Analysis of the Angle of Attack and Aerodynamic Stability of a Small Rocket in Crosswind Conditions

Mihail Serafimov (mserafimov@tu-sofia.bg)

Technical University of Sofia, Sofia, 1000, 8 Kl. Ohridski Blvd, Bulgaria

Abstract **- Atmospheric conditions, particularly crosswind, are an important consideration in the design and mission planning of small rockets. This study aims to determine the range of angles of attack a model rocket can experience during ascent using CFD simulations and trajectory modeling, and to estimate the maximum acceptable crosswind for a given mission. A one-degree-of-freedom MATLAB model calculates velocity using drag from the CFD and the motor thrust curve. The calculated velocity and prescribed crosswind then determine the relative airflow direction, allowing the wind-induced angle of attack to be estimated under the assumed rocket orientation. CFD predictions are compared with analytical results obtained using the Barrowman method, particularly the axial and normal forces and the location of the center of pressure. The approach can reduce unnecessary CFD cases and identify wind conditions that may affect stability or required altitude. Future work will lean on 6-degree-of-freedom models. A one-degree-of-freedom MATLAB model uses data from the CFD simulations and thrust curve to simulate the trajectory.**

Keywords **- Aerodynamic stability, computational fluid dynamics, crosswind, trajectory modeling**

1. INTRODUCTION

Developing a small experimental rocket requires considering aerodynamic characteristics and flight trajectory simultaneously. The broader objective of the present project is the development of a rocket with a target maximum altitude of approximately 100 m, for which the flight trajectory can be both numerically simulated and subsequently compared with experimental flight data. The present work represents an initial stage of this process and focuses on computational fluid dynamics (CFD) simulations and the development of a simplified one-degree-of-freedom (1DOF) trajectory model.

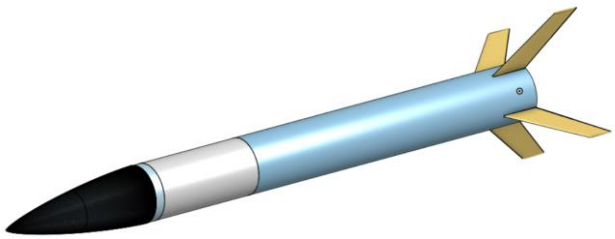


Fig. 1. CAD rendering of the examined rocket.

A key challenge in the preliminary aerodynamic analysis is selecting appropriate flight conditions for the CFD simulations. The aerodynamic forces acting on the rocket depend on its velocity and angle of attack, while the range of velocities and angles of attack encountered during flight cannot be determined accurately without prior knowledge of the trajectory [1]. Conversely, the trajectory itself cannot be estimated without aerodynamic force data. This creates an iterative problem, as investigating the complete flight envelope directly would require many CFD simulations. Wind is a major factor in estimating the trajectory and is the primary destabilising force [2].

To reduce the required computational effort, a simplified procedure is proposed. Initial CFD calculations are first performed at zero angle of attack for a range of flight velocities. The resulting aerodynamic forces are incorporated into a 1DOF MATLAB trajectory model. The calculated velocity history is then combined with an assumed constant crosswind velocity to estimate the evolution of the relative-flow angle and, therefore, the range of angles of attack to consider in the subsequent CFD analysis. This approach allows the aerodynamic simulation envelope to be reduced before higher-fidelity trajectory modeling is performed.

The main objectives of the study are therefore to obtain preliminary aerodynamic data for the investigated rocket, develop a simplified trajectory model, estimate the wind-induced angle-of-attack envelope during ascent, and evaluate whether this methodology can be used to select appropriate conditions for further CFD calculations. These objectives correspond to the workflow developed in the preliminary study: zero-angle CFD calculations, a simplified 1DOF trajectory model, estimation of the angle-of-attack envelope, and subsequent CFD calculations within that envelope.

2. OBJECT OF RESEARCH

The object of the investigation is a small aerodynamically stabilized rocket designed for low-altitude experimental flights. The rocket body is approximately 1.1 m long, with a diameter of 110 mm. The target altitude of the design is 100 m.

The main cylindrical section of the rocket is manufactured from PVC pipe, while the internal structural components, nose section, and aerodynamic surfaces are produced using additive manufacturing. The configuration uses swept, tapered stabilizing fins at the rear of the vehicle. The fin span is 110 mm, and uses a modified Drela HT12 profile.

The geometry provides passive aerodynamic stabilization while maintaining a relatively simple configuration suitable for manufacturing and numerical modeling, and minimizing surface area to reduce drag. The aft location of the fins moves the center of pressure behind the center of gravity and generates a stabilizing aerodynamic moment when the rocket is subjected to a non-zero angle of attack [3].

TABLE I
Rocket parameters

Symbol	Parameter	Value
L	Rocket length	1.1 m
d	Body diameter	110 mm
B	Fin span	110 mm
H	Target altitude	100 m
c_t	Fin root chord	75 mm
c_r	Fin tip chord	50 mm

The rocket is powered by a solid-propellant motor using KNDX propellant. The nominal motor operation lasts approximately 0.92 s. The thrust-time relationship used in the trajectory simulations was defined from the available motor performance data and is shown in Fig. 2.

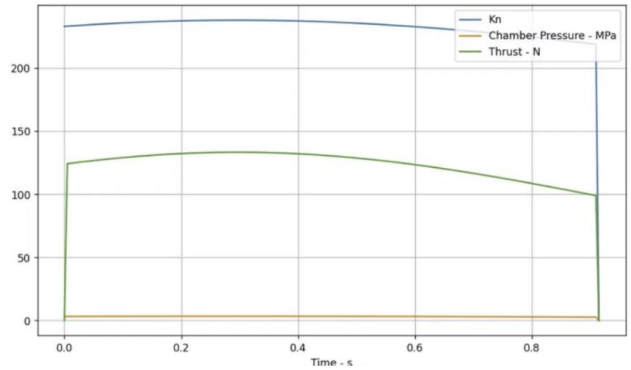


Fig. 2. Thrust curve of the solid fuel rocket engine, used in the trajectory simulation.

Thrust increases rapidly after ignition, peaks at roughly 135 N at roughly 0.3 s, and then decreases toward the end of motor operation. The motor thrust history is used as a time-dependent input to the 1DOF trajectory calculation.

3. METHODOLOGY

The proposed methodology uses a sequence of progressively more detailed numerical analyses. The purpose is to obtain a sufficiently accurate estimate of the flight envelope while limiting expensive, time-consuming CFD calculations.

Initially, CFD simulations are performed for the rocket at zero angle of attack and at several different flow velocities. The resulting aerodynamic drag values are then used as input data for a 1-degree-of-freedom (1DOF) MATLAB flight model. Because CFD data are available only at discrete velocities, the trajectory solver obtains the required aerodynamic forces by linear interpolation between the calculated points. This allows drag to vary continuously with rocket velocity during the trajectory calculation.

The 1DOF model provides the velocity and altitude magnitudes during the vertical flight. The calculated rocket velocity is then combined with an assumed horizontal wind velocity to estimate the direction of the relative airflow. For the simplified case of a vertical rocket axis and a horizontal crosswind, the corresponding kinematic angle of attack can be estimated as:

$$\alpha_{app} = tan^{-1}(\frac{V_\omega}{V}) \quad (1)$$

where: α_{app} - apparent angle of attack, degrees; V_ω - crosswind velocity, m/s; V - rocket velocity, m/s

This calculated angle should be interpreted as a simplified estimate of the incidence of the relative airflow rather than a complete prediction of the actual dynamic angle of attack. The 1DOF model does not include rotational motion and consequently cannot model the tendency of an aerodynamically stable rocket to turn toward the relative wind. Nevertheless, the method provides a conservative preliminary estimate of the range of angles that may be relevant for subsequent CFD calculations.

After the angle-of-attack envelope has been identified, additional CFD simulations can be concentrated within this range. A higher-fidelity 6DOF MATLAB or JSBSim model may then be used later to determine the complete translational and rotational trajectory.

4. DYNAMIC MODEL

A. 1DOF model

A one-degree-of-freedom model was developed in MATLAB to simulate the rocket's vertical motion during powered ascent and the subsequent coast phase. This model considers only motion along the vertical axis. Rotational motion, horizontal displacement, and changes in the rocket orientation are neglected at this stage.

The equation governing the vertical motion can be expressed as:

$$m\frac{dV}{dt} = T(t) - D(V) - mg, \quad (2)$$

where: m - Rocket weight, kg; T - rocket motor thrust, N, D - rocket drag, N

The altitude is obtained from:

$$\frac{dh}{dt} = V, \quad (3)$$

where: h - altitude, m

The motor thrust is obtained from the prescribed thrust-time curve, while aerodynamic drag is calculated by interpolation of the CFD results obtained at discrete velocities.

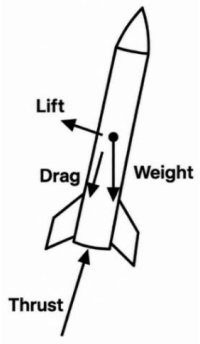


Fig. 3. Forces acting on a rocket

During powered flight, the net acceleration is determined primarily by the difference between motor thrust, aerodynamic drag, and gravitational force. After burnout, thrust becomes zero and the rocket continues to climb due to its existing kinetic energy while being decelerated by gravity and aerodynamic drag [4].

Maximum altitude is reached when the vertical velocity decreases to zero [5].

To estimate the wind-induced incidence angle, the 1DOF velocity solution is then combined with the selected crosswind velocity. This provides an approximate angle-of-attack history for the ascending portion of the trajectory.

B. CFD simulations

The aerodynamic simulations used a three-dimensional CFD model of the rocket. The computational grid contained approximately 3.77 million elements. The kω\omega SST turbulence model was selected, and a coupled pressure-velocity solution scheme was employed. Second-order discretization was used for pressure, momentum, turbulent kinetic energy, and specific dissipation rate.

The calculations were performed on a workstation equipped with an AMD Ryzen 7 7700 processor and 32 GB of DDR5 memory; six processor cores were used for the CFD calculations.

5. RESULTS

A. CFD results

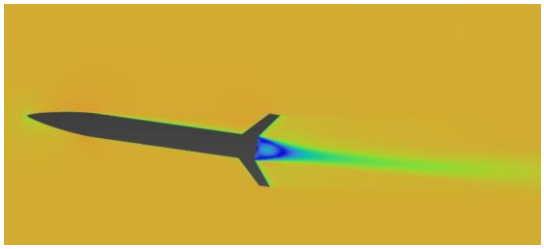


Fig. 4. Velocity magnitude contour of the rocket at seven degrees AoA.

The initial zero-angle calculations were performed over velocities from approximately 15 to 50 m/**s**. The CFD results indicate the expected increase in aerodynamic drag with increasing velocity. At zero angle of attack, the calculated drag increased from approximately 0.41 N at 15 m/s to 2.69 N at 40 m/s, and to approximately 4.13 N at 50 m/**s**. The additional simulations at non-zero incidence also show an increase in drag and a rapid development of the normal aerodynamic force as the angle of attack increases, which is consistent with expectations [6][7].

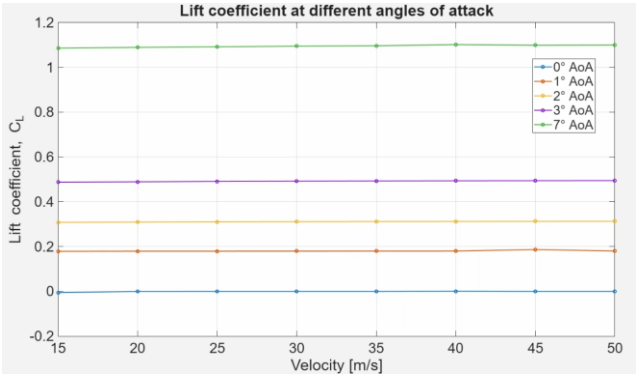


Fig. 5. Lift coefficient as a function of velocity at angle of attack of 0, 1, 2, 3 and 7 degrees.

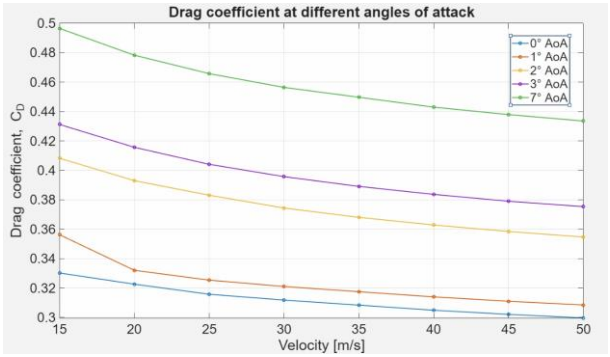


Fig. 6. Drag coefficient as a function of the velocity at 0, 1, 2, 3 and 7 degrees AoA.

The CFD solution was additionally compared with two lower-fidelity aerodynamic methods: OpenRocket and an independently implemented Barrowman model. Both OpenRocket and the Barrowman method predicted a longitudinal center-of-pressure position of approximately 0.86 m from the nose, while the CFD simulations produced values in the range of 0.85–0.87 m.

B. 1DOF model results

The 1DOF trajectory model was evaluated using the motor thrust curve and interpolated zero-angle CFD drag data. The rocket accelerates rapidly during the powered portion of the flight and reaches a maximum velocity of approximately 34 m/**s** close to motor burnout. After burnout, the rocket progressively decelerates due to gravity and aerodynamic drag.

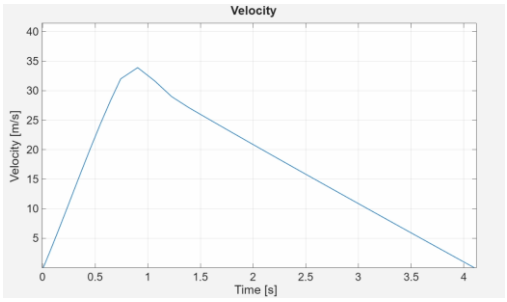


Fig. 7. Plot of the velocity throughout the flight of the rocket.

The altitude predicted by the present model reaches a maximum of approximately 69 m at about 4.1 **s** after launch. The current preliminary configuration therefore remains below the 100 m target altitude, indicating that an increase in the thrust or a reduction in weight, particularly of the rocket motor assembly, or a combination of these parameters may be necessary.

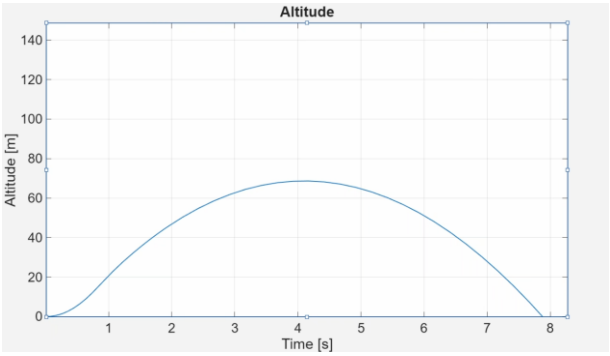


Fig. 8. Predicted rocket altitude during flight

The calculated velocity was subsequently used to estimate the development of the wind-induced angle of attack. Because of (1) the calculated angle is very large immediately after launch and again near apogee, when the rocket's vertical velocity approaches zero. During the high-speed portion of the ascent, however, the corresponding incidence angle is much smaller. The calculated curve in the preliminary study reaches its minimum around the period of maximum rocket velocity and then increases progressively as the vehicle decelerates.

The very large calculated incidence angles near zero velocity must be interpreted carefully. Aerodynamic forces scale approximately with dynamic pressure,

$$q = \frac{1}{2}\rho V^2, \tag{5}$$

and consequently the highest calculated incidence does not necessarily correspond to the most critical aerodynamic loading condition. Additionally, while the rocket is on the launch rails, its rotation about the lateral axis will be restricted, reducing the real angle of attack to zero even in crosswind conditions in that region.

Based on the combined trajectory and CFD results, the preliminary study indicates that detailed CFD calculations should focus primarily on an angle-of-attack envelope of approximately 0–15°, with the highest fidelity needed up to 7°.

Because the fins' stabilizing moment causes weathercocking [8], the actual angle of attack at any point during flight should be considerably lower than the apparent incidence.

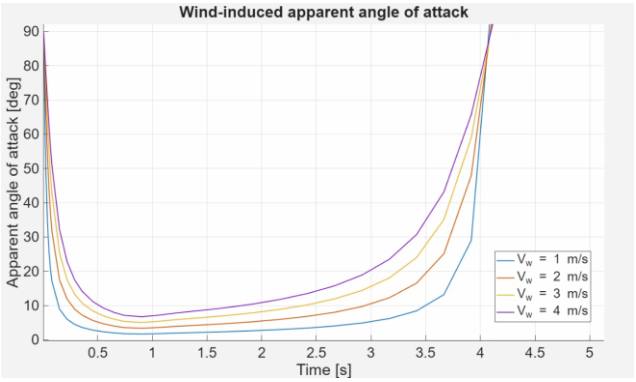


Fig. 9. Wind-induced apparent angle of attack as a function of time at various wind crosswind velocities.

6. CONCLUSION

A combined CFD and simplified trajectory-modeling procedure was applied to estimate the initial aerodynamic and flight characteristics of a small fin-stabilized rocket. The approach aimed to obtain the required CFD flight envelope without running many simulations at arbitrary combinations of velocity and angle of attack.

The initial CFD calculations produced aerodynamic forces over the relevant velocity range, and the center-of-pressure results were consistent with lower-fidelity aerodynamic methods. The CFD drag data were incorporated into a MATLAB 1DOF flight model, producing a maximum velocity of 34 m/s and an apogee of 69 m, below the objective of 100m, requiring a redesign of the rocket motor.

By combining the predicted vertical velocity with an assumed crosswind, the wind-induced angle of attack was estimated without requiring an initial full 6DOF model. The results indicate that most of the aerodynamically relevant part of the ascent can be represented using CFD calculations within an angle-of-attack range up to approximately 15°, with the greatest emphasis placed on the lower-angle region. The procedure therefore provides a computationally inexpensive way to define the preliminary CFD envelope before higher-fidelity aerodynamic and flight-dynamics analyses.

Further work should include additional CFD calculations within the identified angle-of-attack envelope, a mesh-independence investigation, incorporation of the aerodynamic coefficient database into a 6DOF model, and comparison of the predicted trajectory with experimental flight measurements.

ACKNOWLEDGMENT

This research was funded by the scientific-research project № 253CH0001-04 24 “Development of infrastructure and environment for aerospace education and research at 25 TU-Sofia/INSATUS/” by the contract with “Research and development sector at TU- 26 Sofia”.

I would like to express my gratitude to the Dean of the Faculty of transport, Prof. K. Nedelchev, and Prof. M. Todorov for the support that made this paper possible.

REFERENCES

[1] J. S. Barrowman, J. A. Barrowman, “The theoretical prediction of the center of pressure,” NARAM-8 R&D Project presented at *the 8th National Association of Rocketry Annual Meet*, Aug. 1966. [Online]. Available: https://www.apogeerockets.com/downloads/barrowman_report.pdf

[2] G. Leitmann, “Cross-wind Launching,” *Ordnance*, vol. 41, no. 219, pp. 550–552, 1956.

[3] C. H. Murphy, “Free Flight Motion of Symmetric Missiles,” *Ballistic Research Laboratories Report No. 1216*, Interior Ballistics Laboratory, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, July 1963. Report accession number: AD442757

[4] D. Rohini, C. Sasikumar, P. Samiyappan, B. Dakshinamurthy, N. Koppula, “Design & analysis of solid rocket using open rocket software,” *Materials Today: Proceedings*, vol. 64, pt. 1, pp. 425–430, 2022, doi: 10.1016/j.matpr.2022.04.787

[5] S. Niskanen, *OpenRocket Technical Documentation*, for OpenRocket version 13.05, May 10, 2013, pp. 11–13. [Online]. Available: https://openrocket.sourceforge.net/techdoc.pdf.

[6] A. S. Fahizal, Z. Salleh, A. H. Abdul Hamid, N. F. N. Mahadi, and M. A. Muhammad, “Mathematical and Computational Fluid Dynamic (CFD) Analysis of a Low Altitude Rocket Stability for Varying Fin Root Chord,” *Jurnal Kejuruteraan*, vol. 38, no. 1, pp. 209–215, Jan. 2026, doi: 10.17576/jkukm-2026-38(1)-20.

[7] W. Brown, M. Wiesneth, T. Faust, N. Huynh, C. Montalvo, K. Lino, and A. Tindell, “Measured and simulated analysis of a model rocket,” *Proceedings of the Institution of Mechanical Engineers*, Part G: Journal of Aerospace Engineering, vol. 233, no. 4, pp. 1397–1411, Mar. 2019, doi: 10.1177/0954410017752730.

[8] Z. Salleh, U. A. F. Mohd Asy’ari, A. H. Abdul Hamid, M. A. Muhammad, and Z. A. Ghaffar, “Low-Altitude Rocket Stability Under Various Fin Cant Angles and Cross Wind Speeds,” *Journal of Mechanical Engineering*, vol. 22, no. 2, pp. 83–95, May 2025, doi: 10.24191/jmeche.v22i2.2925.