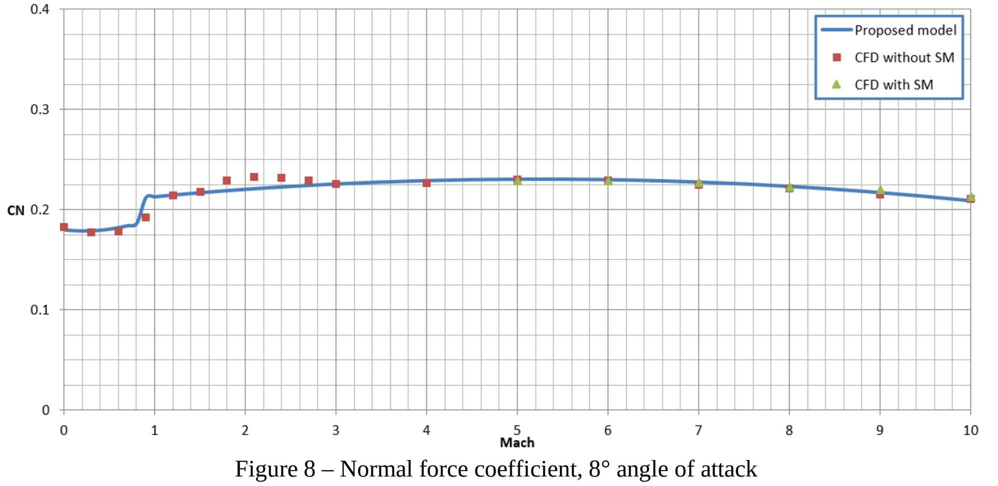

Figure 8 – Normal force coefficient, 8° angle of attack

The axial force coefficient is depicted in Figure 9 and Figure 10 for a 4° and 8° angle of attack, respectively. At 0° angle of attack, the axial force coefficient is identical to the drag coefficient presented above in Figure 4.

Even though the proposed model slightly overpredicts the axial force coefficient (together with the drag coefficient) for Mach numbers below 3, the aerodynamic database obtaiend represents a very good first approximation of the small launcher aerodynamic characteristics.

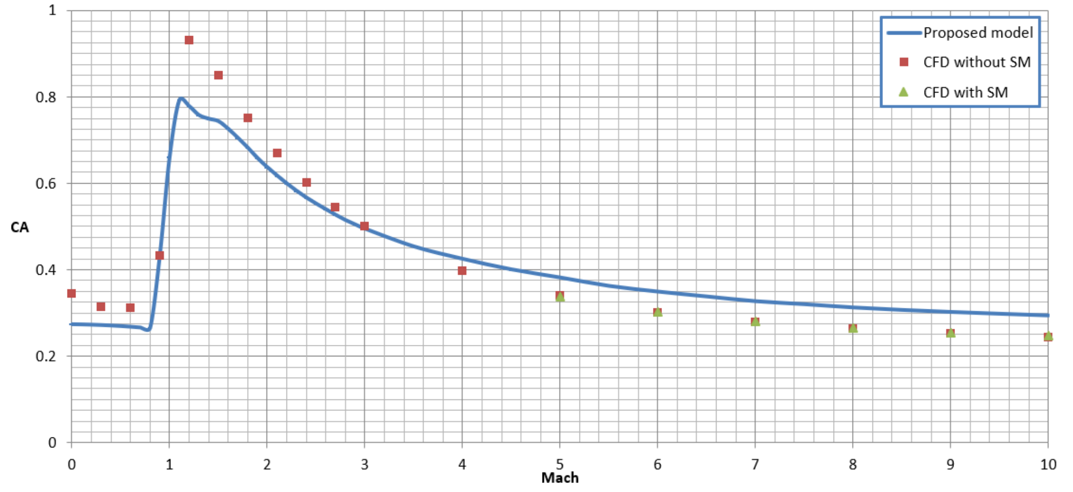

Figure 9 – Axial force coefficient, 4° angle of attack

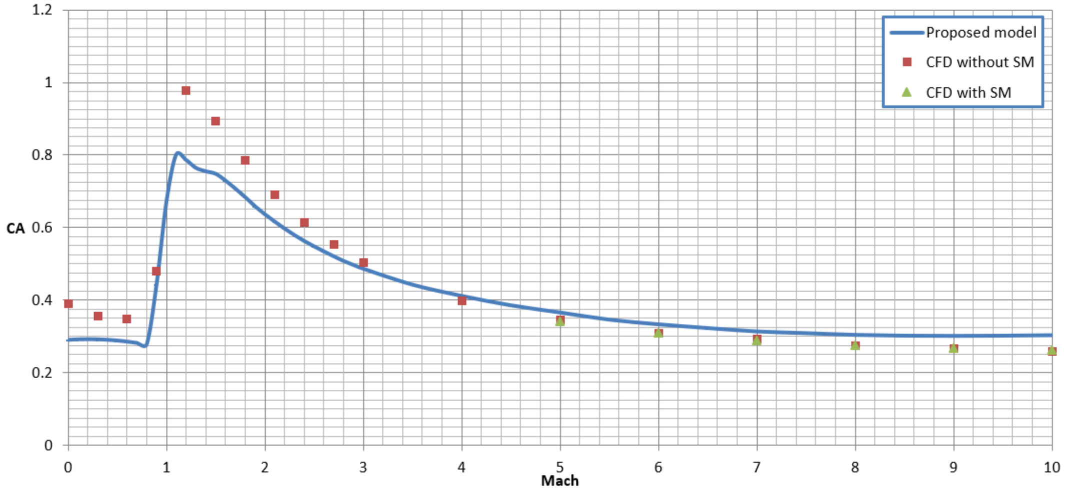

Figure 10 – Axial force coefficient, 8° angle of attack

Lastly, the lift coefficient is depicted in Figure 11 and Figure 12 for 4° and 8° angles of attack.

The proposed model provides very good results for low angles of attack flight conditions, typical for satellite launcher missions.

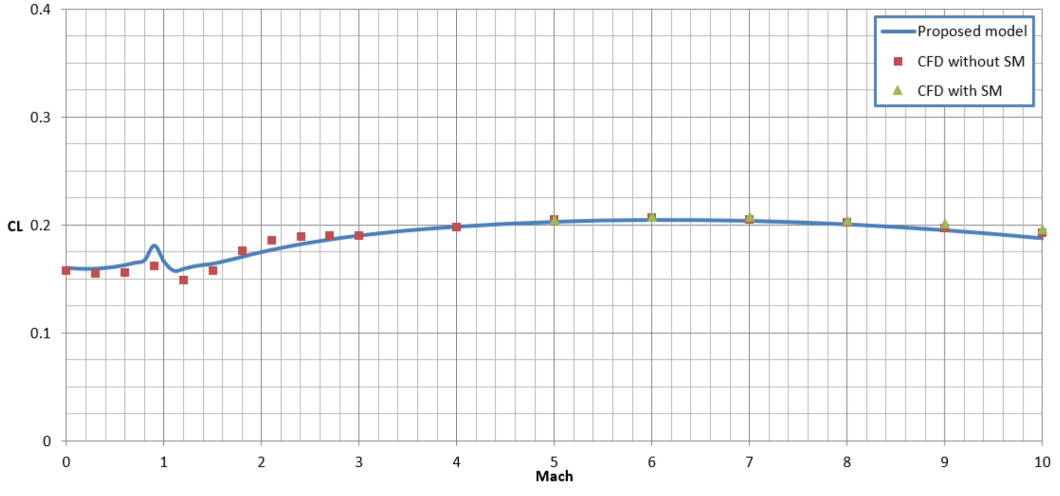

Figure 11 – Lift coefficient, 4° angle of attack

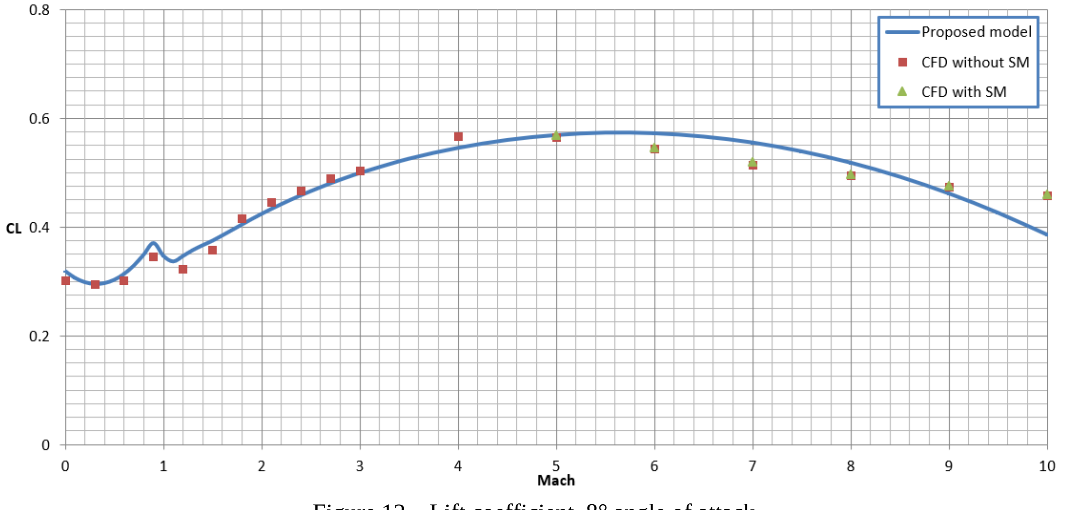

Figure 12 – Lift coefficient, 8° angle of attack

4. CONCLUSIONS

The paper continues the work previous done in [3], extending the preliminary aerodynamic assessment capabilities of small launchers. The mathematical model used for the drag coefficient computation has been updated to include the impact of non-zero angles of attack. A mathematical model for the computation of the normal force coefficient has been provided, based on analytical and semi-empirical methods, together with a proposed compressibility factor expression. The tool developed based on the presented models can be used to quickly assess the aerodynamic force coefficients of most small launchers (with axisymmetric configurations).

The results provide a very good approximation, as seen in the comparison with CFD results. The tool developed based on this mathematical model can be used separately or it can be integrated in a more complex, multidisciplinary optimisation. Because of the low computational time, the proposed mathematical model is suitable to be used in a full loop MDO algorithm.

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