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NUMERICAL INVESTIGATION ON AERODYNAMIC ROLL INDUCTION PHENOMENON OF SUBSONIC WRAP-AROUND TAIL FINNED MISSILES

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ABSTRACT

Wrap-around fins as stability surfaces for tube launched tactical missiles are investigated in this study by using CFD. Precise calculation of roll moment coefficient at different flight conditions with different angle of attack and free stream Mach number is important for wrap-around fins and is of primary importance for the design of roll autopilot. In this study, the aerodynamic performance and especially the roll induction of a wrap-around tail finned missile is investigated by performing steady-state CFD simulations for a selected generic geometry. The computations are performed for a range of angle of attack and Mach number and the roll moment coefficient obtained from the CFD results are compared with the available wind tunnel data of Dahlke. The effects of the wrap-around fins on the roll moment behavior are discussed.

INTRODUCTION

Wrap-around fins as stability surfaces are designed due to the packaging advantage on tube launched tactical missiles. However, the wrap around tails induce roll moment even at zero flight angles, which must be trimmed by control surfaces for an effective performance of guidance system [Dahlke 1974]. For that reason, the precise calculation of roll moment coefficient at different flight conditions which includes angle of attack, side slip angle and free stream Mach number is of primary importance for the design of roll autopilot.

There have been a few experimental and computational studies in the literature on wrap-around tail fins to understand the aerodynamic performance and stability characteristics of missiles at different flight conditions. [Bar-Heim 1983] performed a CFD campaign with Euler equations to extract a mathematical model which induces a roll motion at zero angle of attack in subsonic flow regime. [Abate 1991] developed slotted wrap-around fin configurations for decreasing roll induction while conserving the flight stability of missiles. [Mikhail 1995] performed a set of experiments to generate an algebraic formulation to the roll coefficient of different type and orientation of tails.

[Kim 2012] compared the behavior of wrap-around finned missile roll characteristics with wind tunnel results under supersonic conditions both for static and dynamic conditions. Their computational study was performed by solving 3D Euler equations and the comparisons with the test data were presented for the static cases. In spite of differences in roll damping coefficients with the test data, they noted a similar behavior for different designs and flight conditions in supersonic regime. In a recent study, [Li 2015] generated an aerodynamic model

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for wrap-around fin characteristics at supersonic regime using CFD results at different flight conditions.

Unlike planar fins, there is no symmetry in the wrap-around fin/body junction geometry as can be seen in Figure 1. Because of the flow around the fin and body and interactions of flow with the geometry, there is asymmetric pressure distributions on the area affected by the fin/body junction. Due to the no slip boundary condition, wrap around fin distracts all the streamlines around its body such that the streamlines are separated as decentralized and centralized on the upper and lower regions of the fin, respectively, as shown in Figure 1. Since the vertical area is decreasing between the streamlines in the centralized region, the relative velocity is expected to increase whereas the pressure decreases like a subsonic nozzle section as described by [Abate 1993]. The same aerodynamic phenomenon occurs inversely for the decentralized region. Thus, a pressure difference occurs from decentralized to centralized region from upper to lower surface of the fin. At zero angle of attack flight condition, the net forces cancel out each other while inducing a moment in the x direction. Therefore, a roll moment is induced in the x direction while there is no net force in y and z directions.

In this paper, the aerodynamic performance and especially the roll moment characteristics of a wrap-around tail finned missile is investigated by performing steady-state RANS CFD simulations for a generic geometry. The computations are performed for a range of angle of attack and for a range of Mach number from 0.4 to 0.8.

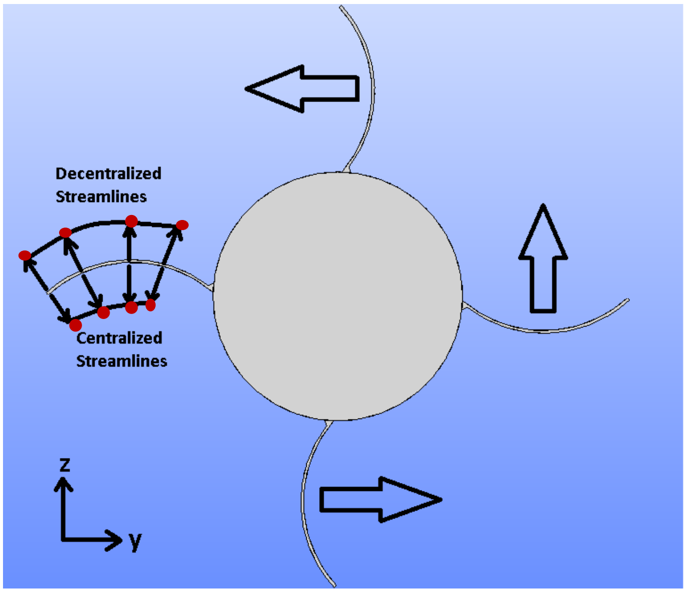


Figure 1. Wrap-around Tail Fin Roll Induction Mechanism

METHODOLOGY

A generic geometry of a missile with wrap-around tail fins is shown in Figure 2. This geometry is taken from Dahlke's wind tunnel experiments [Dahlke 1976] where it was named as F1 geometry with blunt leading edge. Since the tail fins wrap-around the body as a packaging advantage, the bending radius of the wrap-around fin is equal to the radius of the missile body that is actually defined by the design layout of tube launching system. Four wrap-around fins are located at the tail such that the fins do not hold over each other inside the launching tube. In Figure 3 shows some details of the generic geometry with dimensions. For moment calculations, the centroid of the body is selected at 0.22 m from the nose that is 22% of the total length of the body.

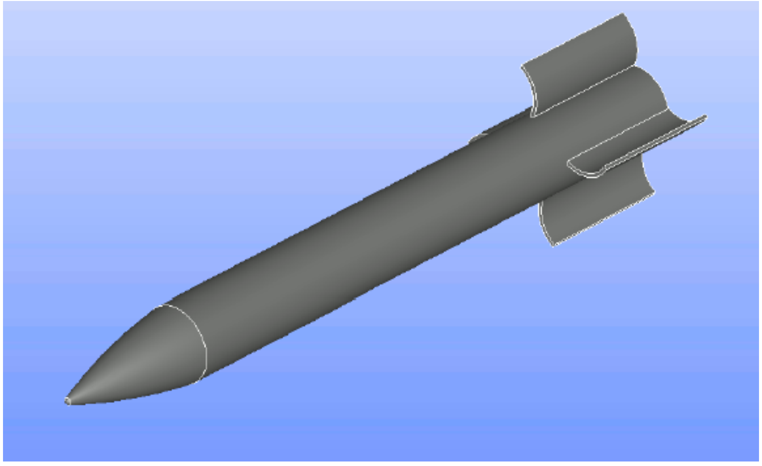


Figure 2. The Dahlke's wrap-around tail finned missile [Dahlke 1976]

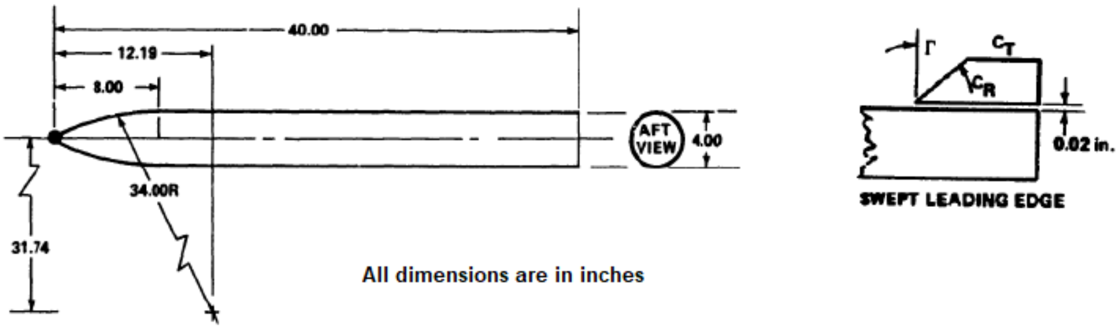


Figure 3. Dahlke F1 Geometry Details [Dahlke 1976]

For CFD simulations performed in this study, the unstructured grid is generated by using Pointwise software. The nose is located at the center of the spherical computational domain with a size of 6 m diameter as shown in Figure 4. The grid has 31 million unstructured cells with 15 viscous sublayers to keep surface y+ values close to 1. In Figure 5, the grid refinement regions around the missile are shown as blocks. In Figure 6-8, the unstructured grid around the missile with local grid refinement regions around its head and tail fins, and in the wake of the fins and missile body, are shown. In order to avoid numerical diffusion, the wake region is refined along a three missile length downstream.

The parallel CFD simulations are performed on TRUBA HPC cluster of TÜBİTAK Ulakbim with 112 cores by using an open source CFD solver, SU2 (version 7.1.1 Blackbird). Implicit density based coupled solver settings are used with Spalart-Allmaras turbulence model. Surface y+ values are kept smaller than 1 on wall boundary conditions and no wall function is used. The JST (Jameson-Schmidt-Turkel) method [Jameson 2017] is chosen as the convective numerical method with artificial viscosity on the pressure related flux terms. GMRES linear solver with ILU preconditioner is chosen with 25 maximum number of iterations for the implicit solver.

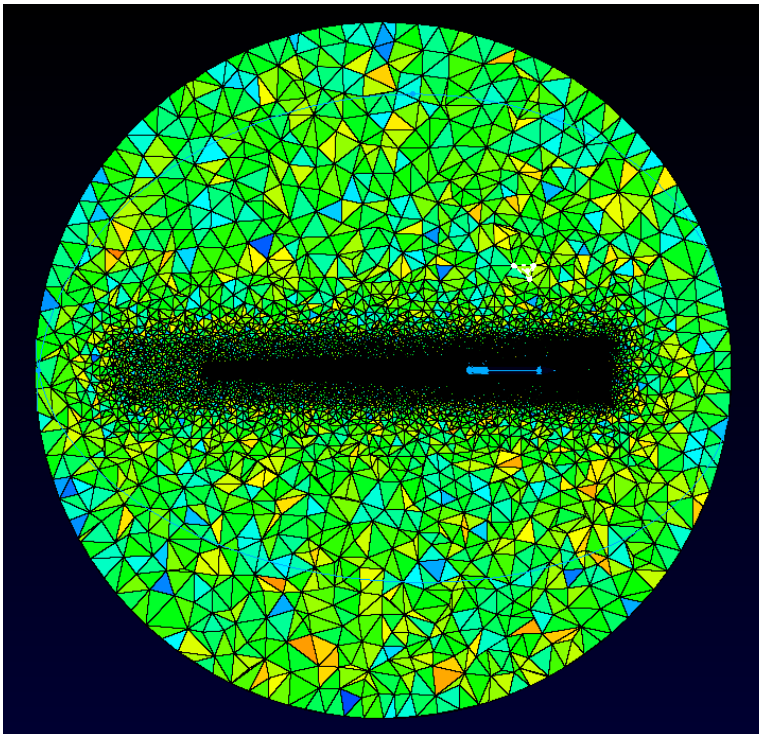


Figure 4: Spherical Computational Domain and Unstructured Grid

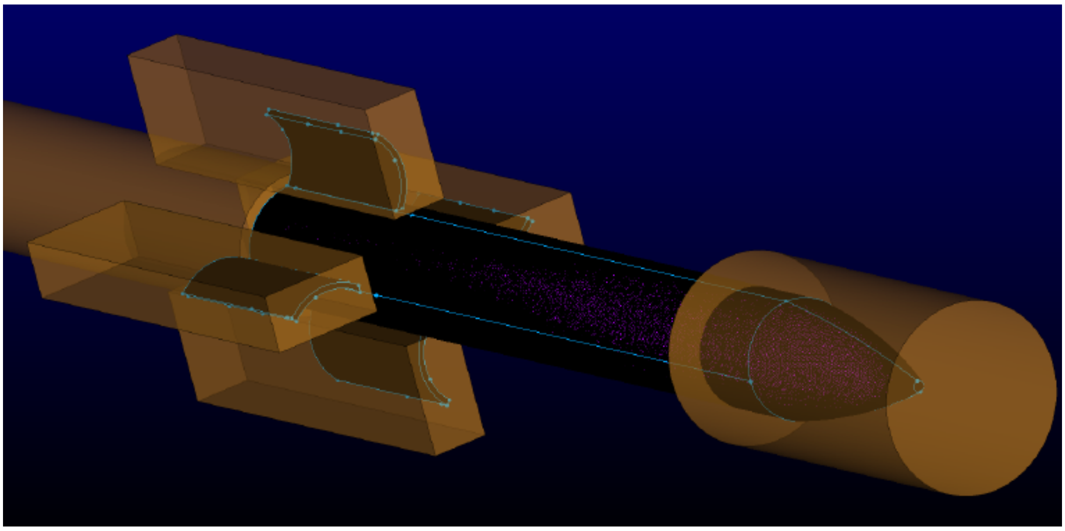


Figure 5: Grid refinement regions around the missile

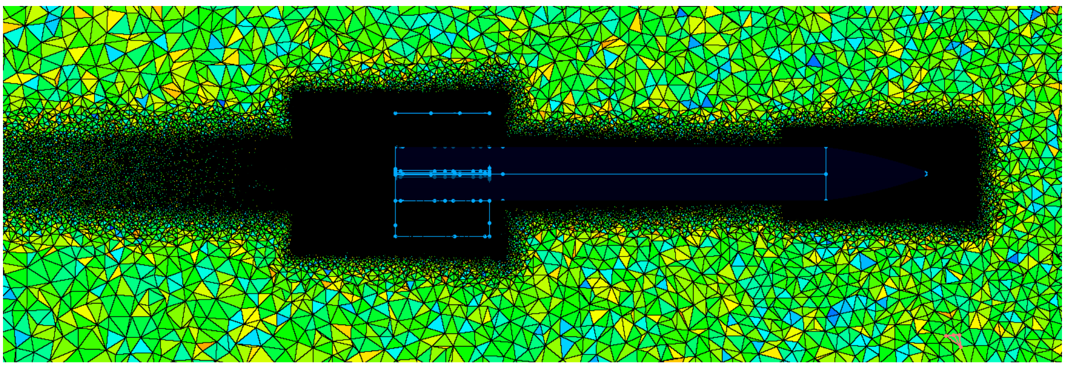


Figure 6: Unstructured grid around the missile with grid refinement regions

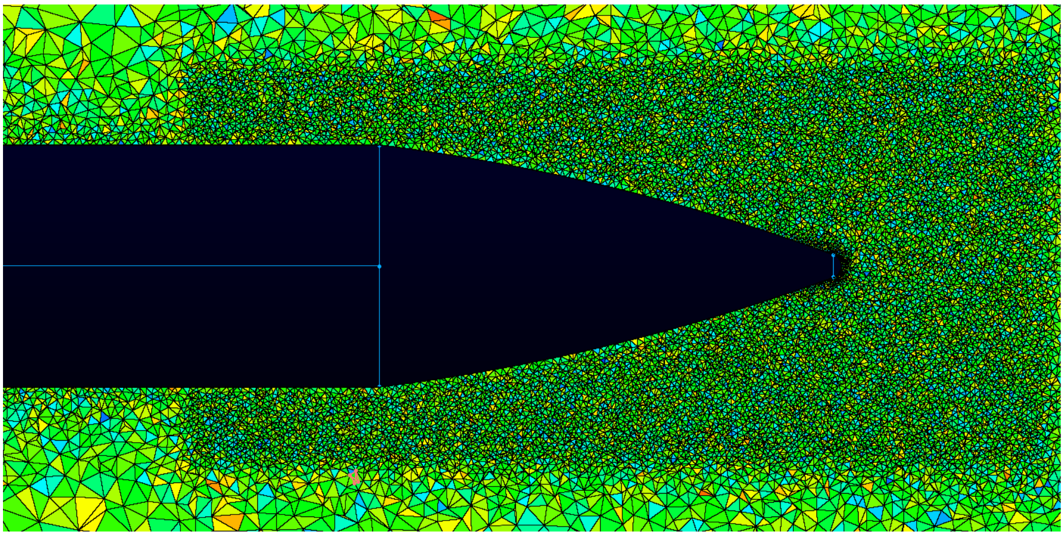


Figure 7: Locally refined regions around the missile head

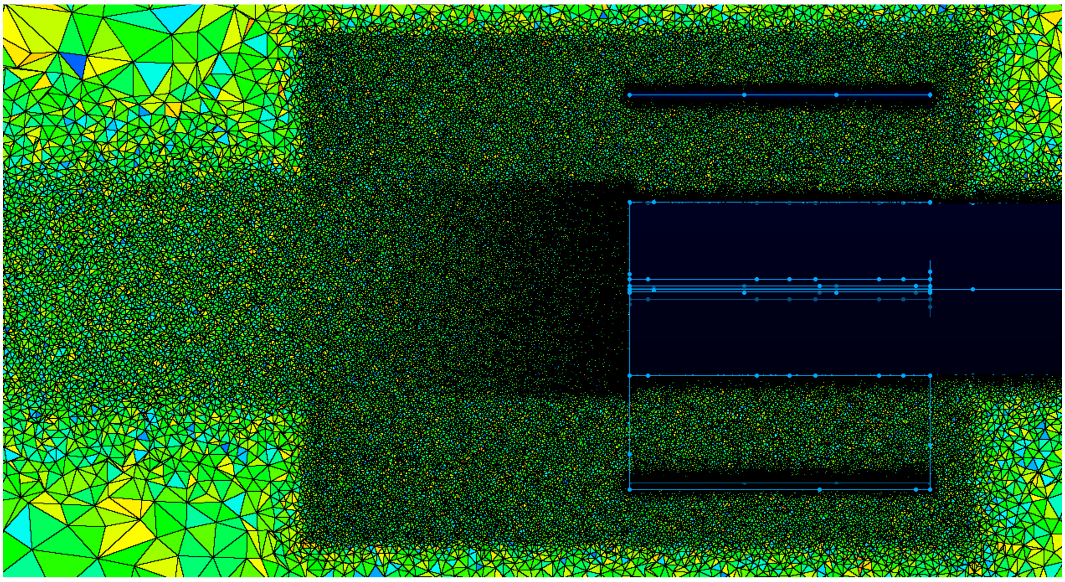


Figure 8: Locally refined regions around the tail fins and in the missile wake region

RESULTS & DISCUSSIONS

The CFD simulations for the generic missile geometry of Dahlke [Dahlke 1976] are performed for Mach number range of 0.4 to 0.8, and for different angles of attack. The computational results are compared as shown in Figure 9 with the wind tunnel experimental data given with uncertainty marks [Dahlke 1976]. The CFD results are much closer to the experimental data at lower Mach numbers. As Mach number increases, the flow separation begins. The effect of Mach number on roll moment coefficient in high subsonic regime has tendency to increase the roll moment coefficient until transonic effects appear around Mach number of 0.8. Since the converging-diverging analogy of [Abate 1993] requires sign shift of roll moment under supersonic conditions, the transonic effects make the sign reversal of the coefficient in a more continuous manner.

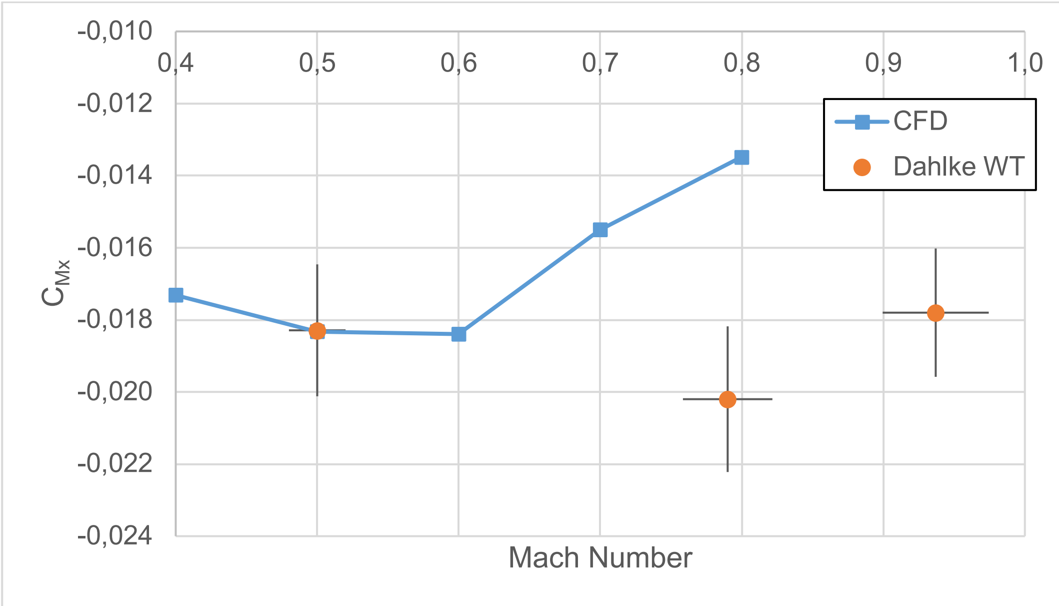


Figure 9. Comparison of Computational Results with Wind Tunnel Data: Roll Moment Coefficient versus Mach Number

The separated flow in the wake, i.e., downstream of the missile's flat base, is mostly due to the inviscid scheme JST with artificial viscosity. In the analyses, the diffusion coefficients of second and fourth order are kept the same as 0.5 and 0.02. Since the spectral radius of the Jacobian is used as a parameter in both artificial viscosity coefficients, the scheme becomes more diffusive as the difference between acoustic eigenvalues grows. In addition, the multiplicative vector is linear combination of both acoustic eigenvectors i.e. higher dissipative contribution is added to the inviscid flux term. For that reason, as Mach number grows the difference between CFD and wind tunnel results grows. Nevertheless, the CFD results are seen close to the wind tunnel results in their uncertainty range at Mach numbers less than 0.6.

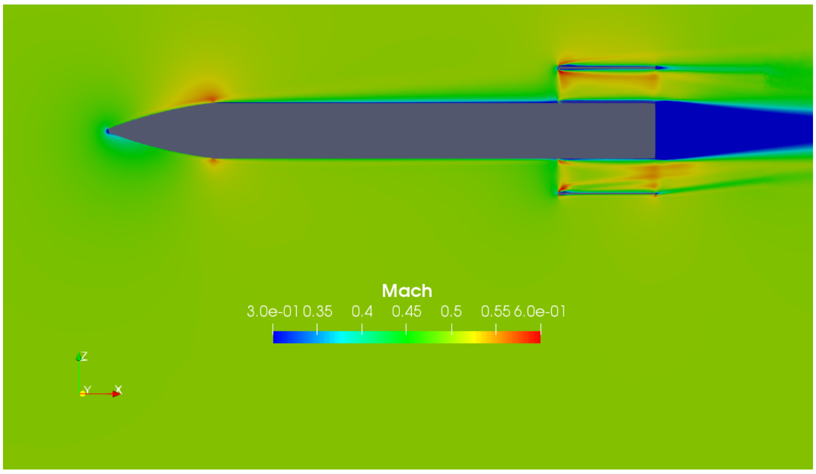
The effect of angle of attack on the roll moment coefficient is examined by a series of CFD analyses between 0 and 8^{o} angle of attack. The side slip angle is not taken into consideration due to its generation of roll moment even for planar fins under asymmetric flight conditions. In Figures 10 and 11, the Mach number and pressure contours are shown, respectively, for different angles of attack. The change in the pressure contours with respect to varying angle of attack are visible around the head and tail regions.

a) AoA = 0°

b) AoA = 2°

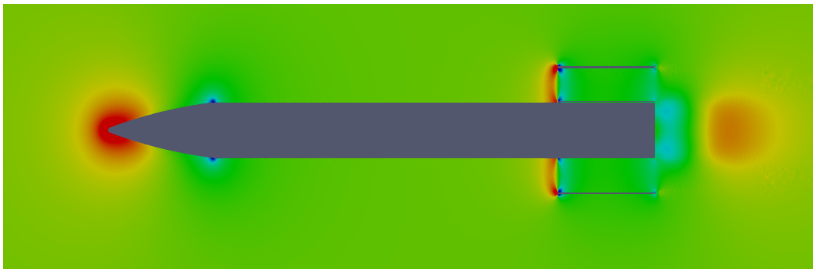
c) AoA = 4°

d) AoA = 6°

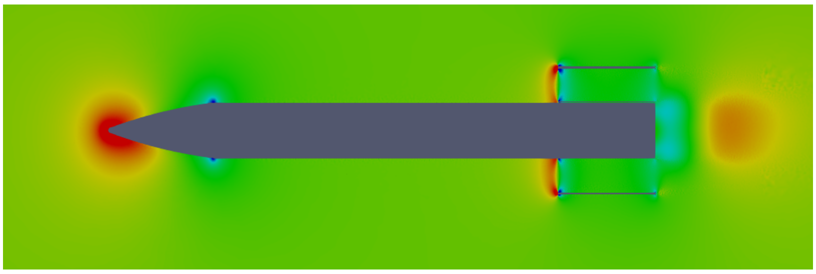


e) AoA = 8°

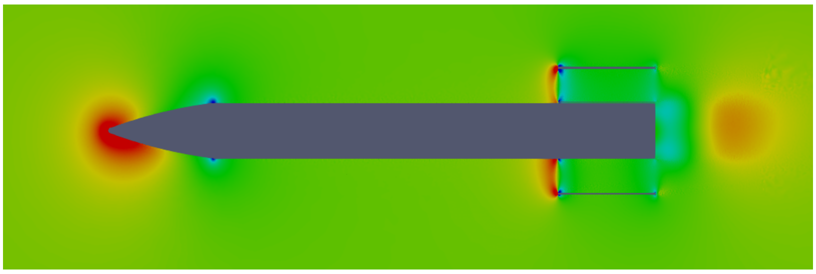
Figure 10: Mach contours at different angles of attack



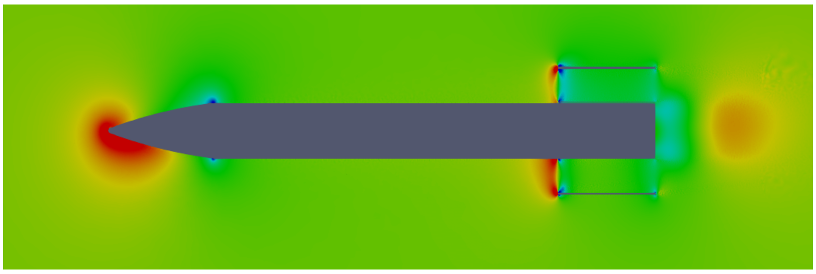
a) AoA = 0°



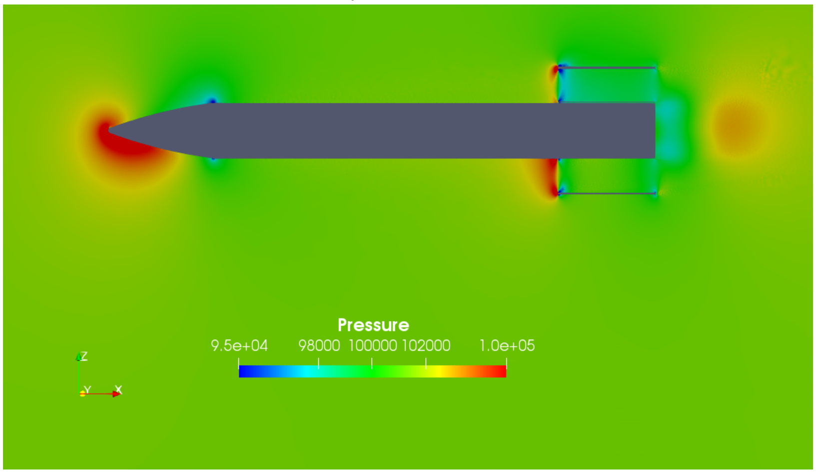
b) AoA = 2°



c) AoA = 4°



d) AoA = 6°



e) AoA = 8°

Figure 11: Pressure contours at different angles of attack

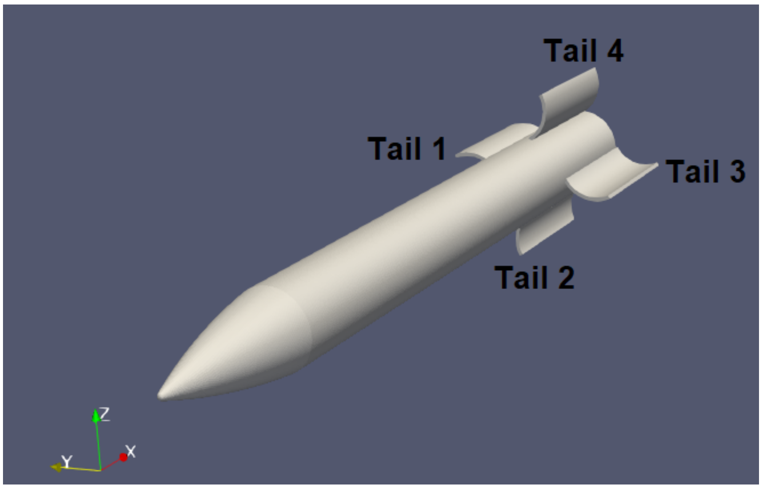


Figure 12: The numbering and names of wrap-around tail fins

In order to analyze the effect of each fin separately, the tails are numbered from 1 to 4 as shown in Figure 12. In Figures 13 and 14, the normal force coefficients and roll moment coefficients computed at several angles of attack are shown, respectively. The normal force coefficient has an almost linear variation with respect to angle of attack as expected from the literature. Unlike the normal force coefficient, the roll moment coefficient does not have a linear relation with the angle of attack. To understand the behavior of the roll moment coefficient, each part of the missile is considered separately as shown in Figure 15. Since the positive angle of attack is applied on the positive z direction, the resultant roll moment of Tail 1 and Tail 3 are considered as summation in order to avoid lift generating tails on the roll moment calculation alone.

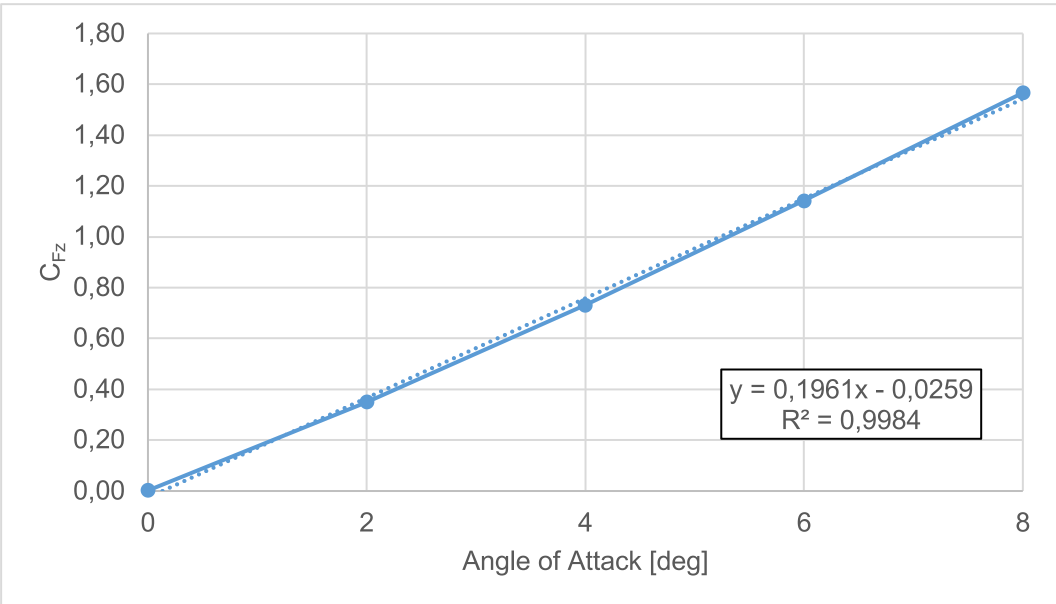


Figure 13. Normal Force Coefficient versus Angle of Attack

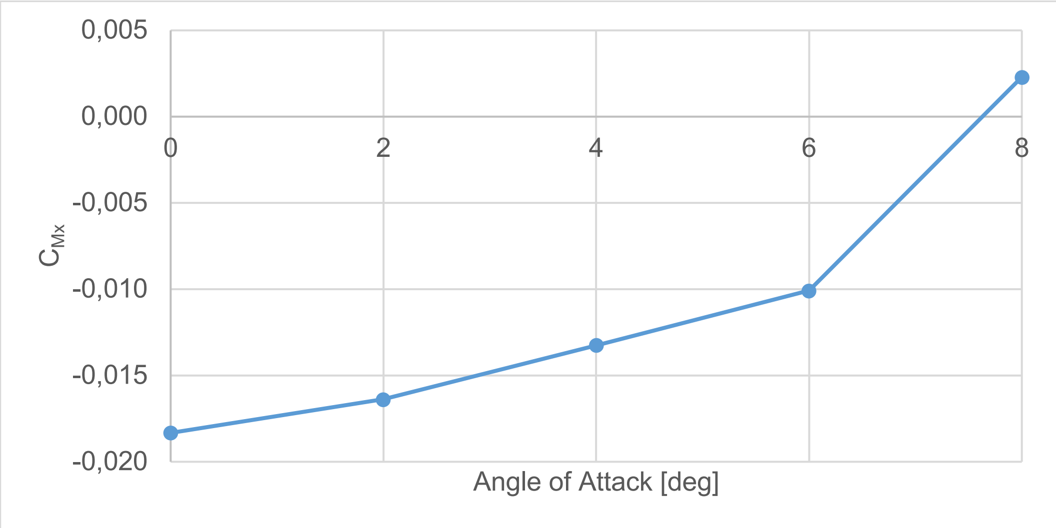


Figure 14. Roll Moment Coefficient versus Angle of attack

In Figure 15, the specific contribution of different sections to the roll moment is shown. As expected, body has no contribution to the roll moment. The contributions from Tail 2 and Tail 4 show a linear tendency with respect to the Tail 1 and Tail 3 combination.

Since the flow velocity is higher on the inner section of the wrap-around fin, the pressure is lower on that section. However, as the flow velocity gains a component towards the inner section with an increase in the angle of attack, it increases the pressure in that region. Therefore, the roll moment contribution of Tail 2 gains an inverse tendency with respect to the 0^{o} angle of attack orientation. The inverse of this phenomenon occurs for Tail 4 with an increasing tendency. However, Tail 4 has smaller derivative with respect to angle of attack than that of Tail 2 due to the body blocking effect on Tail 4.

The total contribution of Tail 1 and Tail 3 has the least deterministic nature than the others. Since the Tail 1 produces a negative force with respect to the angle of attack direction, the increasing angle of attack reduces the stall margin and vice versa for Tail 3. For that reason, the local separation regions over those fins are less anticipated than the others.

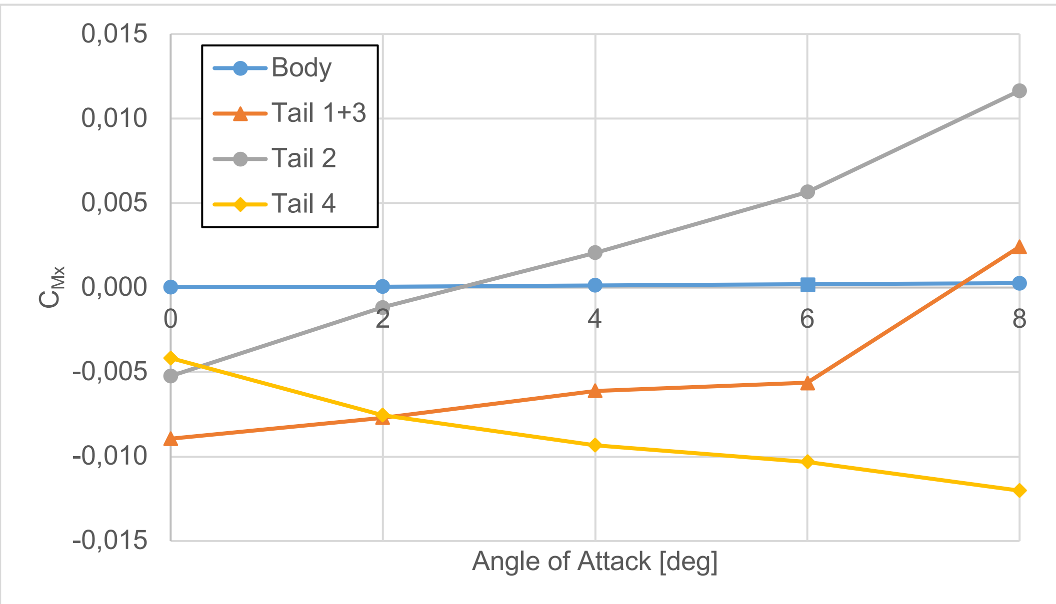


Figure 15. Roll Moment Contributions of Different Body Parts at Different Angles of Attack

CONCLUSION

In this study, the effects of angle of attack and Mach number on the induced roll moment of a generic missile geometry with wrap around tail fins are investigated by performing steady-state CFD simulations. The induced roll moment variations which are important for an effective roll control are presented by considering the contributions of each body part of the missile. The induced roll moment coefficient has tendency to increase with the Mach number until the transonic region starts at 0.8 Mach. On the other hand, the roll moment coefficient has tendency to decrease parabolically towards zero as the angle of attack increases. The change in roll moment is greatly affected by the lift generating fins at nonzero angles of attack.

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